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New Petroleum plays in the Dutch Northern Offshore

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Management Summary

We investigated the subsurface of the Dutch Northern Offshore by focusing on the presence of source and reservoir rocks in the Carboniferous and Permian Systems. The Dutch Northern Offshore has long been a relatively underexplored region and the discovery of reservoirs and mature source rocks could warrant a renewed interest in the area. This project, referred as the Northern Offshore Project, started in 2013 and lasted until May 2015. The present report summarizes and compiles all of the results obtained by the TNO research team.

In this report we describe the multidisciplinary approach that was implemented to investigate the geology of the Dutch Northern Offshore in relation to potential source and reservoir rocks. The project area encompasses several structural provinces, namely the Step Graben, the Dutch Central Graben and the Elbow Spit High (Figure 0-1.1). The main stratigraphic levels of interest are:

1. the Carboniferous interval, which is considered to incorporate the main source rocks, and
2. the Permian-age Rotliegend interval that holds known reservoir rocks in the southern part of the Dutch Offshore but which is far less constrained in the Northern Dutch Offshore.

The project started with an extensive data gathering exercise. A literature review was conducted early in the project, which focussed on the tectono-stratigraphy of the Carboniferous and Permian. Extensive stratigraphical analyses and seismic interpretations were then performed to decrease uncertainties in the stratigraphic and structural settings of the study area. The source rock intervals (Dinantian and Westphalian) were mapped, and a series of stratigraphic cross sections and paleogeographic maps were produced for the Rotliegend reservoir intervals. The results were used as input for petroleum system modelling to provide insights into the thermal maturity as well as the timing of hydrocarbon generation and expulsion from the Carboniferous source rocks. Maps where also produced to illustrate the relationship between location of mature source rocks and the presence of Rotliegend-age reservoir rocks.

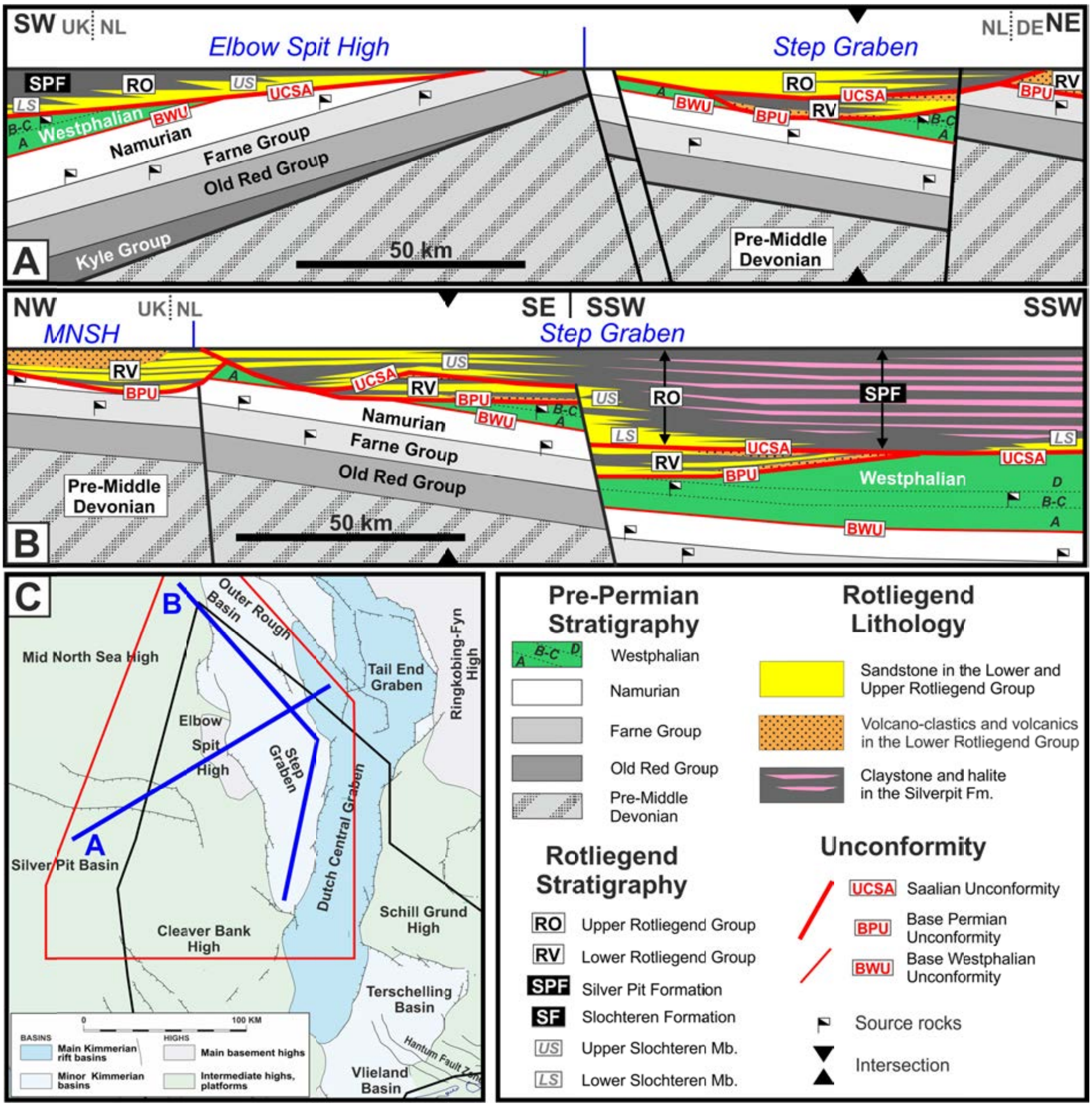


Figure 0-1.1: Stratigraphic setting of the Rotliegend in the Dutch Northern Offshore. This conceptual interpretation is based on tectono-stratigraphic results obtained in the present project. These conceptual models are vertically not to scale. A) NE-SW trending cross section through the Step Graben and the Elbow Spit High. B) N-S trending cross section, with a bend, across the eastern part of the Mid North Sea High (MNSH) and within the Step Graben. C) Location map with the red box indicating the project's study area. Black line shows the edge of the Dutch Offshore. Modified from de Jager (2007).

Literature Review

The literature review results in an improved understanding of the evolution of the Dutch Northern Offshore area during the Late Palaeozoic. During the course of the project the TNO research team identified a possible time equivalent of the Lower Rotliegend on the northern side of the Mid North Sea High. Referred as the Grensen Formation by Martin *et al.* (2002), this siliciclastic interval is located in the Eastern part of the offshore UK sector around the Auk and Flora Fields. This added the

Lower Rotliegend as a potential reservoir rock in the most Northern part of the study area.

Source rocks

Dinantian and Westphalian source rocks where investigated. The presence of the Dinantian source rocks (namely the coals of the Scremerston Formation (UK), equivalent to the Elleboog Formation in the Dutch sector) in the Dutch Offshore is uncertain since it has not yet been drilled in the Netherlands. However, seismic mapping of this interval from the UK sector southward into the northern part of the Dutch Northern Offshore (Blocks A, B) suggest that this source rock is present in the study area but may be limited in its extent toward the northern zones.
Seismic mapping of the Westphalian suggests that this source rock is present in a large part of the Step Graben and it seems to be in hydrocarbon generating windows for the majority of the wells used in the petroleum modelling (see Figure 0-1.2). The results show that active hydrocarbon generation and expulsion occurred from Westphalian source rocks in the Step Graben and Dutch Central Graben.

Reservoir Rocks

The presence of sandy strata of Rotliegend-age in the Dutch Northern Offshore has been known for many years but the detailed stratigraphic setting of this interval remained broadly unknown. The stratigraphic and tectonostratigraphic results obtained in this project prove the presence of regionally extensive Rotliegend reservoir rocks in the study area, including within the Lower Rotliegend Group that is often perceived as a volcanic-prone interval but in reality includes large volume of sands. A series of new paleogeographic maps was constructed that show the presence of Lower Rotliegend strata in the north-eastern part of the study area and E-W to NE-SW trending sandy coastal zones along the northern margin of the paleo Silver Pit Lake for the Upper Rotliegend. These coastal and aeolian sandy zones migrated northward through time due to a major transgression.
Figure 0-1.2 shows the relationship between the Rotliegend sandy deposits (stripped area) and the new Westphalian maturity map (coloured). By combining the maturity map and sand map, a few prospective areas were identified. One of the most prospective areas covers the A15 and B13 blocks, where the Westphalian is mature and where the Rotliegend contains good amount of proven sands. Another interesting area include the F01, F02, F04, F05 blocks, where the Westphalian is also mature, and where a significant amount of sand is expected on the hanging wall side of syn-depositional faults.

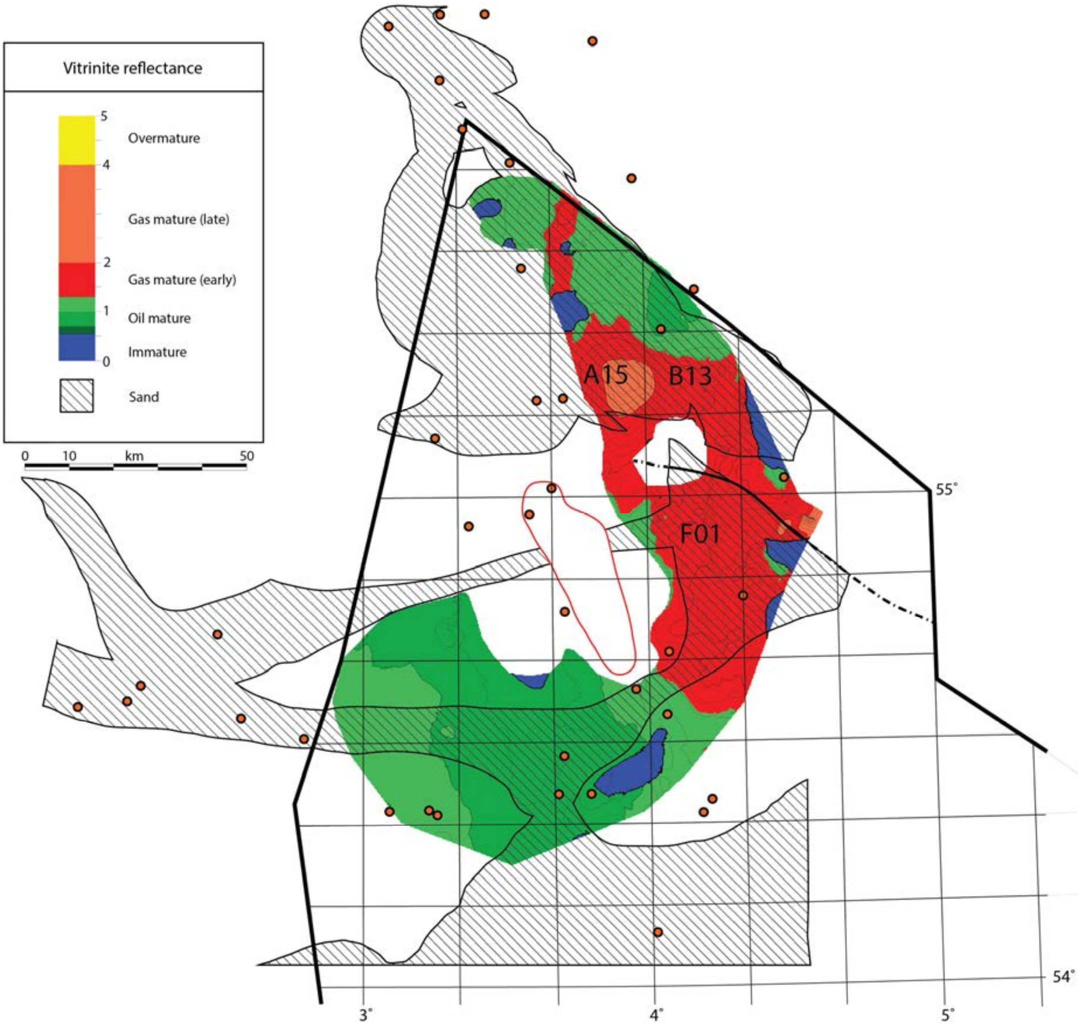


Figure 0-1.2: Overlay of the Westphalian maturity map with the Rotliegend sand map indicating possible prospective regions.

Conclusions

This multidisciplinary project has drastically improved our understanding of the Permo-Carboniferous in the Dutch Northern Offshore and has shown real exploration potential in the Rotliegend.

After a thorough lithostratigraphic well re-interpretation and a regional seismic mapping study, the Westphalian interval is interpreted as being present in a large part of the Dutch Northern Offshore and only absent above the Elbow Spit High. Part of the Westphalian is interpreted as effective source rocks that are mature in the Step Graben and in the northern part of the Cleaver Bank High, where good amounts of Rotliegend sands have been identified.

The information on the occurrence and distribution of Rotliegend-age sands has been greatly improved through this project. Lower Rotliegend deposits (Basal Rotliegend Clastics and Grensen Fm.) turned out to comprise significant volumes of reservoir-quality sands but are aerially confined within the north-eastern part of the study area in structural lows and are interbedded with non- to low-reservoir quality

facies including volcanics and volcanoclastics. The distribution of reservoir sands of Upper Rotliegend-age is now geographically better constrained. The results also show that paleo-topography and syn-depositional faulting highly controlled the reservoir sand deposition by locally affecting accommodation and sediment dispersal.
The combination of the basin modelling and stratigraphic results helped to define prospective areas where good reservoir sands are located above matured Carboniferous source rocks.

Contents

1 Introduction

The Northern Dutch Offshore remains a relatively underexplored area in the North Sea. The often assumed lack of reservoirs, source rocks and adequate sealing capacity has so far hampered any extensive exploration activities in the area. Discovery of quality pre-Zechstein reservoirs (e.g. Rotliegend sands) and mature source rocks (e.g. Westphalian) could warrant renewed interest in the area. Recent activity in the UK sector, in an area neighboring the study area (Cygnus Field), proves that the northern side of the paleo Silver Pit Lake has clear potential for the presence of Rotliegend-age reservoir sands and Westphalian source rocks. Following the interest in the Dutch Northern Offshore of several parties, a research proposal was initiated by TNO to reinvestigate the prospectivity of the area.

1.1 Study area: Location and stratigraphy

The project’s study area encompasses several structural provinces including the Step Graben, the Dutch Central Graben, the northern part of the Cleaver Bank High, and the Elbow Spit High (Figure 1.1). The area covers the A, B, D, E and part of the F offshore blocks (DEFAB), and also extends slightly into the British, German and Danish offshore sectors. The project comprise primarily the stratigraphic interval from base Carboniferous to base of Zechstein, with increased focus on the Westphalian (source rocks) and Rotliegend (reservoir rocks) intervals.

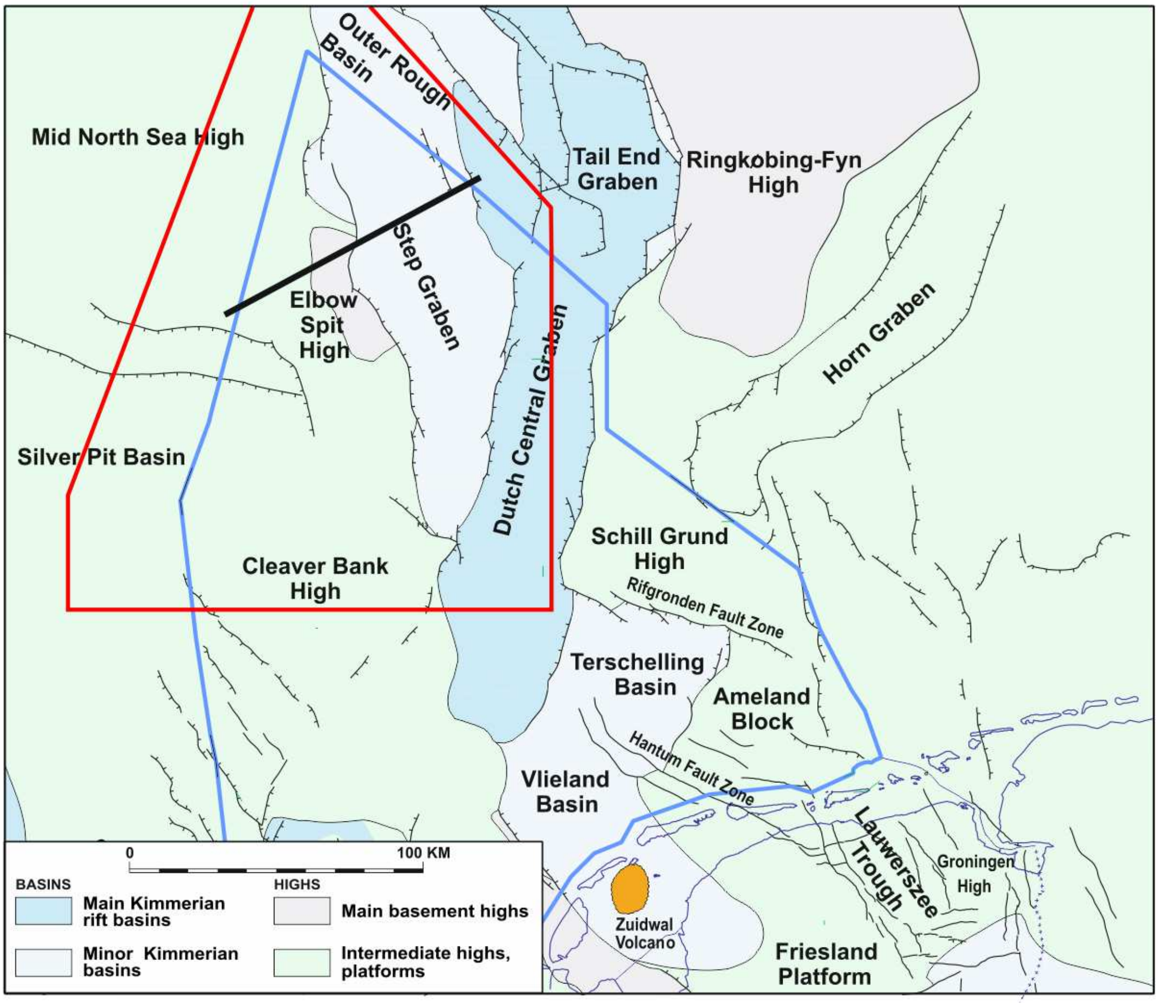


Figure 1.1: Dutch Offshore map showing the main structural provinces. Study area is shown as a red outlined polygon. Location of Figure 1.2 shown as thick black line

To test some hypotheses, an integrated multidisciplinary research project was set up. The hypothesis, which is the basis for the research proposal and subsequently the project, goes as follows:

Initial Hypothesis: A Carboniferous stratigraphic interval, approximately 120 meter-thick with high TOC values, was encountered in the Step Graben (F10-02 well). Initial biostratigraphic dating placed this interval with the Stephanian stage. One of the initial hypotheses at the start of this project was that, if this interval was wide-spread throughout the Step Graben and the Dutch Central Graben, it could be an important source rock and help renew interest in the Dutch Northern Offshore. Furthermore, in well K02-02, a thin red-coloured conglomerate has been found stratigraphically between the Westphalian and the Upper Rotliegend. Due to its stratigraphic position, it was proposed that these coarse deposits were laterally equivalent to the TOC rich interval in well F10-02. If true, this would mean that a lateral facies change from source rocks to reservoir rocks occurs between F10-02 and K02-02. This hypothesis was however discarded during the course of the project.

From the start, the project was divided into 3 main parts (or themes) each focussing on different research subjects (see Appendix 1). These themes focused on 1) the presence of Stephanian-age reservoir and source rocks, 2) the presence of Rotliegend-age reservoir sands along the northern margin of the Silver Pit Lake (or Northern Fringe Sands), and 3) the Devonian Kyle Group western onlap onto the Elbow Spit High. During the course of the project, it was jointly decided not to perform (parts of) Themes 1 and 3 but to rather pay full attention on the research linked to Theme 2. Part of Theme 1 was merged with Theme 2 since early stratigraphic analysis revealed that the alleged Stephanian-age strata were rather of Westphalian in age. Phase 3 was cancelled due to budget cuts and decreased interest from stakeholders.

Revised Hypothesis: During the latest part of the Carboniferous, the Dutch Central Graben and Step Graben started to subside. The emerging basin configuration persisted during Rotliegend time, during which the basin may have captured sediments (possibly coarse) from Southern and possibly Northern source areas. During the basin initiation, the Step Graben and Dutch Central Graben may have acted as north-south conduits for sand-rich sediments. One of the main research goals was to evaluate the prospectivity of the Dutch Northern Offshore area in terms of 1) the source rock occurrence and maturity, and 2) the reservoir rock occurrence and distribution.

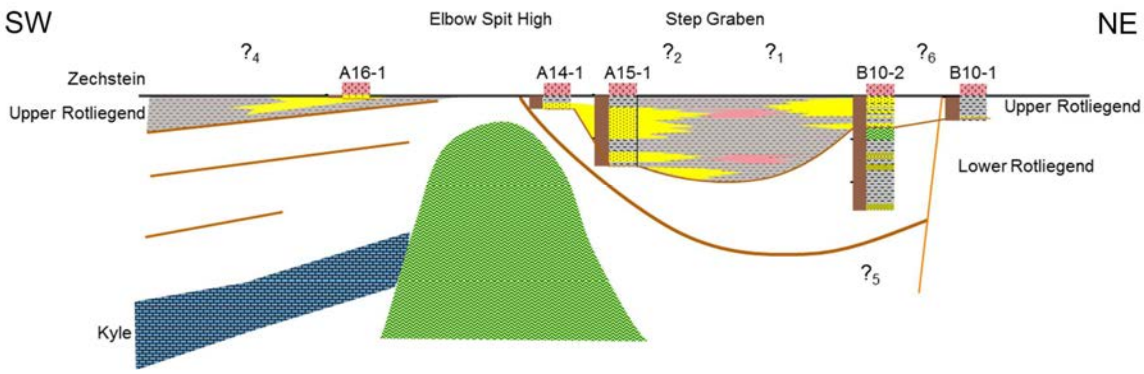


Figure 1.2: Conceptual tectono-stratigraphy cross section illustrating the main initial research questions of the project. See Figure 1.1 for location.

1.2 Project execution

The project was planned to last 1½ years and officially started in January 2013, although activities relating to content only started in September 2013, with an extensive data gathering and evaluation exercise. All wells within the area of interest that penetrated the Permian and older strata were identified and selected. The project used well data from Dutch, British, and Danish wells. Information from Dutch wells was acquired through the NLOG data base (NLOG.NL), whereas data for the selected British and Danish wells was acquired through the respective geological surveys (BGS, GEUS). Data from only one German well was acquired (i.e. B10-01), which used to be a Dutch well when drilled. The project made extensive use of seismic data, with 2D and 3D seismic surveys obtained from the NLOG data base and additional proprietary 2D seismic data provided by Fugro.

Early in the project a literature review was conducted and focused on the tectono-stratigraphy of the Carboniferous and Permian for the area of interest. This review can be found in Appendix 2

During the course of the project, an integrated seismic interpretation/lithostratigraphy analysis was carried out, using 2D/3D seismic and well data. A biostratigraphical effort was also included in this project, which made use of published palynological and drilling reports, composite logs and core descriptions. Additionally new biostratigraphical and geochemical (in the form of ^{13}C isotopes) analyses were performed to increase confidence in age determination of key intervals. However, early in the seismic interpretation phase, it became clear that a number of age discrepancies existed between seismic and wells information as provided in the NLOG database. Consequently an inventory was made to identify the wells that required a stratigraphical re-evaluation. Therefore, the re-evaluated and updated lithostratigraphic information for the pre-Zechstein was compiled for 18 key wells and was incorporated into the Petrel database. The updated stratigraphy and the seismic interpretation were subsequently used as input for petroleum system modelling. The petroleum system modelling focused on maturity prediction at 12 well locations plus one pseudo well location.

1.3 The project team

Vincent Vandeweijer	Project Manager	Project and financial management
Geert de Bruin	Lead Scientist	Scientific team management /seismic interpretation
Renaud Bouroullec	Senior Geologist	Well correlations, seismic interpretation and geological analysis and integration
Kees Geel	Senior Geologist	Well reinterpretation
Tom van Hoof	Biostratigrapher	Palynology and Isotope Stratigraphy
Rader Abdul Fattah	Basin Modeller	Basin and maturity Modelling
Mart Zijp	Geologist	Geological interpretations
Maarten Pluymaekers	Geologist	Seismic time-depth conversion
Frank van der Belt	Geologist	Literature review
Johan Ten Veen	Senior geologist	Advisor and quality control
Mark Bouman	Senior geologist	Advisor and quality control

2 Geological Setting

The description of the geological setting of the Dutch Northern Offshore has been divided into two parts in this report. The large scale geological setting including the Southern North Sea geological evolution during the Carboniferous and Permian was compiled from a literature review and is presented in Appendix 2 and briefly summarized below (Chapter 2.1). The second part of this chapter (Chapter 2.2) focuses specifically on the Rotliegend geological setting and summarizes the current knowledge of the Rotliegend in the study area.

2.1 Overview of the tectono-sedimentary evolution of the Dutch Northern Offshore within the Northwest-European paleogeographic context

The synthesis of various publications has resulted in an improved understanding of the evolution of the Dutch northern offshore area during the Late Palaeozoic, which primarily concerns the early activity and tectono-sedimentary evolution of the proto-Dutch Central North/Step Graben system from the Early Westphalian onwards.
In short, this geological history of the study area gathered from published research was compiled and summarized in a report and is illustrated in Figure 2.1, while the entire report can be found in Appendix 2.1.
The main conclusions are summarized as follows:

- The evolution of the proto-Central Graben/Step Graben system seems to have strongly controlled the distribution of fluvial sands into the NW European basin system during the Carboniferous and Permian:
- Initially, during the Dinantian and Namurian, a point source existed that roughly coincided with the southern tip of the proto-Viking Graben.
- During the Westphalian A, the Caledonian highlands seem to have developed towards a more extensive line source, but the area east of the Step Graben did not receive significant fluvial sands. This suggests that the proto-Step Graben system may have acted as a divide (topographic high) rather than a low.
- During the Early Westphalian B the fluvial systems abruptly retreated from most of the Southern North Sea. This might be related to the initiation of the proto-Central/Step Graben system as an extensional system. Accelerated subsidence may have caused fluvial systems to stay within the system (potential reservoirs) and no longer prograde out into the basin.
- The Late Westphalian compressional direction seems to be parallel to the general direction of the graben system, allowing for extension during the Variscan culmination. This may explain the presence of thick Westphalian D strata in the Step Graben. Furthermore, accelerated subsidence may have allowed longer accumulation of peat in these grabens as subsidence may have kept the sediment surface at ground-water level (unlike in the main basin).
- During the Permian, the graben system remained active as a low, as reflected in the major fluvial pathway running N-S toward the Step Graben system.

- Thick Rotliegend “Northern Fringe” sands can be expected towards the west, due to a combination of overall palaeo-wind direction (blowing (south)westward) and the absence of northern source.
- The results of this literature review show that any previous conclusions about Palaeozoic activity of a proto-Dutch Central Graben may possibly apply to the proto-Step Graben.

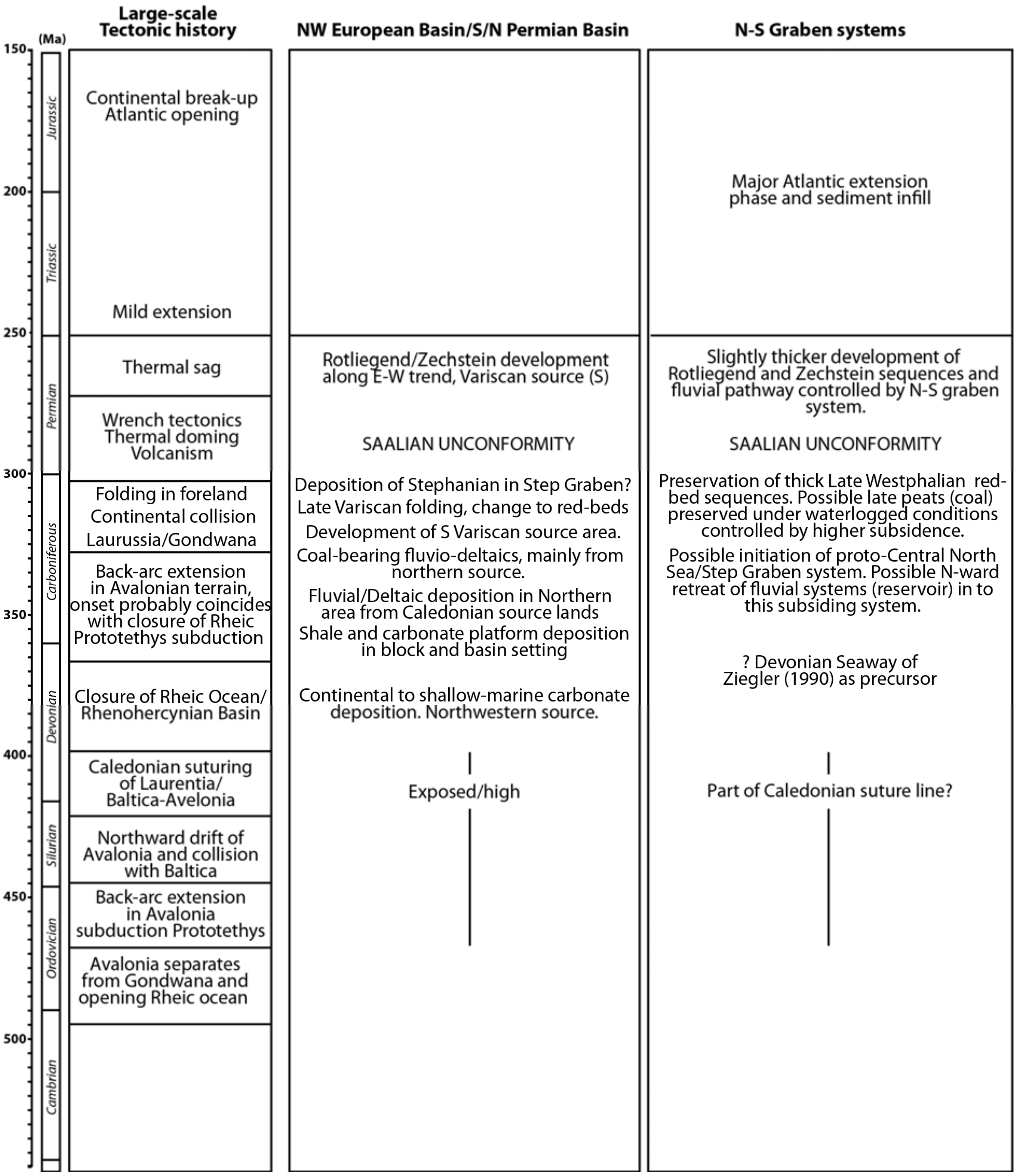


Figure 2.1: Summary of main tectono-sedimentary events in the NW European basin system and cross graben systems, compiled during the literarture review (Appendix 2.1)

2.2 Overview of the Rotliegend

The distribution of the Rotliegend stratigraphic interval within the Southern Permian Basin has been described in many publications and in the recent substantial compilation with the Southern Permian Basin Atlas (Gast et al., 2010), which constitutes a valuable summary of the current knowledge on the subject. The Rotliegend is present across the Dutch Northern Offshore but is locally very deep in the Dutch central Graben (Figure 2.2). Figure 2.3 and Figure 2.4 are from Gast et al. (2010) and show the regional correlations of the Lower and Upper Rotliegend strata from east (i.e. Poland and Germany) to west (UK). It is important to notice that in the Dutch sector only relatively young Lower Rotliegend strata are preserved. These strata are referred to as Lower Rotliegend Volcanics Subgroup in Figure 2.3 or the Karl Formation and the Emmen Volcanic Formation in Figure 2.4. However, older Lower Rotliegend strata are deposited in the eastern part of the Southern Permian Basin, in Germany and Poland (Havel Subgroup). During the course of the project the TNO research team identified possible reservoir rocks that are time equivalent of the Lower Rotliegend on the northern side of the Mid North Sea High. Referred as the Grensen Formation by Martin et al. (2002), this siliciclastic interval is located in the Eastern part of the offshore UK sector around the Auk and Flora Fields (see Appendix 2.2 for a more detailed description of the Grensen Formation).

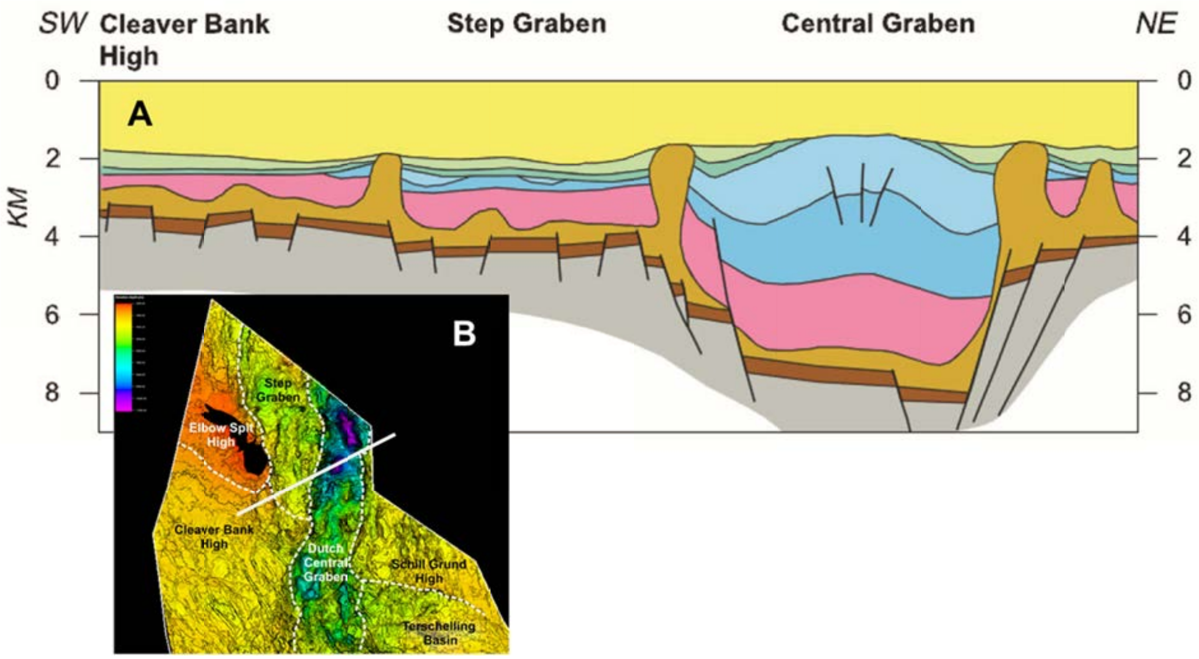


Figure 2.2: Regional cross-section in the Dutch Northern Offshore. A) Cross-section from De Jager (2007). B) Base map showing the location of section A, with the base Zechstein time structure map as background. Note that the Rotliegend (brown unit) is around 8 km deep in the Central Graben, making it often difficult to image on seismic.

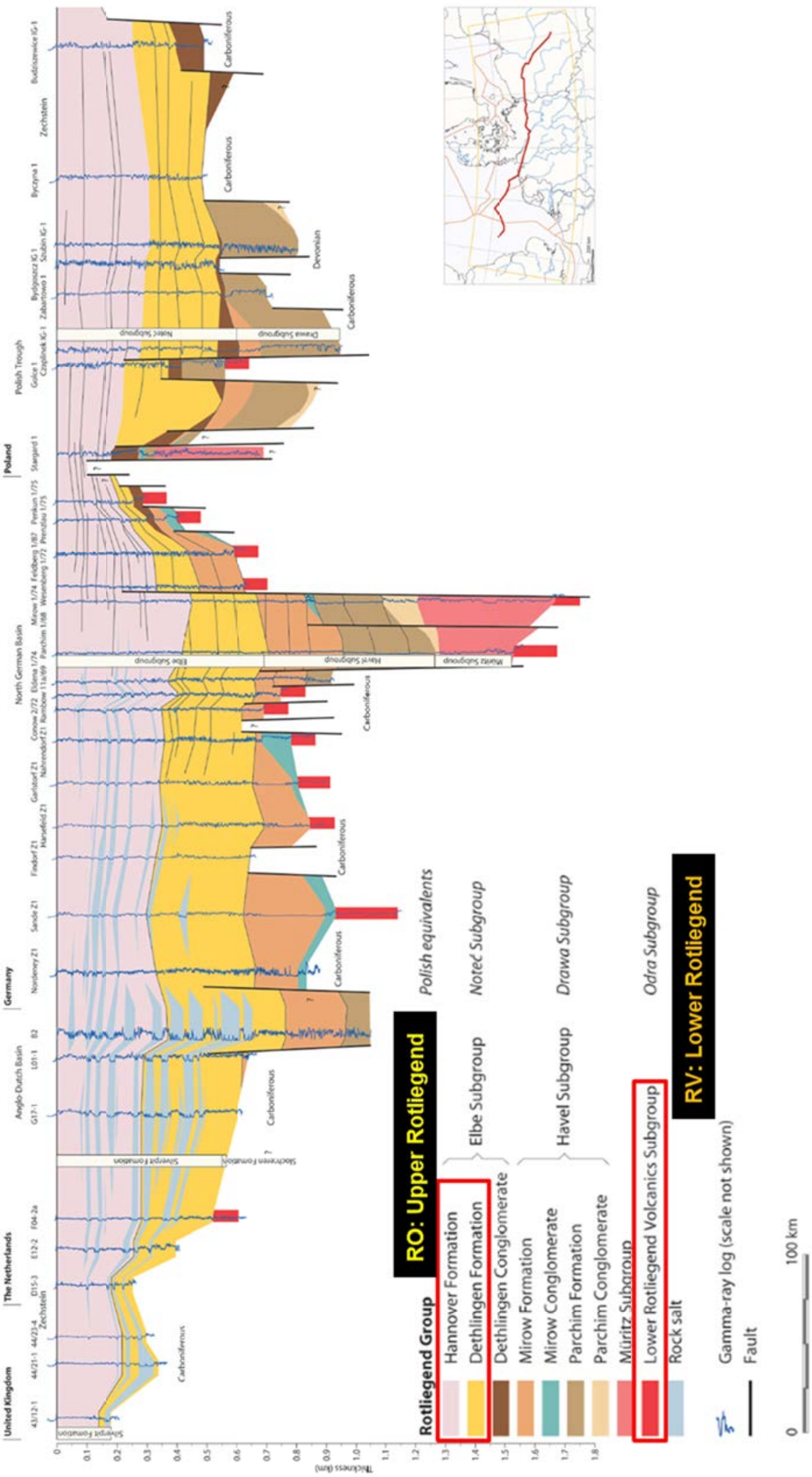


Figure 2.3: E/W oriented regional stratigraphic cross-section of the Rotliegend Group through the Southern Permian Basin. From Gast. *et al.* (2010). Note that the halite intervals within the Upper Rotliegend can be correlated for long distances and are often useful for basin-scale stratigraphic correlation in saline confined basins

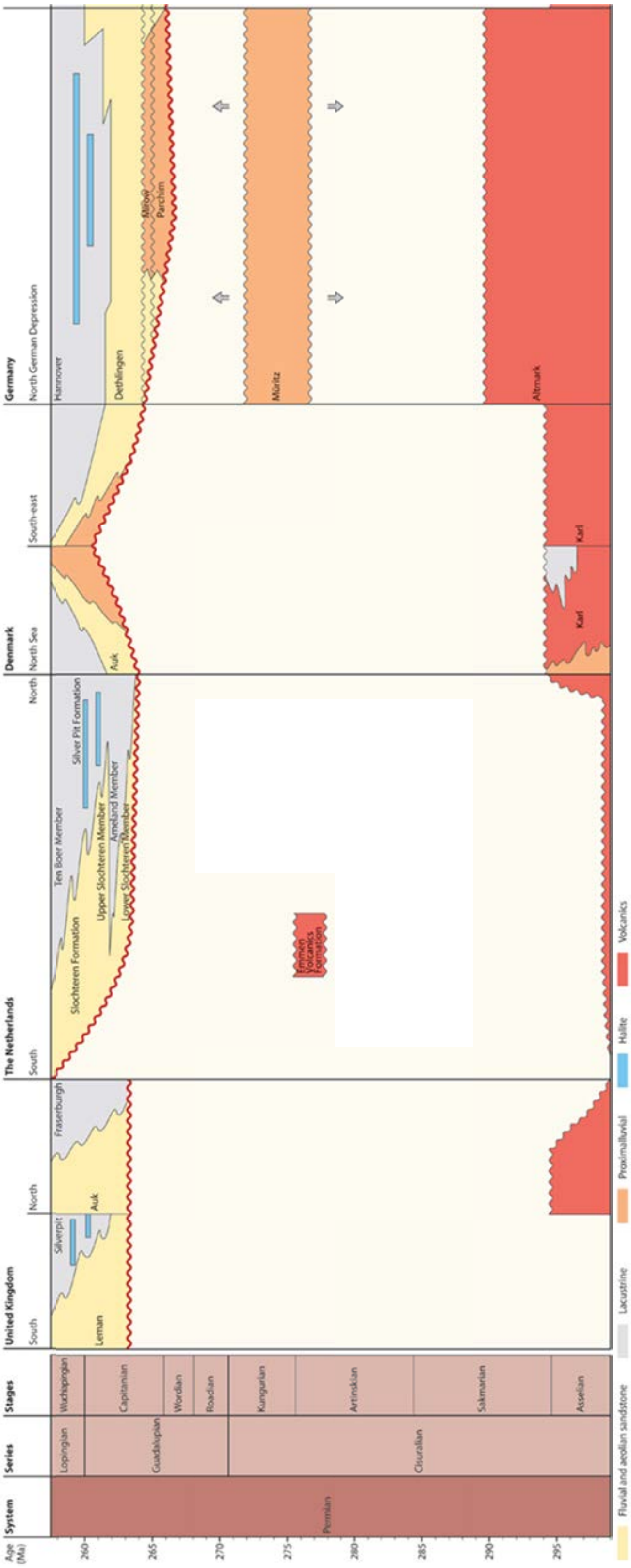


Figure 2.4: Rotliegend chronostratigraphical chart. Based partly on Glennie (2007) and Gast R. *et al.* (2010). Note that most of the Rotliegend time is recorded as a hiatus (Saalian Unconformity) in the Dutch Sector.

The simplified Upper Rotliegend stratigraphy in the Netherland is shown in Figure 2.4) with a southern sand-rich zone (Lower Slochteren and Upper Slochteren Members of the Slochteren Formation) and a northern low net-to-gross zone (Ameland and Ten Boer Members of the Silver Pit Formation). The isopach of the Upper Rotliegend (Figure 2.5) shows that the average thickness in the Dutch sector ranges from 700m in the east to 0m on basement highs (e.g. Mid North Sea High). This map also shows how rapidly the Upper Rotliegend interval thickens eastward with more than 1.3 km of strata accumulated in the German Offshore.

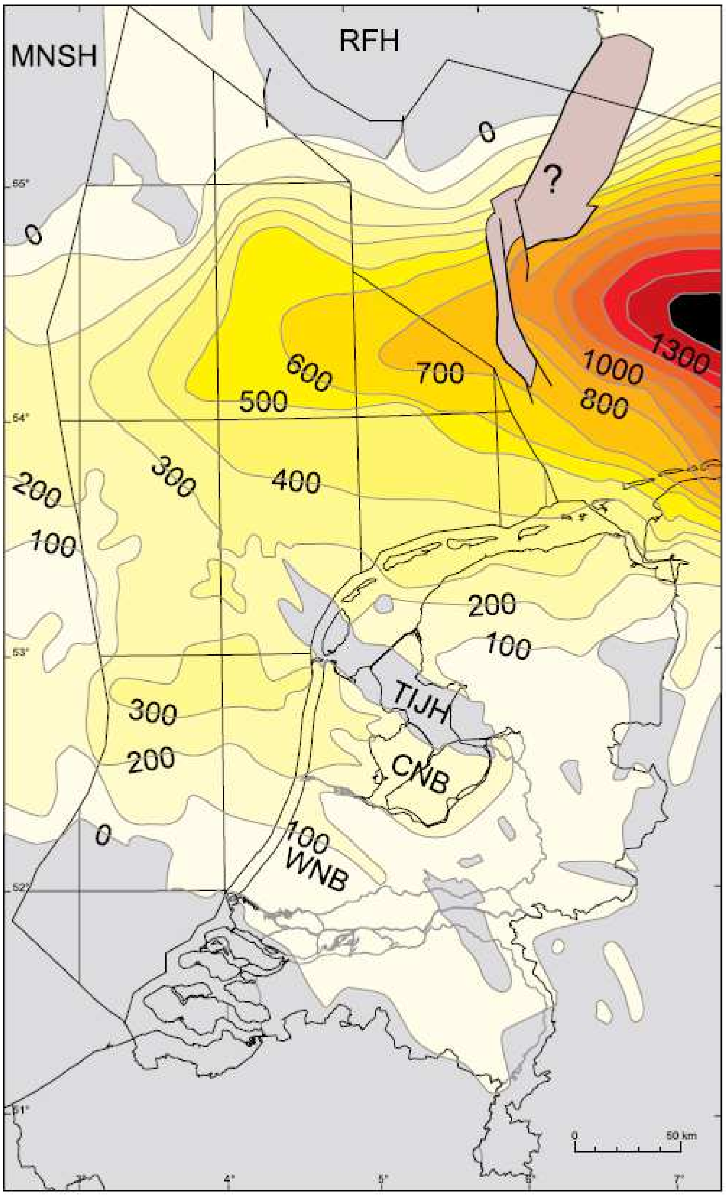


Figure 2.5: Isopach map of the Upper Rotliegend Group (after Lokhorst et al, 1998). Contours interval is 100 m. WNB: West Netherland Basin; CNB: Central Netherland Basin; TIJH: Texel-IJsselmeer High; MNSH: Mid North Sea High; RFH: Ringkøbing-Fyn High. From Geluk et al. (2007)

The “Northern Fringe Sand” is defined as the northern sandy basin margin of the Southern Permian Basin during Rotliegend time in this study area. It constitutes the north-western margin of the SPB and is bounded by two paleo-highs to the north (Mid-North Sea and Ringkøbing-Fyn Highs). The relationship between the Rotliegend and those topographic highs will be discussed in this report.

During the Upper Rotliegend time, sandy reservoir strata (i.e. upper playa, playa margin and erg depositional settings in Figure 2.6) may have been deposited along the northern basin margin.

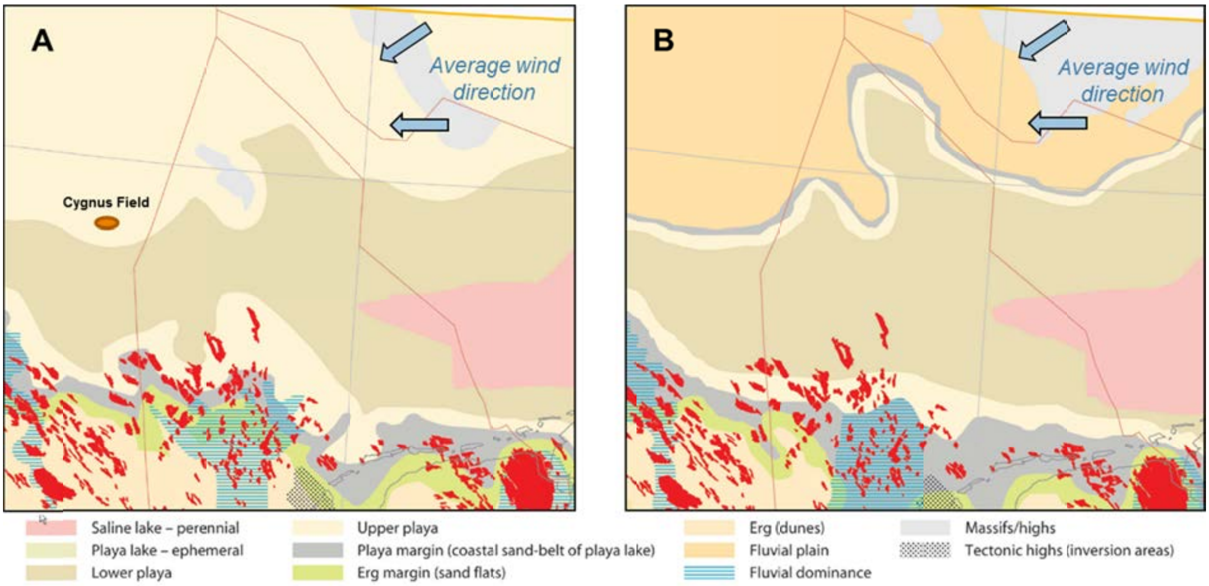


Figure 2.6: Reservoir facies distribution in the western-central part of the Southern Permian Basin. A) The lower part of the Slochteren Formation and its equivalents. B) The upper part of the Slochteren Formation and its equivalents. Fields with Rotliegend reservoir are also shown. Modified from Gast et al. (2010)

The present study provides a more detailed stratigraphic model that previously published and produces new paleogeographic maps for the Lower and Upper Rotliegend intervals.

3 Methodology

Several analytical techniques were performed in this project, including well (re)interpretation, seismic mapping, biostratigraphic analysis, Carbon isotope analysis, stratigraphic correlation, basin modelling (including sensitivity analysis and maturity mapping)

3.1 Well (re)interpretation

Robust stratigraphic interpretation is crucial in this area since 1) seismic data quality varies widely, especially due to the presence of Zechstein salt, 2) well data is sparse, and 3) up to four different stratigraphic unconformities are known to occur within the Upper Carboniferous-Permian stratigraphic interval, and can be locally misinterpreted. A successful seismic interpretation exercise depends strongly on the well information and the validity of key stratigraphic markers for intra well correlations.

After reviewing all the wells within the study area, a re-evaluation of pre-Zechstein lithostratigraphy was carried out for 18 wells. We critically reviewed and reinterpreted these wells using:

- various documents from the NLOG database, including end-of-well reports, well logs, core descriptions, cuttings descriptions, biostratigraphical reports and geochemical reports;
- non-NLOG biostratigraphical information (palynology) compiled by Tom van Hoof (TNO)
- new stratigraphic interpretation highlighting inconsistencies in NLOG lithostratigraphical interpretation, such as the presence in-situ anhydrite in Westphalian, or the presence, omission, misinterpreted, or underestimated of volcanics and volcano-clastics sediments in the interval of interest;

A systematic approach was used to establish a rigorous well interpretation for the Rotliegend in this part of the Dutch Offshore. Two basic rules were established and followed to distinguish the presence of Upper Rotliegend (RO) and Lower Rotliegend (RV):

- Rule #1: Occurrence of in-situ anhydrite lithology below the base Zechstein indicates the presence of Upper Rotliegend Group. The only exception is attributed to the Buchan Formation (Devonian).
- Rule #2: Volcanics or volcano-clastic lithologies identified above the base Permian unconformity (BPU) and below the base Zechstein are interpreted as part Lower Rotliegend Volcanics (RVVE) and therefore are part of the Lower Rotliegend Group (RV)

A total of 18 wells were subject to this lithostratigraphic (re)interpretation. The results are presented in Appendices 3. The proposed lithostratigraphic modifications were reviewed by both the Geology and GeoBiology groups of TNO and validated.

3.2 Seismic mapping

The seismic interpretation exercise focused on seven regional seismic lines made available by Fugro (see also appendix 4.01). These lines proved to have the highest resolution below the Zechstein salt and were of great value for this project. In addition, multiple other 2D and 3D seismic surveys were used to cover the rest of the study area. All seismic data was converted to European Zero Phase convention (Figure 3.1). An overview of the data and the applied phase shift can be found in appendix 4.21.

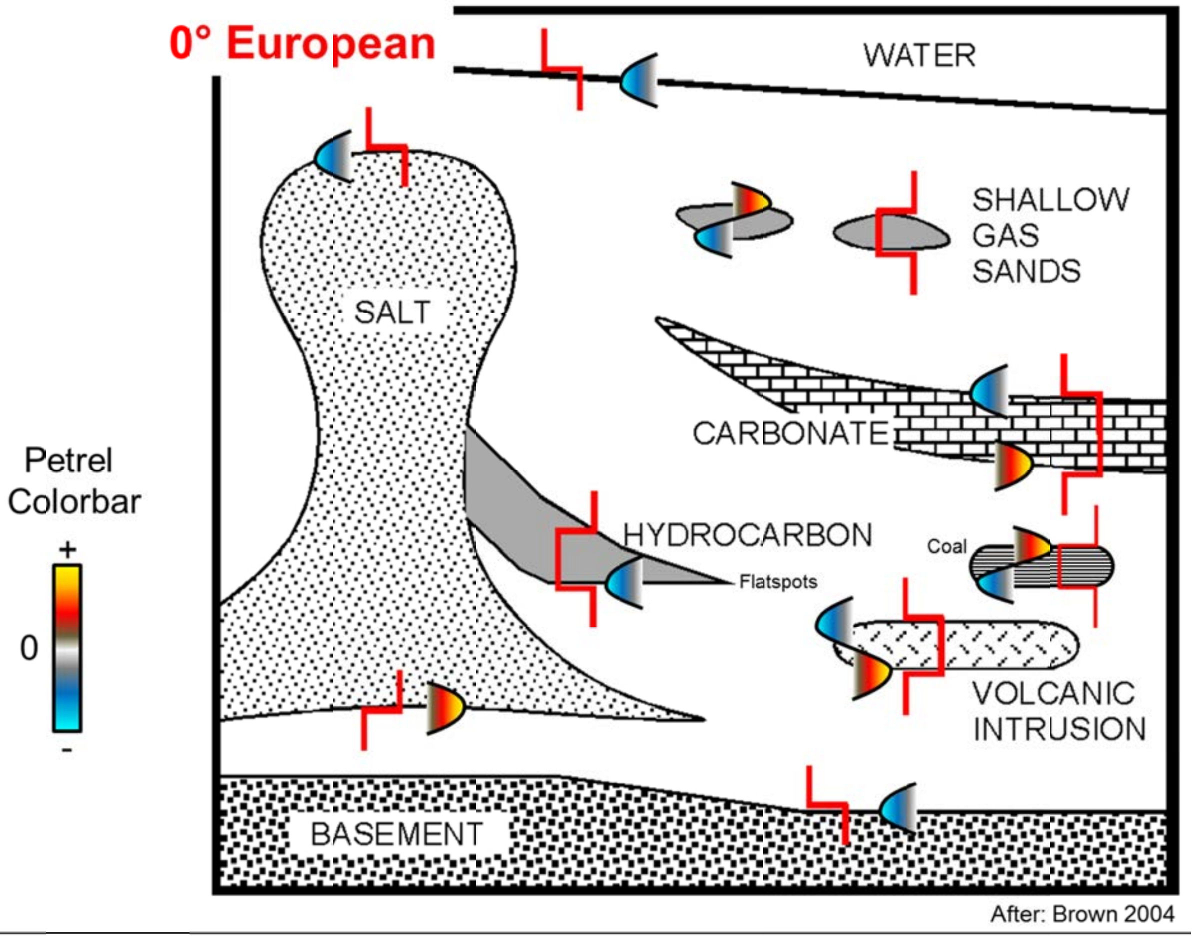


Figure 3.1: All seismic data is made European Zero phase. The relative acoustic impedance contrasts of various rock types and their corresponding seismic reflection are depicted in the Petrel colour-bar. Modified after Brown 2004

The following seismic horizons are mapped within the study area:
- Scremerston Coal
- Base Westphalian Unconformity (BWU)
- Base lower Rotliegend (RV)
- Base Upper Rotliegend (RO)
- Base Zechstein (ZE)

In addition the following horizons (Bases) are mapped on the selected Fugro lines:
- Upper North Sea Group NU
- North Sea Group N
- Chalk Group CK
- Rijnland Group KN
- Upper Germanic Trias Group RN
- Lower Germanic Trias Group RB

The reader should refer to Appendix 4 for a detailed account on 1) well–tie, 2) synthetic to seismic matching, 3) seismic definition of the mapped horizons, 4) the process of surface creating and computation, and 5) time-depth conversion.

3.3 Biostratigraphy

A search for biostratigraphical legacy data was conducted in this project to enhance the stratigraphic resolution of the available well data (see Appendix 5). For those wells with no or questionable biostratigraphical data, a few new live samples were processed for new palynological analyses (Table 3-1). For wells A14-01 and A15-01 the goal was to verify the suggested Westphalian age. For well B10-02 there was a suspicion of preserved palynological information (from legacy data counts sheets) in the Lower Rotliegend interval, which raised interest for an additional analysis to validate or discard (e.g. caving) such information.

Table 3-1: Selected wells and intervals for palynological processing

Well	Interval (m)
A14-01	2598 - 2708
A15-01	3273 - 3912
B10-02	3708 - 3780

3.4 Carbon Isotope stratigraphy

It is very difficult to obtain independent chronostratigraphical correlations in sections where biostratigraphy is not available (e.g. this is often the case in red beds).
A new approach to decrease correlation uncertainties in Permo-Carboniferous red-bed sections is the application of carbon isotope stratigraphy in combination with a new biostratigraphical tool based on biogenic silica fossils (van Hoof et al., 2014). This technique makes use of the isotopic variations (expressed as $\delta^{13}C$) occurring in the global carbon pool through time. Such fluctuations are enclosed in the isotopic

composition of organic matter like that derived from terrestrial plants. By measuring the $\delta^{13}C$-composition of bulk organic matter, large scale trends can be correlated to the global standard curves (Gradstein et al., 2012). By evaluating trends in the $\delta^{13}C$-records, correlation to chronostratigraphical time scale can be achieved. However, an important complexity of applying this technique in terrestrial settings is caused by the overprint of variations within the organic facies, which may drive changes in the $\delta^{13}C$-patterns. This issue can be solved by using the quantitative variations in biogenic silica fossils (Phytoliths) as a proxy for the variation in plant material (which in these settings dominates the organic matter). In this way the high frequency variability (noise) of the stable isotope curve can be separated from the low frequency atmospheric signal, and hence enables a more clear correlation to the global standard curve.

Detailed processing techniques and subsequent analyses are described in Appendix 5.

3.5 Stratigraphic correlation

The stratigraphic correlation was carried out using detailed 1) well log analysis, including electrofacies analysis[1], 2) lithostratigraphic and sequence stratigraphic analysis, and 3) paleotopographic and structural considerations

3.5.1 Well interpretation and electrofacies analysis

The Rotliegend interval was identified in most of the project's wells, with the exception of two (A17-01 and E02-01), where it was either not deposited or was eroded (Figure 3.2). Several types of data gathered from previous studies were used to identify the Rotliegend interval, and to differentiate the Lower Rotliegend (RV) and the Upper Rotliegend (RO). Data sources used are as follow:

- Biostratigraphy data and reports from NLOG and TNO.
- Lithostratigraphic information from NLOG and from the re-interpreted lithostratigraphy scheme of this project (see Chapter 3.1)
- New seismic interpretation, especially the mapping of key unconformities at well location, such as the Base Permian Unconformity (BPU and base of the Rotliegend) and the Saalian Unconformity (base of the Upper Rotliegend).
- Identification of specific lithofacies in well data. Any volcanics or volcano-clastics identified above the Base Permian Unconformity have been attributed to the Lower Rotliegend interval, whilst any halite facies has been allocated to the Upper Rotliegend interval (specifically associated with the Silver Pit Formation, Figure 0-1.1).

Electrofacies information was collected for the Rotliegend stratigraphic interval and compiled for 30 wells (Figure 3.2 and Figure 3.3). Five different electrofacies types were established and classified based on Gamma Ray and Resistivity information. They are Sand, Shale, Halite, Volcanics and Limestone electrofacies types. Four

[1] Automatic lithofacies classification based on multiple wireline logs. Electrofacies can usually be assigned to one or more lithofacies as log responses are measurements of the physical properties of rocks.

stratigraphic correlation panels were constructed using these 30 wells to illustrate the stratigraphic setting and internal correlation of the Rotliegend in the study area, (Figure 3.5). All constructed correlation panels use the Base Zechstein surface as datum. The only exception is the northern edge of Section 1 where no Zechstein is present and where the base of the Rijnland Group was used as datum (Figure 3.4). These correlation panels link most of the wells present in the study area. Only three wells are not included within those panels: E06-01, E10-03 and E12-04-S2 (Figure 3.2). The vertical exaggeration on these correlation panels is 1:250.

The Lower Rotliegend was identified in eleven wells and its top was used, when present, as a key correlation surface (Figure 3.4). The intra-well correlation of the top Upper Rotliegend surface was carried out using information from the seismic interpretation.

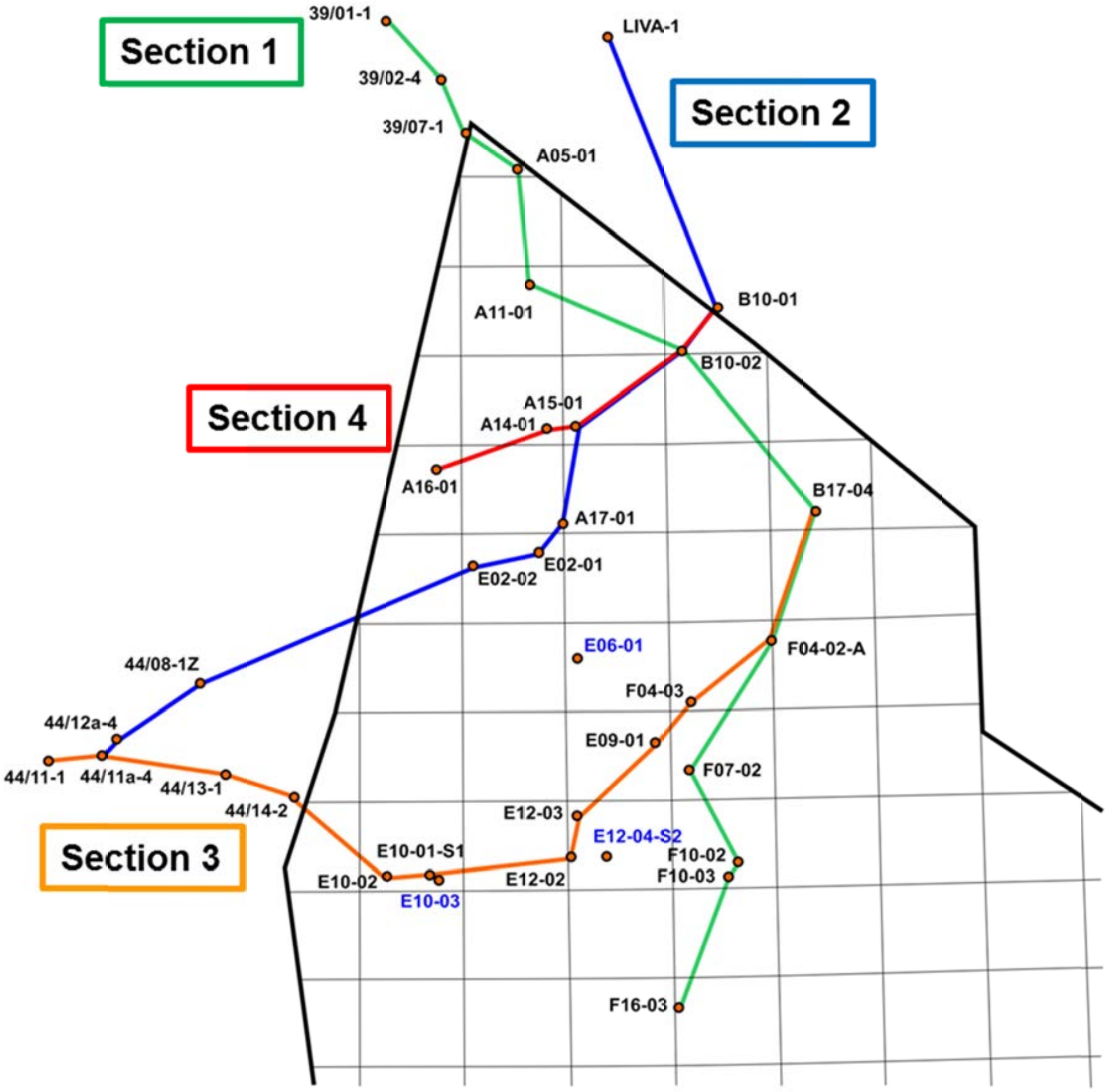


Figure 3.2: Location map of the stratigraphic correlation panels. All key wells beside three (E10-03, E12-04-S2 and E06-01) that are located within the study area have been used to construct these panels.

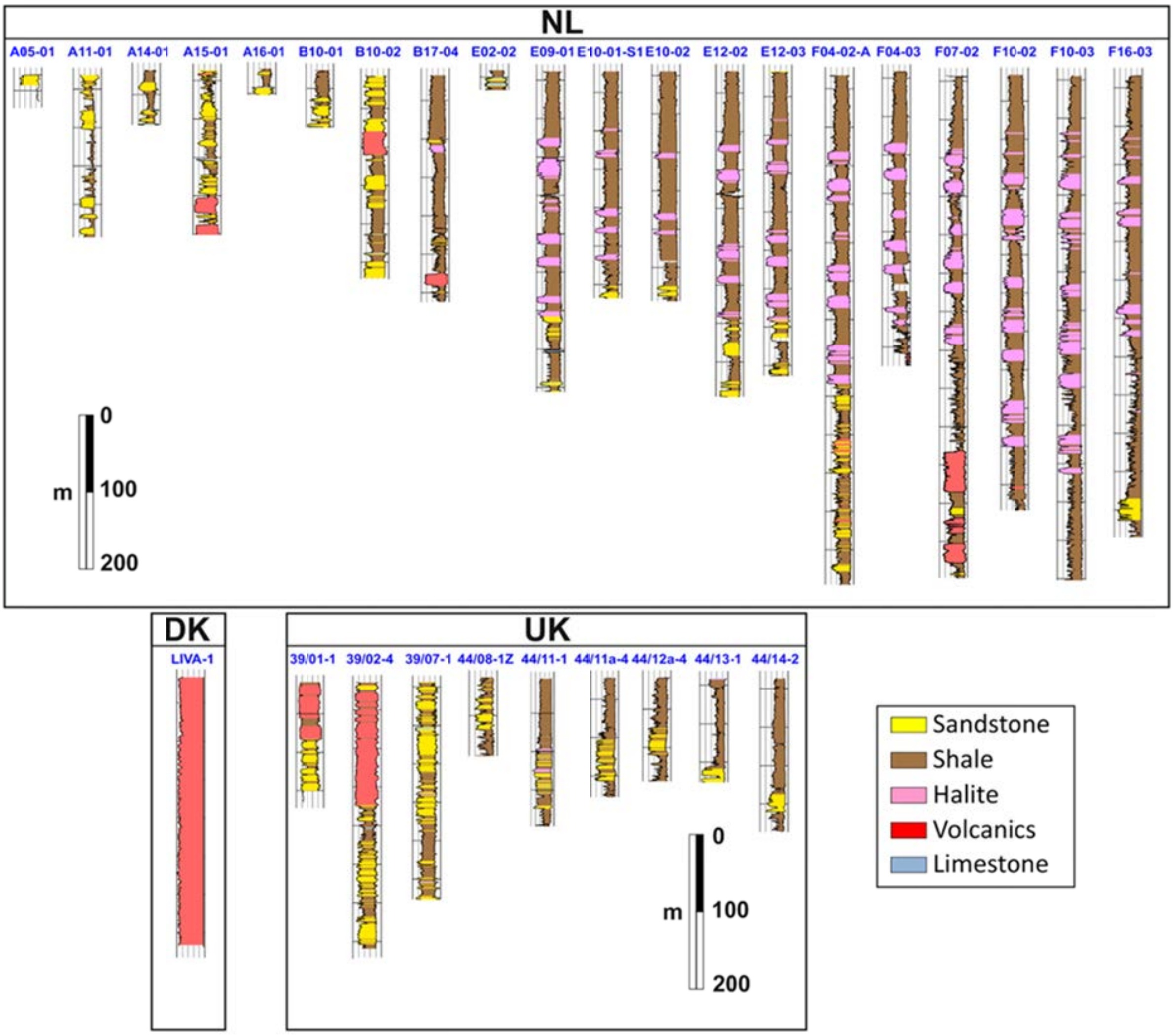


Figure 3.3: The Rotliegend interval as present in the project well database. 30 wells were selected for the construction of four stratigraphic correlation panels. 20 wells are located in the Dutch offshore, one in the Danish offshore and nine in the United Kingdom offshore. Only the Rotliegend interval is displayed in this figure.

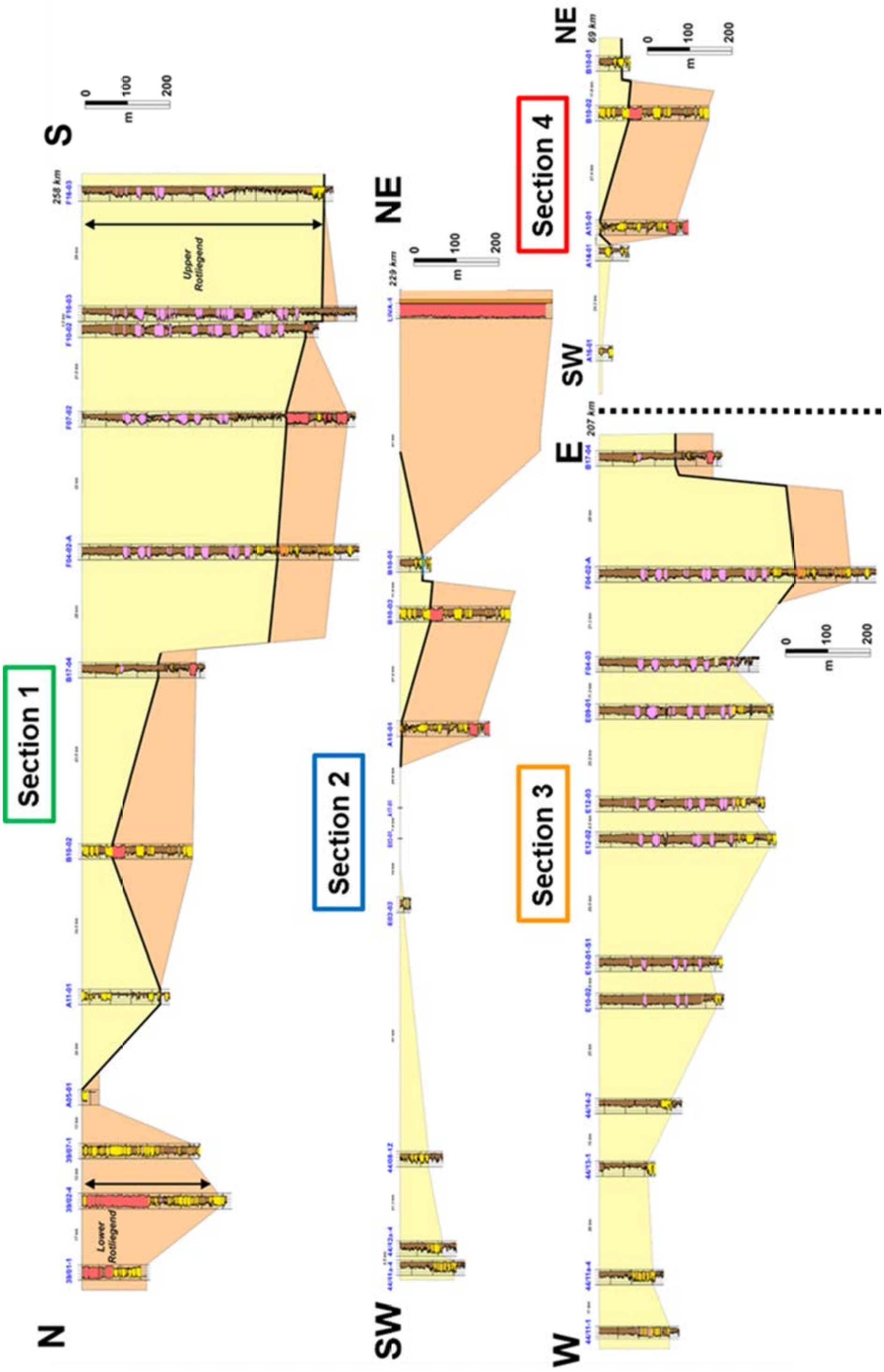


Figure 3.4: Four stratigraphic correlation panels of the Lower (orange polygons) and Upper Rotliegend (yellow polygons) in the Dutch Northern Offshore. The base Zechstein was used as datum. See Figure 3.2 for location.

The subcropping stratigraphic intervals below the Rotliegend (below BPU) are shown on the correlation panels, along the base of the sections (Figure 3.5) Figure 3.5. The subcrop information is accurate at the well locations but is inferred between wells. However, local trends gathered from seismic data between well locations were used to interpret the lateral extent of these subcropping intervals.

3.5.2 Lithostratigraphic and sequence stratigraphic analysis

For the internal correlation of the Lower and Upper Rotliegend intervals, a variety of lithological information has been used. Correlation techniques consisting of a mix of lithostratigraphic and sequence stratigraphic concepts that are used to describe the stratigraphic evolution of the basin in a more realistic manor.

- Halite units
  Halite lithofacies (electrofacies) proved to be one of the most useful lithology for basin axis correlation. Up to 22 individual thick halite units can be observed in twelve wells (i.e. in well F10-2, Figure 3.3) located in the southern part of the study area (Figure 3.5). Individual intervals can be up to 23m in thickness.
  They form excellent markers as they can be recognized over distances of tens of kilometres and, as such, they proved to be extremely useful to build a robust correlation framework for the southern part of the study area. This is true despite the fact that these halite units often change character laterally (i.e. in thickness, vertical stacking pattern and purity) especially when correlated from basin axis toward the basin margins. Correlation of these halite units was carried out based on: 1) the number of stacked recognizable halite units, 2) their vertical stratigraphic strand, 3) their thickness patterns, 4) their lateral thickness variations, and 5) the lateral characteristics of the intra halite strata (mainly the shales of the Silver Pit Formation), which are also thinning from basin axis to basin margins. The halite units have been correlated laterally (on the basin margins) to sandy intervals (part of the Slochteren Formation) located near the basin margins. The latter are thought to represent dry events on the basin (lake) margins (Figure 3.5).

- Sandy intervals
  Correlations based on sandy intervals within the Rotliegend are not highly reliable due to lateral heterogeneity in such depositional systems. However, particularly thick (10 to 50m) sand-rich intervals identified within the Rotliegend interval, especially in the Upper Rotliegend, can be laterally correlated with a relatively high level of confidence. Detailed correlation of thinner coarse-grained siliciclastic units (1 to 10m) has not been attempted due to decreased confidence and due to distance between some of the wells (locally over 60km). It is worth noting that the use of thick sand-rich units for regional correlation was more successful in the Upper Rotliegend than in the Lower Rotliegend due to the more regionally extensive nature of this younger interval.

- Fine-grained siliciclastic units
  The most common lithology within the Rotliegend in the study area consists of shales (i.e. 70% of all lithologies encountered). The vertical stacking patterns within these, often thick, shale-rich intervals, can be easily used for correlation purposes. Correlatable coarsening and fining upward trends are frequently observed in different well logs within those fine-grained siliciclastic units. Such correlations were used with relatively high confidence on the marginal zones of the southern part of the study area (Silver Pit Lake), as halite units are often absent in such marginal depositional settings.

- Volcanics and volcanoclastic units
  Using volcanics and volcanoclastic units for regional stratigraphic correlation purposes has to be done with great care and are of lower confidence compared to other lithological units. Therefore, in this project, only limited use was made of volcanic and volcano-clastic units for correlation purposes. Only in the northern part of the study area (Section 1, Figure 3.5) volcanics and volcanoclastic units were used for intra-Lower Rotliegend stratigraphic correlation.

3.5.3 Subdivision and maps

The Lower Rotliegend and Upper Rotliegend are subdivided in 3 and 5 layers, respectively. This subdivision is not a pure lithostratigraphic subdivision (e.g. Members), but is used to described the stratigraphy of the Rotliegend by incorporating lithostratigraphic and sequence stratigraphic concepts. Since no single lithostratigraphic layer can be defined as a regional stratigraphic surface, the boundaries of the units described are therefore not purely lithological, but timelines that cross various facies and depositional environments (e.g. coastal to deep basin), (e.g. a halite is laterally interfingering with mudstones distally, which are interfingering themselves with sands proximally). These timelines are not purely sequence stratigraphically defined (e.g. sequence boundaries, MFS, etc…) since we lack detailed information concerning the high resolution stratigraphic setting of the Rotliegend. However, the correlation obtained in this project do depict transgressive and regressive trends (e.g. in RO1, RO5).

3.5.4 Paleotopography and structural considerations

Both paleotopographic and structural information were incorporated to the stratigraphic correlations panels (Figure 3.5).

Seismic interpretation of the base Rotliegend (Base Permian Unconformity) and the base Upper Rotliegend (Saalian Unconformity) have revealed that syn-depositional fault activity occurred during the deposition of the Rotliegend. Seismic interpretation also shows that the distribution of the Rotliegend was highly affected by paleotopography, as also stated by other authors (George and Berry, 1997; Howell and Mountney, 1997). Three of the main faults interpreted in the study area (see Chapter 6) have been added to the stratigraphic correlation panels Figure 3.5) to highlight the syn-depositional nature of the Rotliegend strata. It is important to note that many other faults, some possibly large, may have been active during the deposition of the Rotliegend. However, such tectono-stratigraphic analysis was beyond the scope of this project. In addition large well spacing, low resolution of seismic imaging of the Rotliegend and the size of the study area make any detailed tectono-stratigraphic characterisation a cumbersome process. Therefore, the faults added on the correlation panels (Figure 3.5) are illustrating what is more likely an intensely syn-depositionally deformed stratigraphic interval.

In a similar manner, the stratigraphic correlations panel constructed for this project incorporate some paleotopographic aspects, especially in the lower part of the Rotliegend where rapid stratal thinning are observed. Such stratigraphic thinning is interpreted as the results of topographic control on the distribution of the Rotliegend basal strata within the study area (e.g. between wells 44-11a-4 and 44/12a-4, Section 2, (Figure 3.5).

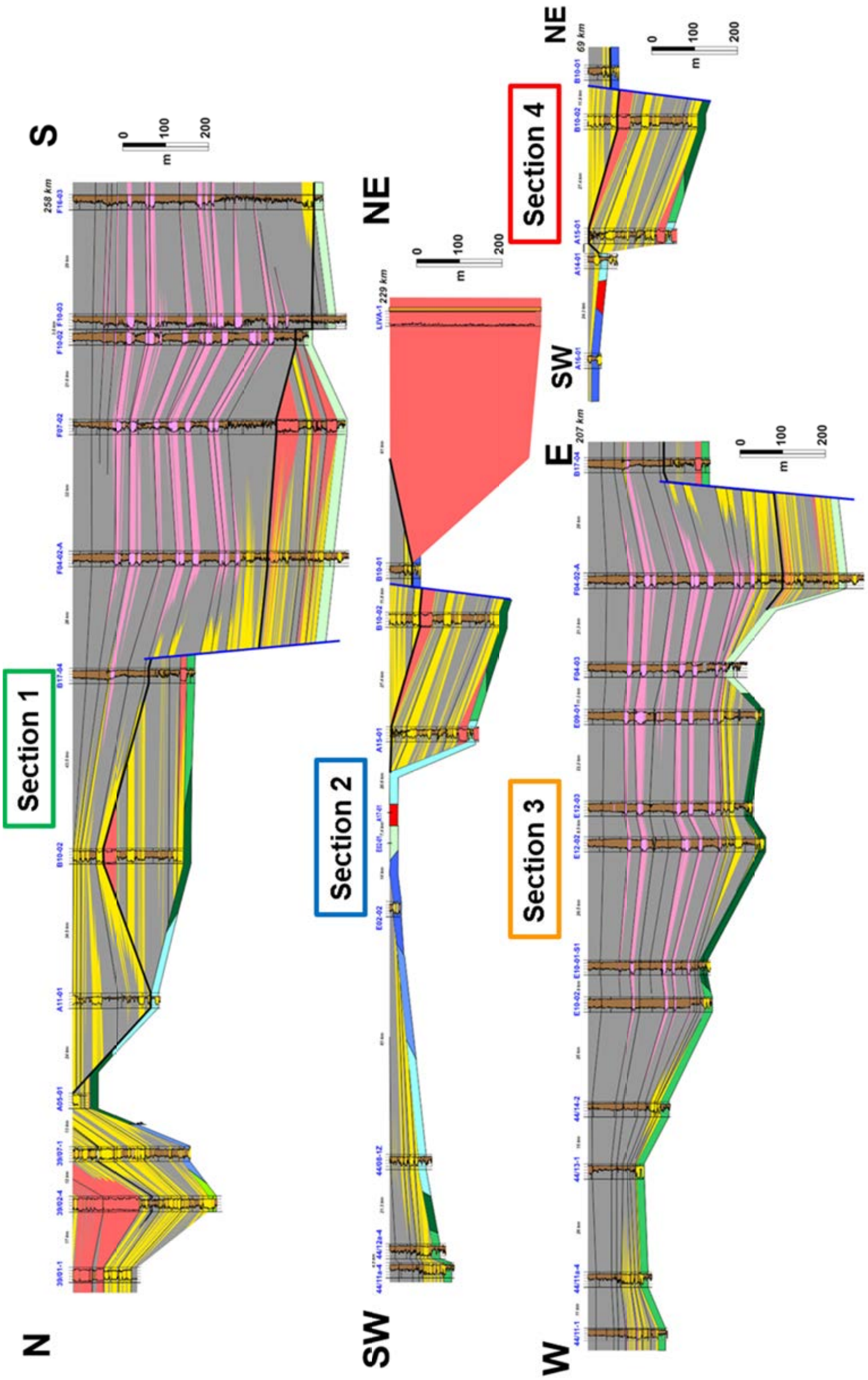


Figure 3.5: Stratigraphic correlation panels of the Rotliegend in the Dutch Northern Offshore. The base is Zechstein used as upper datum. See Figure 3.2 for location.

Many iterations of possible correlation frameworks were generated using all the previously described techniques and until robust stratigraphic correlations were achieved. The resulting correlation panels (Figure 3.5) combined with the well log analysis and the seismic interpretation were used to construct depositional maps that are presented in the following Chapter (Chapter 3).

3.6 Basin Modelling

The aim of the basin modelling was to provide insights into the thermal maturity of the basin as well as the timing of hydrocarbon generation and expulsion from the main Carboniferous source rocks. 1-D basin modelling was carried out in a number of wells in the study area. Synthetic wells (pseudo wells) were also constructed and modelled in selected locations.

3.6.1 Modelling input

The main input for basin modelling includes the stratigraphy, source rock properties, boundary conditions and calibration data.

3.6.2 Stratigraphy

The stratigraphy and lithological description of the 1-D models at the location of the selected wells was based on the descriptions from the on NLOG database and the revised lithostratigraphic analysis carried out in this project (see Chapter 3.1). For the synthetic wells, the latest results of the mapping program of the Dutch Subsurface (NCP-2, Kombrink et al., 2012) and the seismic results from this study were used to describe the stratigraphy and model the geometry.
We assumed erosional thicknesses for the main erosion phases based on published values, seismic interpretation and regional stratigraphic comparisons with surrounding wells (for example: Abdul Fattah et al., 2012). The depositional ages for the various stratigraphic intervals follow the Dutch Nomenclature and Gradstein et al. (2004) time scale.

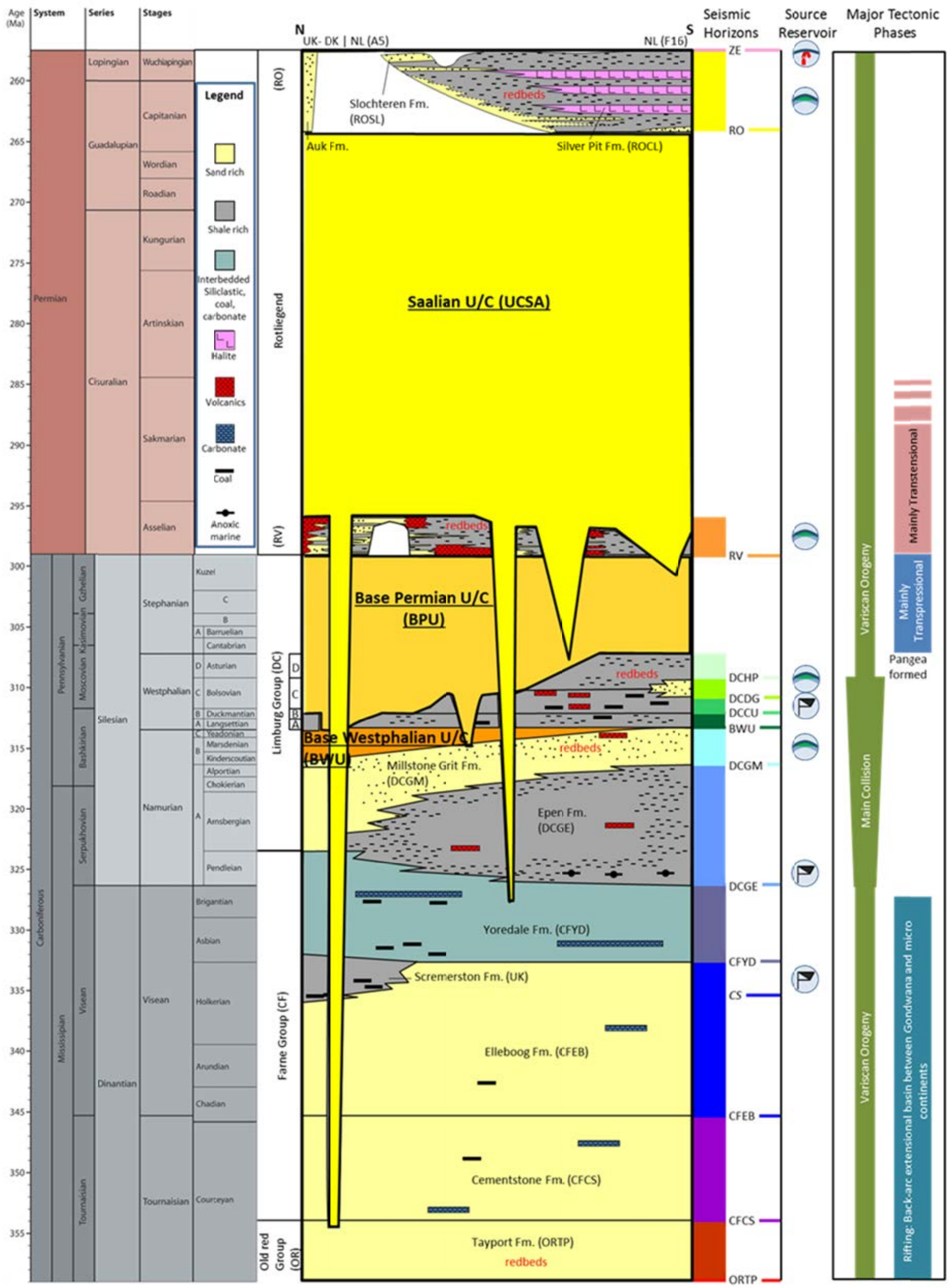


Figure 3.6: Updated chronostratigraphical chart of the Carboniferous and Permian. The three main unconformities are also shown as polygons to illustrate their relative impact in the study area. They are namely the Base Westphalian Unconformity (dark orange), the Base Permian Unconformity (orange) and the Saalian Unconformity (yellow). Based on Kombrink et al 2010 and Gast et al 2010

The geometry and depositional ages of the Carboniferous and Rotliegend sections were derived from the stratigraphic results obtained in this project (Chapter 3.1) (Figure 3.6). Three erosional phases were introduced into the Palaeozoic section; the Base Westphalian (320-313 Ma), the Base Permian (307-299 Ma) and the Saalian event (280-267 Ma). In addition to these phases, three more erosional events were included in the models. These events are: the Mid-Upper Jurassic Kimmerian, the Upper Cretaceous Laramide and the Mid Miocene event.

3.6.3 Boundary conditions

The model's thermal boundary conditions include the Paleo-Water Depth (PWD), the Surface Water Interface Temperatures (SWIT) and the Basal Heat Flow (BHF) (Figure 3.7). The Paleo-Water Depth (PWD) and the Surface Water Interface Temperatures (SWIT) were provided by TNO and are based on a compilation of various sources including biostratigraphical analysis (Verweij et al., 2012; Abdul Fattah et al., 2012). The tectonic heat flow was modelled in well A11-01 using TNO developed heat flow modelling tool (PetroProb) which considers the tectonic evolution of the basin (Van Wees et al., 2009). The heat flow model was in some cases modified in order to achieve a better calibration with temperature and maturity data.

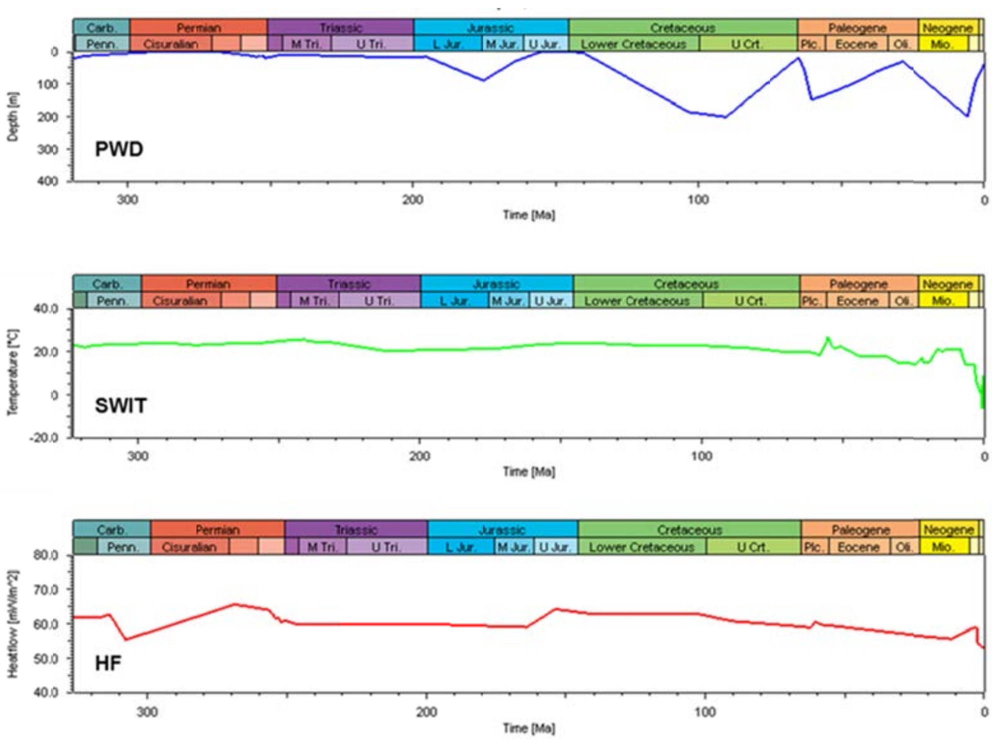


Figure 3.7: Boundary conditions used in the basin modelling. Paleo-Water Depth (PWD), the Surface Water Interface Temperatures (SWIT) and the Basal Heat Flow (HF)

3.6.4 Source rock properties:

The main source rocks identified in this study belong to the Westphalian Maurits and Klaverbank Formations and the Dinantian Scremerston Fm. Potential Namurian source rocks, such as the Epen Formation (DCGE) and the Yoredale Formation (CFYD), have not been identified. The properties of the Carboniferous source rocks as used in the modelling exercise are based on the information provided by previous studies (e.g.: Abdul Fattah et al., 2012; Schroot et al., 2006; PGL, 2005). These properties include: the source rock type (kerogen type), the total organic carbon content (TOC %) and the Hydrogen Index (HI %) (Table 3-1).

Table 3-2: Source rock properties as used in the 1-D basin modelling.

Formations	Lithology	Source Rock Type	TOC %
Westphalian Maurits Fm.	Shale, Sand, Coal	Gas-prone (Kerogen type III)	4 %
Westphalian Klaverbank Fm.	Shale, Sand, Coal	Gas-prone (Kerogen type III)	2 %
Scremerston Fm. (UK)	Clastics, Carbonates	Gas-prone (Kerogen type III)	1.2 %

3.6.5 Model calibration:

All models were calibrated to present-day temperature and maturity (Vr %) data as measured in the wells. The calibration data were quality controlled and are based on the TNO database.

3.6.6 Well selection

A total of twelve wells, three of which are located in the UK offshore sector, as well as one pseudo well in the Dutch offshore, were selected for 1-D basin modelling (Figure 3.8). Table 3-3lists the modelled source rocks, the thicknesses of the formations as well as the erosional thicknesses for the Carboniferous section for each of the modelled wells.
The selection of the wells followed several criteria such as presence of the source rock, availability of calibration data and significance for the assessment of the potential of the petroleum system.

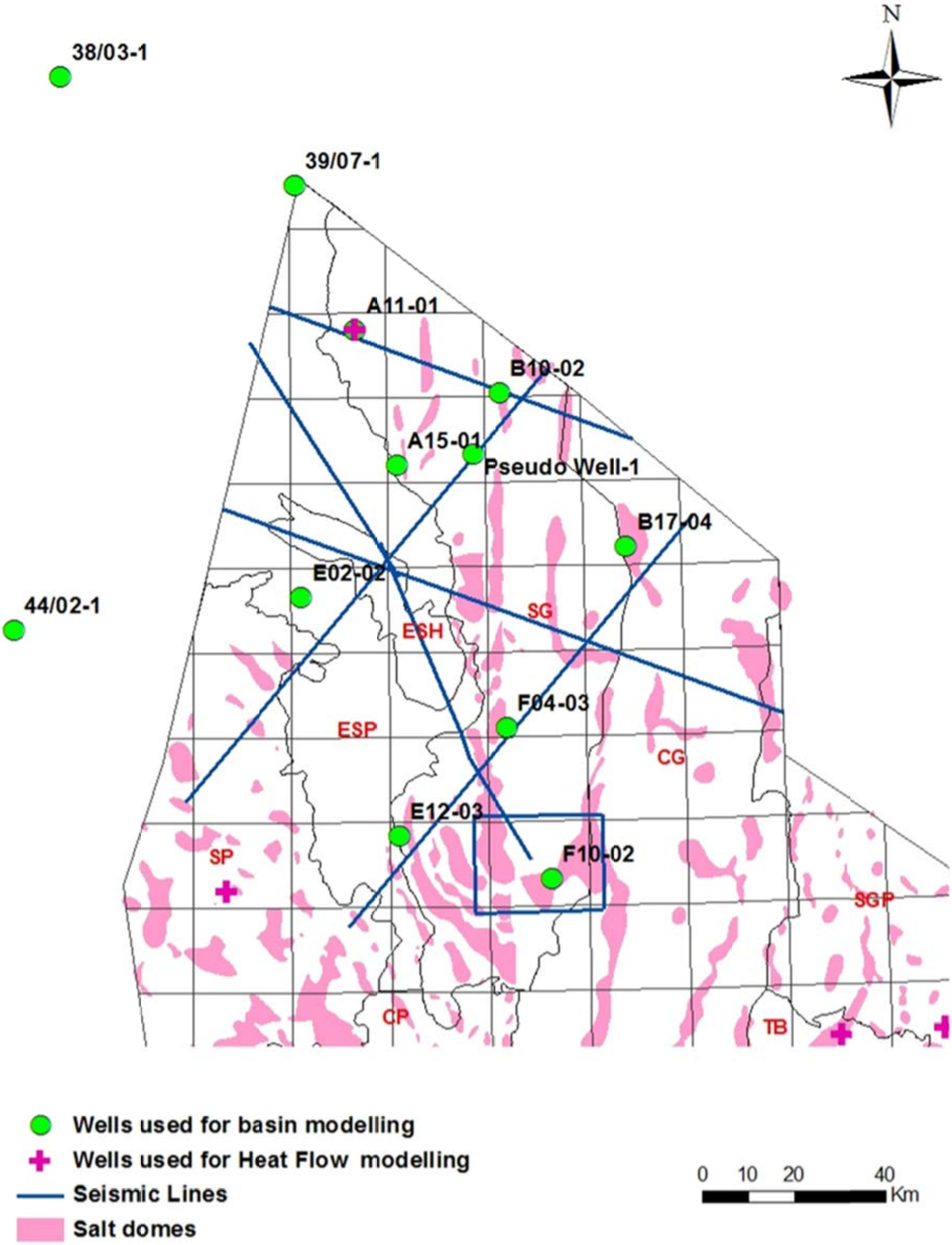


Figure 3.8: Location of the modelled wells and some of the regional seismic lines provided by Fugro. Note that 4 wells are located outside the Dutch sector.

Table 3-3: List of the modelled wells. “Annex” refers to source rock information being used from an adjacent well when not drilled.

Well Name	Location	Analysed source rock	Source rock thickness (m)	Total Carboniferous erosional thickness (m)	Possible other source rocks (not included in the model)
B17-04	NL	Maurits Fm. (DCCU)	205	550	Dinantian Visean (Yoredale Fm), Scremerston Fm. (CFEB)
F04-03	NL	Maurits Fm. (DCCU)	234	100	Dinantian Visean (Yoredale Fm), Scremerston Fm. (CFEB)
E12-03	NL	Maurits Fm. (DCCU)	25	575	Dinantian Visean (Yoredale Fm), Scremerston Fm. (CFEB)
Pseudo Well-1	NL	Maurits Fm. (DCCU)	243	0	Dinantian Visean (Yoredale Fm), Scremerston Fm. (CFEB)
F10-02	NL	Maurits Fm. (DCCU) (Annex)	588 (Annex)	100	Dinantian Visean (Yoredale Fm), Scremerston Fm. (CFEB)
B10-02	NL	Maurits Fm. (DCCU) (Annex)	200 (Annex)	50	Dinantian Visean (Yoredale Fm), Scremerston Fm. (CFEB)
A11-01	NL	Scremerston Fm. (CFEB) (Annex)	18	550	Elleboog Fm. (CFEB)
A15-01	NL	Scremerston Fm. (CFEB) (Annex)	18	1200	Elleboog Fm. (CFEB)
E02-02	NL	Scremerston Fm. (CFEB)	191	650	Elleboog Fm. (CFEB)
39/7-1	UK	Scremerston Fm. (CFEB)	629	500	Elleboog Fm. (CFEB)
44/02-1	UK	Visean (Yoredale Fm)	423	720	Scremerston Fm. (CFEB), Elleboog Fm. (CFEB)
38/03-1	UK	Buchan Fm_T (Fransian)	1082	0	Unknown

3.7 Sensitivity analysis for basin modelling

The outcome of the basin modelling is to a large extent dependent on the input. In order to understand the results of the models and constrain the involved uncertainties, the sensitivity of the model to various inputs had to be assessed. The relationship between various input parameters and the outcome of the modelling is usually complex. Therefore no simple correlations can be made and generalized statements are provided wherever possible. The sensitivity of the model was assessed for the following elements:

- Surface Water Interface Temperature (SWIT):
  The sensitivity analysis has shown that variations in the SWIT can affect the temperature evolution in the basin. This can change the history of the source rock maturity and hydrocarbon generation. Thus, it was concluded that the TNO SWIT model would be best suited for the maturity modelling. In general, higher SWI temperatures appear to result in models with higher formation temperatures and thus higher maturities. The TNO SWIT model is more refined based on a compilation of various studies as well as biostratigraphical analyses especially for the Tertiary section.

- Basal heat flow
  Two different heat flow scenarios have been assessed for their impact on source rock maturity and hydrocarbon generation. Variations in the heat flow through geological time can affect the history of hydrocarbon generation. Higher heat flow values results in higher thermal gradients and thus higher maturities of the source rocks. Tectonic heat flow was modelled and calibrated to temperature and maturity data in the A11-01. This model was used for all the wells and was recalibrated to present-day temperatures and maturities for each well.

- Source rock kinetics
  Two different kinetic models were tested: the Pepper & Corvi (1995) II, III models and the Burnham (1989) model. The comparisons have shown that using different kinetic models have limited impact on the bulk hydrocarbon generation in the study area under the same thermal conditions. However, the ratio oil/gas can change depending on the input kinetic model. The Pepper & Corvi (1995) kinetic model resulted mainly in oil (or larger percentages of generated oil), whereas the Burnham (1989) model resulted in oil and gas. Therefore the latter model was used in the present exercise.

- Stratigraphy of the Tertiary:
  Previous modelling has shown that crucial generation and expulsion activities from Carboniferous rocks took place in the Tertiary in this part of the North Sea (Abdul Fattah et al, 2012). The sensitivity analyses indicated that the complex stratigraphy of the Tertiary section (thick, prograding delta) can have important impact on the hydrocarbon generation and expulsion. The relationship between the modelled maturity and the level of detail of the stratigraphy used for the modelling is rather complicated. In general, the stratigraphy affects the burial history of the formation and thus their temperature evolution. In order to reduce the uncertainties in our models related to this factor, a detailed stratigraphy of the Tertiary was used in the modelling including a new definition of the Mid-Miocene Unconformity.

- Salt movement
  In the Northern Offshore area many salt domes and salt structures exist. The sensitivity analyses indicated that salt movement during geological time has affected the burial history of the formations and therefore the history of temperature and source rock maturity. When salt movement is not incorporated in the modelling (e.g. an equal thickness, post movement is used), areas that has seen salt moving into it (salt pillow and salt diapirs) will have an unrealistic early and deep burial. This result in early heating of the source rock which will result in earlier modelled maturity and hydrocarbon generation. In areas that has seen salt withdraw, the opposite is modelled. The thermal effect of salt domes can also have an impact on the temperature around the salt structure. Salt movement and salt deformation at different geologic times was therefore taken into account in the modelling at the well locations where anomalous salt structures exist.

- Post- Carboniferous (Jurassic) erosion
  Several scenarios representing various amounts of eroded strata for the Jurassic event have been investigated (i.e. Mid-late Kimmerian event). The analyses have shown that although the deepest burial is generally at present day, Jurassic erosion can influence the history of hydrocarbon generation and expulsion from Carboniferous source rocks. In general, higher erosion amounts will result in deeper burial (prior to the uplift) and thus higher temperatures and maturities that may exceed the maturities as observed at present day. For this reason and other reasons, the amount of erosion should be constrained in the models. The erosional amounts in the different wells were carefully determined based on regional stratigraphic correlations and seismic interpretation with in the surrounding areas.

3.8 Maturity map of the Westphalian source rock

In addition to the 1-D basin models (conducted at the well location of the selected wells, Table 3-3), a maturity map was produced for the entire Westphalian section. The seismically mapped base and top of the Westphalian were selected to define the geometry of the source rock and a single heat flow value of 55 mW/m^2 was assumed. The produced map was then calibrated to the modelled present-day maturities at the well locations of the 1-D modelling.

4 Results

The analytical results obtained in this project are presented below in detail, including the well (re)interpretation, seismic interpretation, stratigraphic, biostratigraphic, isotope stratigraphy and basin modelling results. In the following chapter (Chapter 5, Synthesis) all these results are interpreted, discussed and integrated in relation to the Permo-Carboniferous geological history (stratigraphic and structural) and the petroleum system history of the study area.

4.1 Well reinterpretation

In total 18 wells were reinterpreted. Some modifications were only minor and concerned the boundary between the Silver Pit Evaporitic Member (ROCLE) and the overlying Upper Silver Pit (ROCLU), or the underlying Lower Silver Pit Member (ROCLL). In other cases, stratigraphic revisions were quite substantial. For example, well A15-01 loses its Silver Pit Formation and a large part of its Millstone Grit Formation in favour of Lower Rotliegend Group (RV).
Another example is for well B10-02, which used to have 14m of Upper Rotliegend, almost 200m of Millstone Grit Formation, and 59m of Yoredale Formation. In the revised interpretation, it has 72m of Upper Rotliegend Group (RO), and almost 200m of Lower Rotliegend Group (RV) down to TD.

Table 4-1: Pre-Zechstein stratigraphic revisions. Symbols: ✶ = newly assigned; ✓= present but depth not changed; ⇳ = present and depth changed; × = deleted

Well	ROCLU	ROCLE	ROCLL	ROSLL	RO	RV	DCHP	DCDG	DCCU	DCCK	DCGM	DCGE	CFYD	CFEB	CFCS	ORTP	ORBU	ORPA	ORKY
A05-01					×	✶													
A11-01					⇳						⇳								
A15-01					⇳	✶					⇳								
A17-01																✶	⇳	⇳	✶
B10-02					⇳	✶					×		×						
B17-04					✓	✓	×		⇳		✶								
E02-01							✶					×	⇳	⇳	⇳	⇳			
E10-01-S1	✶	✶	✶							✓									
E10-02	✓	✓	✶						✓	✓									
E10-03-S2	✶	✶	✶							✓									
E12-03	⇳	⇳	✓							✶	⇳								
E12-04-S2	⇳	⇳	✓							✓									
F04-02-A	✓	✓	⇳			⇳	✓												
F04-03	✓	✓	⇳			×	⇳		✶										
F07-02	⇳	⇳	✓				✓		✓										
F10-02	⇳	⇳	⇳			✶	⇳												
F10-03	✶	✶	✶				⇳	✶											
F16-03	✓	✓	✓			✓													

Table 4-1 shows the current stratigraphic interpretations, as well as the older NLOG (December 2014) interpretations. A graphic overview of the main changes is shown in Appendix 3.1 and Appendix 3.2. Detailed rationale for our reinterpretations can be found in Appendix 3.3.

The main conclusions of the well reinterpretation are as follows:

- Changes in Carboniferous stratigraphy resulted in a more accurate Base Permian subcrop map and a better evaluation of the major erosional events

- The entire Rotliegend interval has now frequently become thicker. A few wells in particular show important increases in thickness: i.e. A11-01 (+163m), B10-02 (+ 250m) and A15-01 (+138m).

- An overall increase of Rotliegend thicknesses occurred in some wells due to the addition of Lower Rotliegend (RV) strata that were previously interpreted as Carboniferous.

- With the revised interpretation the stratigraphy is either younger (i.e. A11-01, B10-02, A15-01, F10-02, A17-01 and E02-01) or older (i.e. A05-01, B17-04, F04-02, F04-03, F10-03, A17-01) than previously interpreted.

- The total amount of sands allocated now to the Rotliegend (combined RO + RV) has increased compared to the previous interpretation, and allows for the definition of new Rotliegend-age sand fairways (see below).

4.2 Seismic interpretation

The aim of the seismic interpretation was to provide a stratigraphic framework and to get a better understanding of the geology of source and reservoir rocks. It was never intended to be a regional mapping project. However, to get a good understanding of the reservoir and source rocks in the study area, multiple intervals were mapped regionally, on a coarse grid of 2D and 3D seismic data (see Figure 4.1).

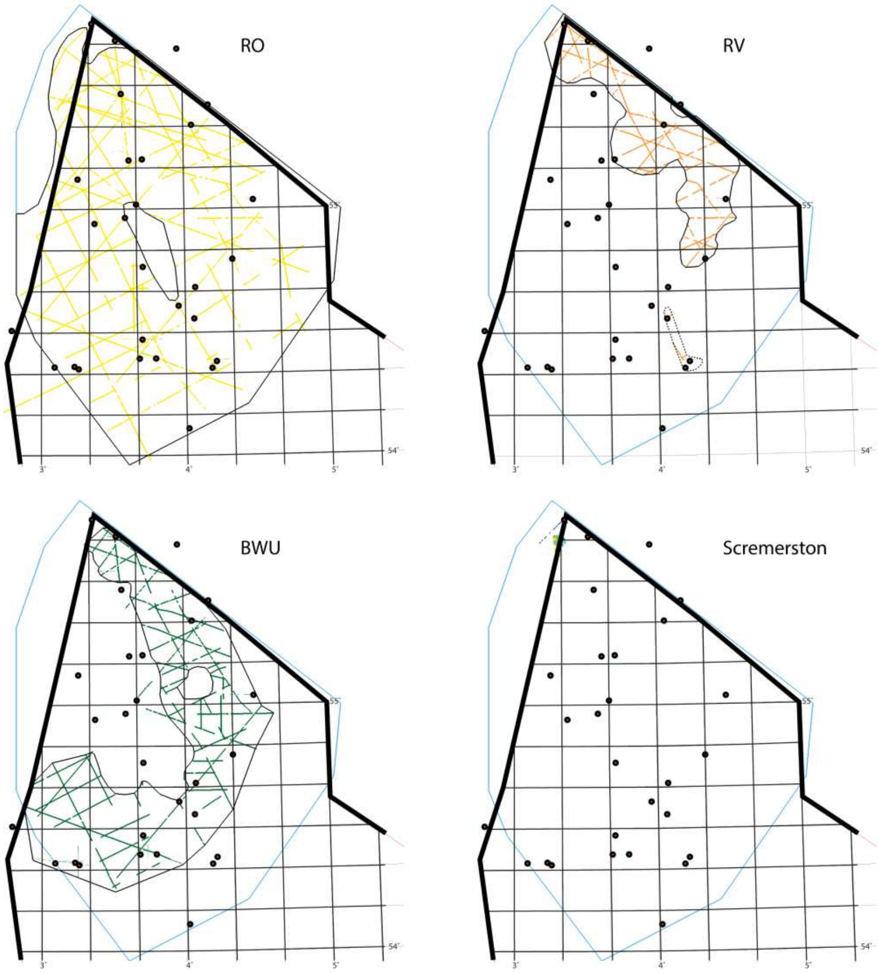


Figure 4.1: Maps of showing the extent of seismic interpretation of the Base Upper Rotliegend (RO), the Base Lower Rotliegend (RV), the Base Westphalian Unconformity (BWU), and Top Scremerston coals. See also Appendices 4.01 to 4.16.

4.2.1 Scremerston Formation

The Scremerston seismic horizon is the top of the coal measures, which show up as bright events on seismic data. These coals are an intra Scremerston Formation horizon. The Scremerston horizon was interpreted from the UK sector (well 39/07-1, see Figure 4.2 and Figure 4.3) and mapped towards the southeast across some large faults (significant fault throw observed along the N85-01 2D seismic line). At the location of well 39/11-1 the Scremerston coals have not been encountered since the Old Red Group is found directly below the Rotliegend. Bright events are observed in this area (around well 39/11-1) and they seem to have a seismic character comparable to the Scremerston coals farther north. However, the polarity of these seismic events is opposite to the Scremerston coals, indicating the presence of a hard, dense layer rather than a soft kick, as expected with the low density of the coal measures. These bright reflectors do not represent the Scremerston Coals but are possibly related to volcanics intra-Carboniferous or intra-Devonian. This result highlights the risk of interpreting the presence of coals (in this case Scremerston coals) only based on the presence of bright amplitudes and in disregards of structural complexities and seismic polarity configuration.

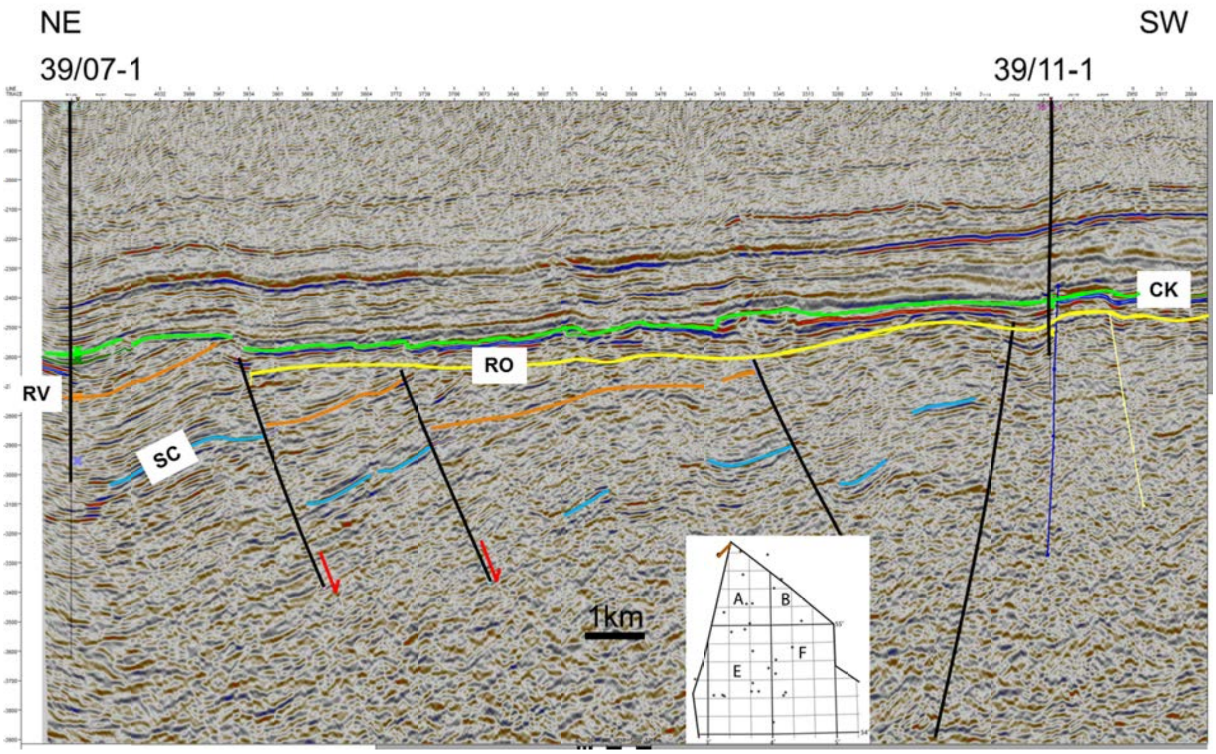


Figure 4.2: Seismic line (N85-01) showing various fault blocks in the border are with the UK. The top of the Scremerston coals (intra Scremerston Formation (Blue interpretation marked with SC)) is clearly visible. In well 39/11-1 the Scremerston was not encountered.

In the A08_A09_Z3NAM1993A seismic survey, the Scremerston horizon can be interpreted in the north-western corner. There, the Scremerston horizon is mapped across several fault-blocks. These normal faults have a NW-SE orientation and are predominately dipping towards the SW.

When interpreting the Scremerston horizon from 39/07-1 towards the A05-01 well to the south-east, the bright amplitudes stop at the position of a large fault (Figure 4.3). On the eastern side of the fault the bright amplitudes disappear. This could be due to the fact that the Zechstein salt is only present on the east side of the fault (masking the Scremerston coals below), or due to the fact that the Scremerston horizon is much deeper there and cannot be as well imaged. The Scremerston Formation could also be absent in this area, but we believe this to be unlikely, since the Scremerston Formation can also be found further to the east, in the German sector (e.g. A/9-1, Kombrink et al, 2010).

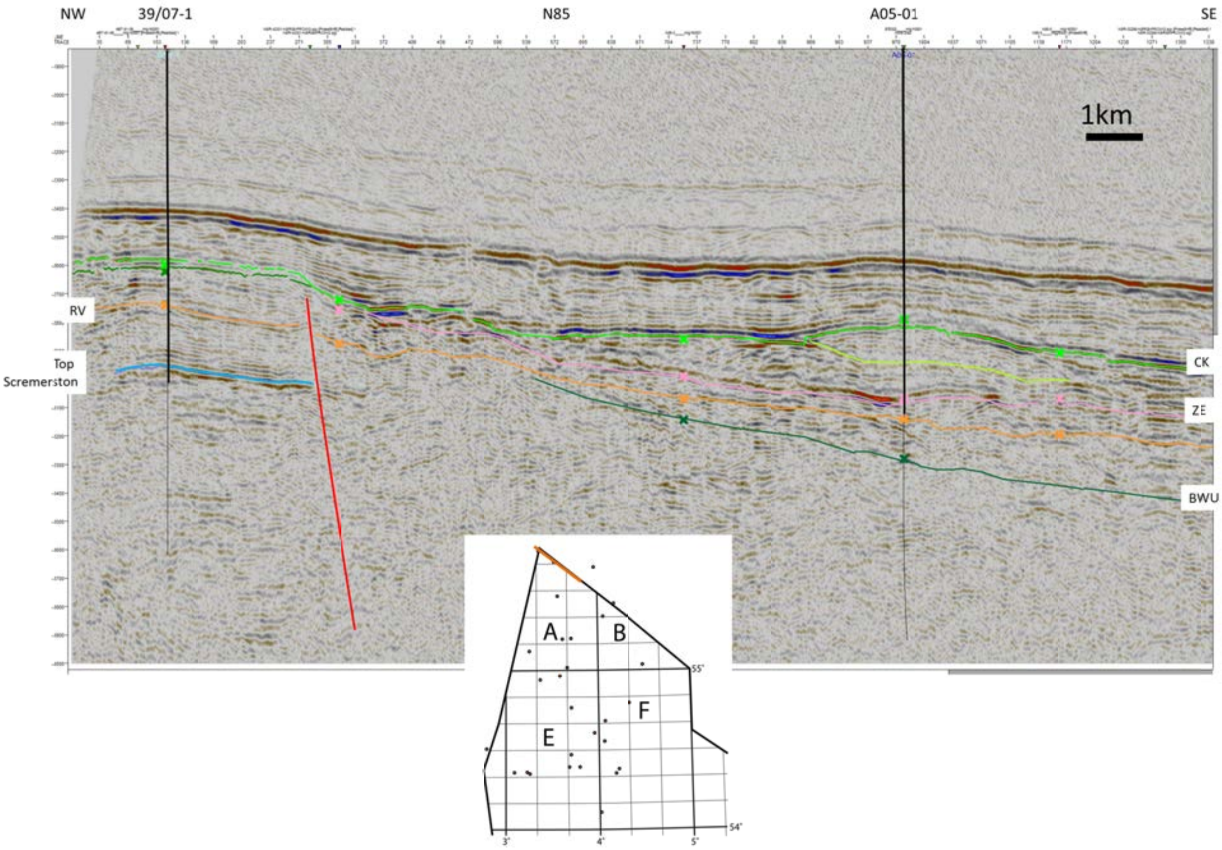


Figure 4.3: Seismic line across wells 39/07-1 and A05-01. The top Scremerston coals (intra Scremerston Formation) is clearly visible on the left (blue interpretation).

On the western flank of the Elbow Spit High the Scremeston coals are found in well E02-02, within the Elleboog Formation (Scremerston equivalent in the Dutch Sector). In regards of the Scremerston coals, the exact relationship between this southern area and the northern part of the study area, where their presence is also proven, is still unclear. We hope to do additional research on this topic in a potential follow up project.

4.2.2 Base Westphalian Unconformity (BWU)

In Mijnlieff (2002), the Westphalian was initially interpreted to be present only in the Southern part of our study area, with an extension towards B17-04, such as presented in his published Base Permian subcrop map. In this project, several unconformities were encountered within the deepest part of the Step Graben. The initial assumption was that this unconformity (represented by the green horizon in Figure 4.4 and Figure 4.5) was the base Stephanian unconformity, since this was the original hypothesis at the start of this project. However, after detailed well and seismic analysis, this unconformity, which has been interpreted towards the south (Figure 4.5), turned out to be the base of Westphalian (found in F04-02A). Furthermore, this horizon is clearly connected to Westphalian strata encountered in well B17-04. Therefore, the green-coloured unconformity in Figure 4.4 is interpreted as the Base Westphalian unconformity.

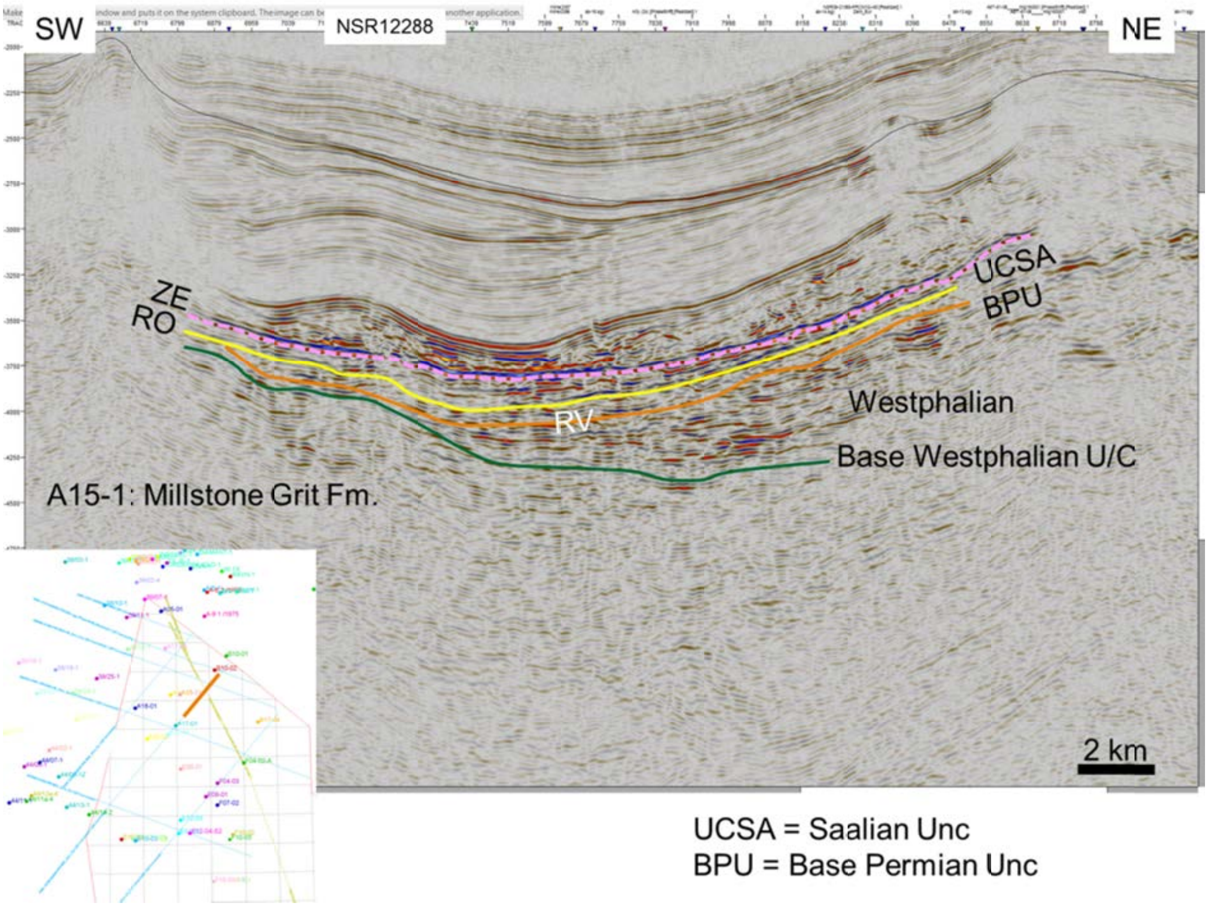


Figure 4.4: Seismic line showing the main unconformities the Carboniferous and Permian. 2D Seismic line (NSR1288) (for large version see appendix 4.22 and 4.23)

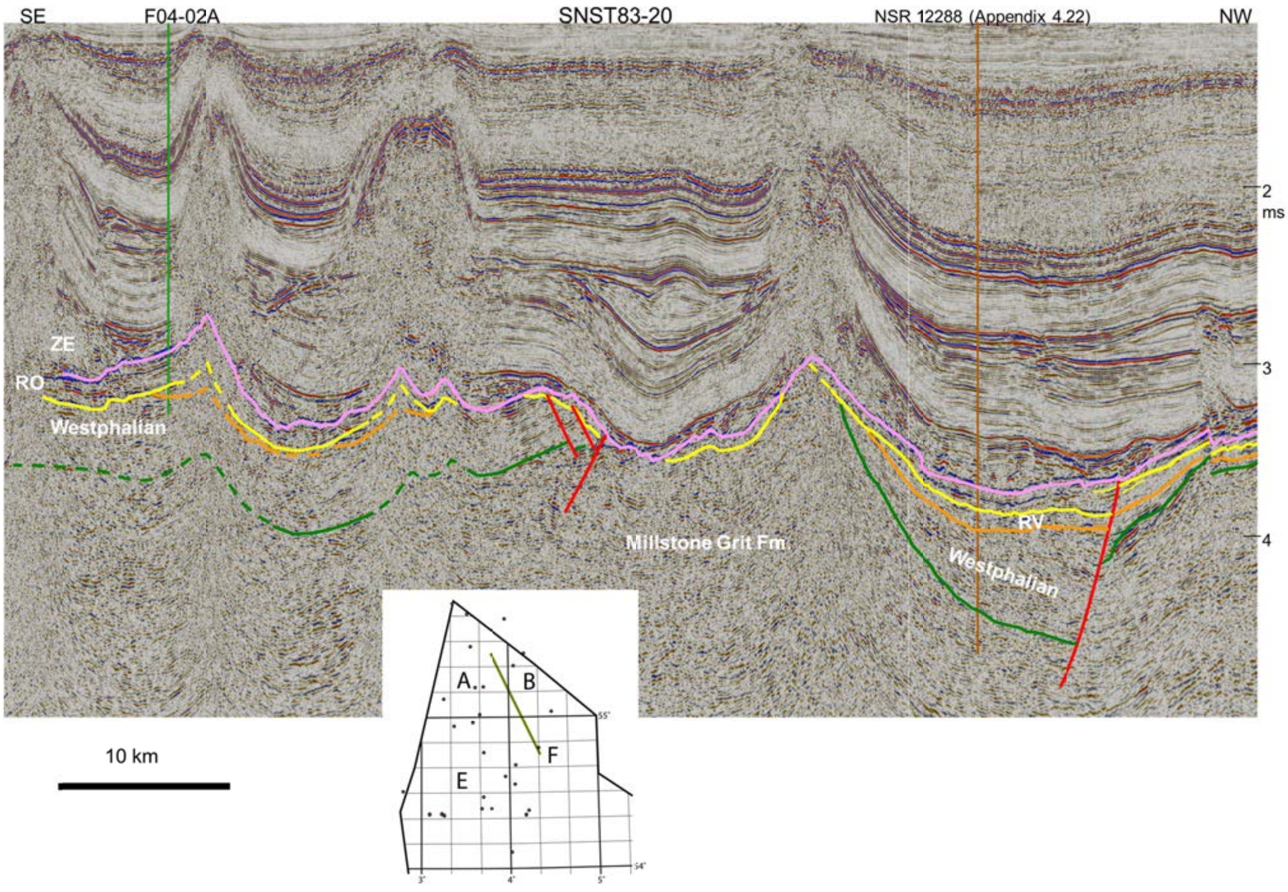


Figure 4.5: 2D seismic section SNST 83 (multiple sections) showing the Base Westphalian Unconformity and the bases of the Lower and Upper Rotliegend

The interpretation of Base Westphalian unconformity is more difficult towards the north due to the lack of penetrating wells and the often lower quality of the seismic data used in this part of the study area.

The Base Westphalian horizon (BWU) is only observed south, east and north of the Elbow Spit High, within the northern part of the Cleaver Bank High and the Step Graben. Its northern limit is interpreted to be located in block A05. Its eastern limit is unknown since the seismic interpretation of such deep interval was not achievable within the Central Graben (seismic data quality too low in such deep part of the basin), but going by the eastward increasing thickness, it is likely that it is present in the Central Graben. The Westphalian was likely deposited on top of the Elbow Spit High but was later eroded (see Appendix 4.23 and Figure 4.6). This is concluded from the fact that there is limited onlap and major erosion at the top. The deepest part of Westphalian is found in the eastern part of the A15 block and its highest location in block E-04/E-05, along the southern edge of the Elbow Spit High.

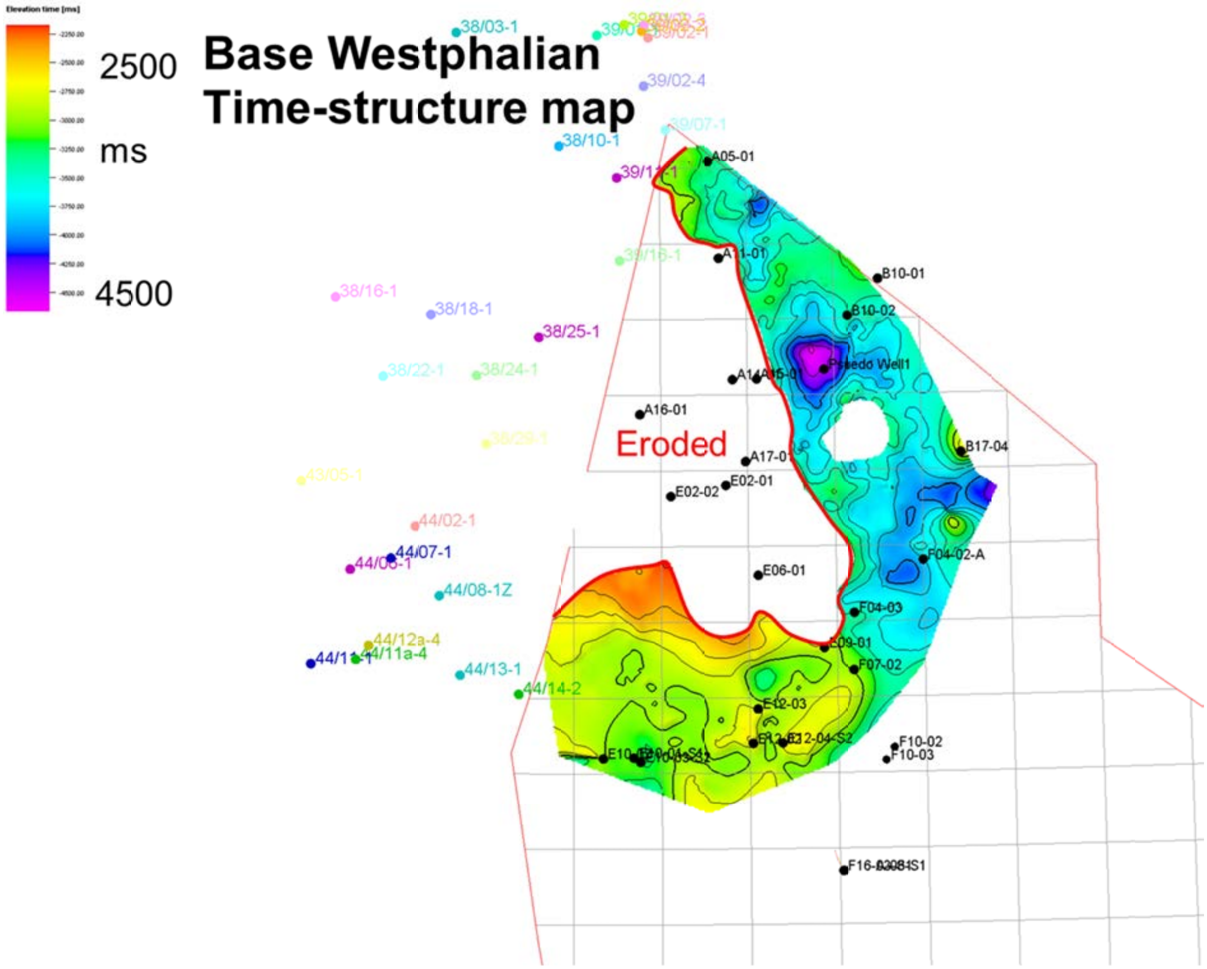


Figure 4.6: Time-structure map of the base Westphalian unconformity (for larger image see appendix 4.10)

The Westphalian time-thickness map (isochore from Base Westphalian to Base Rotliegend) is showing a series of thicks and thins (Figure 4.7). The Westphalian is thickest in three areas: 1) A15, B13 and B14 blocks; 2) F04 and F05 blocks; and 3) E10 tot E12 blocks. It thins to the northwest and southeast as well as along the north eastern and southern flanks of the Elbow Spit High. The Westphalian is expected to be present in the Central Graben, but due to the lack of resolution it was not interpreted there.

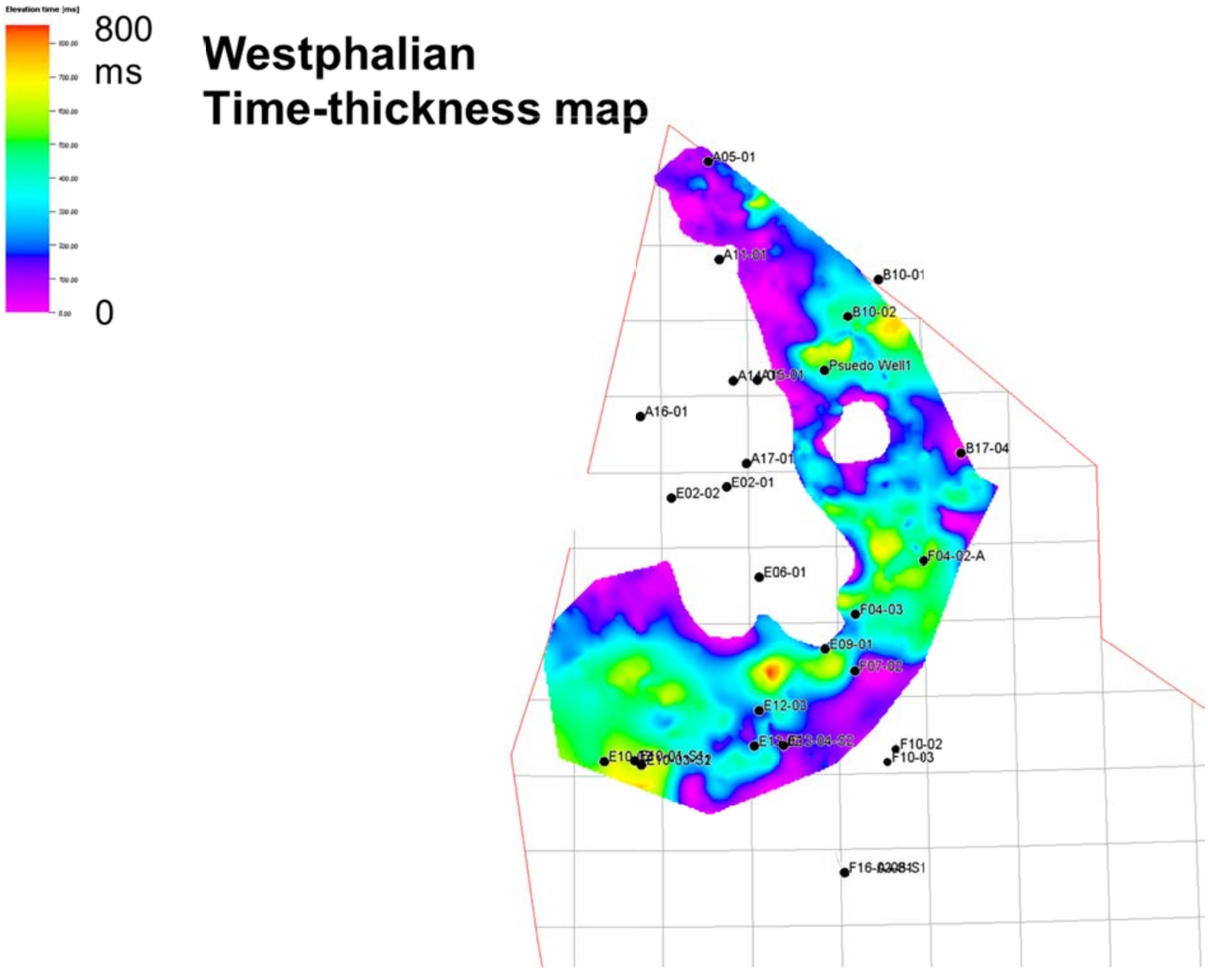


Figure 4.7: Time-thickness map of the Westphalian (for a larger image see appendix 4.13)

4.2.3 Base Lower Rotliegend (RV)

Due to the heterogeneous character of the lower Rotliegend, it is seismically not always clearly distinguishable. Therefore, the seismic interpretation relies heavily on the occurrence of this interval in wells. The lower Rotliegend was found in eight Dutch wells (A05-01, A15-01, B10-02, B17-04, F04-02, F07-02, F10-02 and F10-03) and in at least six foreign wells (LIVA-1, SAXO-1, 39/01-1, 39/02-3, 39/02-4, 39/07-1) in the North-eastern part of our study area. Since the Lower Rotliegend is not present in all wells in the north-western part of the study area, it is often challenging to correlate this interval (see Figure 4.8 or appendix 4.04, 4.09, 4.12, 4.15).

The Lower Rotliegend horizon (RV) was interpreted in the north-eastern part of the study area and in an isolated zone in the south-eastern part of the study area (in F07 and F10 blocks) (Figure 4.8). This southern small zone is expected to be potentially larger than interpreted in this study, but it was mapped in a conservative way since the poor seismic data quality doesn't allow to interpret this horizon with great confidence away from the wells' locations.

The conglomerates observed in K02-02 are possibly also Lower Rotliegend in age and could illustrate the fact that remnants of the Lower Rotliegend could be expected further to the south-west.

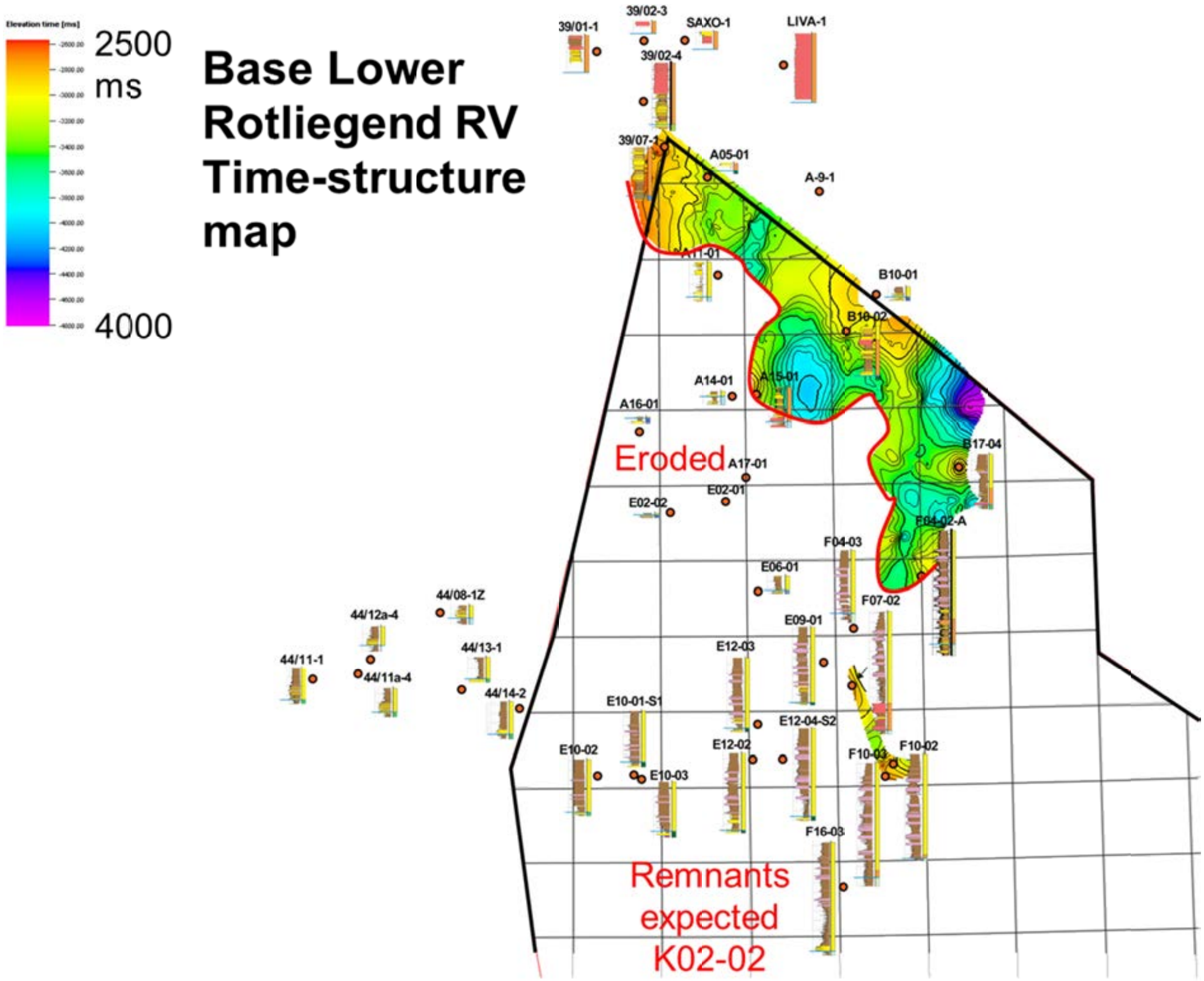


Figure 4.8: Time-structure map of the Lower Rotliegend (for a larger image see appendix 4.12)

The lower Rotliegend interval is thickest in two areas: 1) in the A15, B13, B14 blocks and 2) in the A05 block (Figure 4.9)

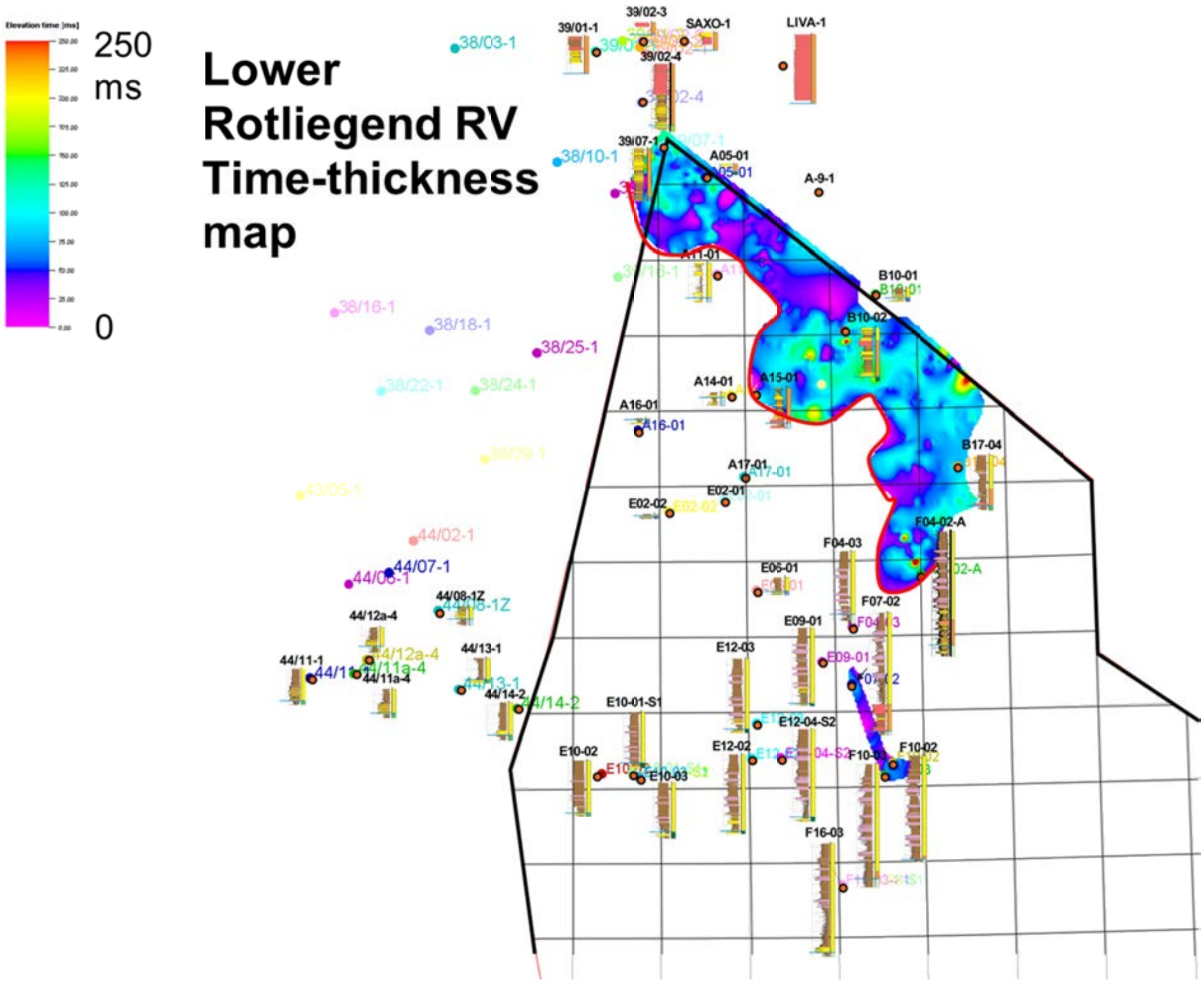


Figure 4.9: Time thickness map of the Lower Rotliegend (RV)

4.2.4 Base Upper Rotliegend (RO)

The Base Upper Rotliegend was encountered in most wells, except in wells A05-01, A17-01 and E02-01 in the Dutch Offshore and in the Danish and northern UK wells (Figure 4.10). The Base Upper Rotliegend is also present in the UK blocks 44 but lack of seismic data in this area prevented it from being mapped in this project. The base is an unconformity (Saalian) and shows a clear angular stratal relationship between the Upper Rotliegend and its subcropping intervals (e.g. Figure 4.5). Therefore, this horizon has been mapped with a higher degree of certainty.

The Base Rotliegend horizon is deepest in the Central Graben and shallows up towards the West, especially above the elbow Spit High (Figure 4.10). Many N-S oriented structures (fault-bounded grabens, half-grabens, horsts) are observed on the time-structure map.

The Upper Rotliegend is thickest in the south-eastern part of our study area where the Silver Pit Formation is the thickest (Figure 4.11 and Figure 4.12). This interval thins and onlaps onto underlying strata (Figure 4.12). Therefore, the oldest Upper

Rotliegend strata are found in the south-eastern part, and gets younger northward. The Upper Rotliegend is thinner in the Dutch Central Graben than in the Step Graben (see Figure 4.11and Figure 4.12).

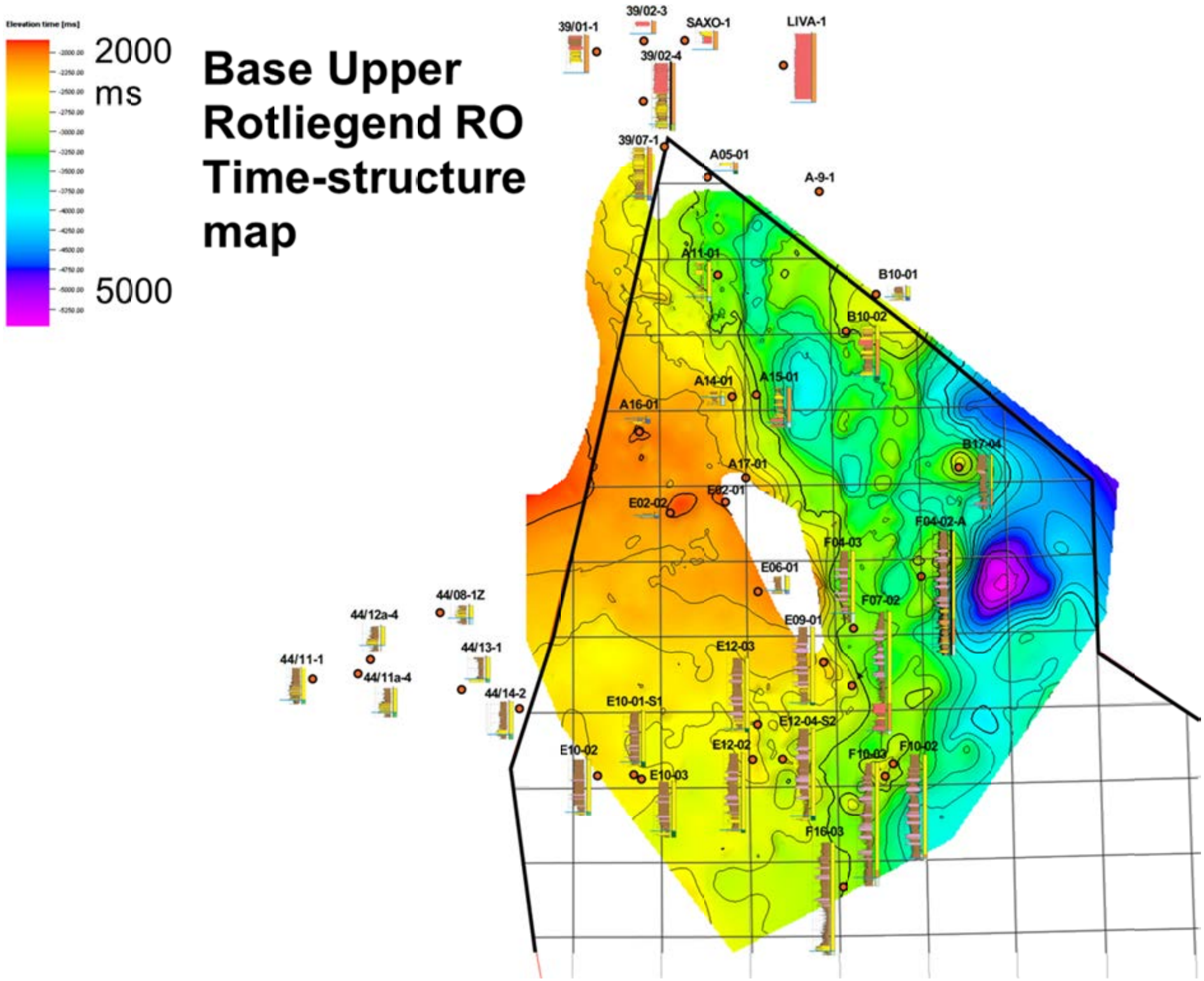


Figure 4.10: Time-structure map of the base Upper Rotliegend (for a larger image see appendix 4.08)

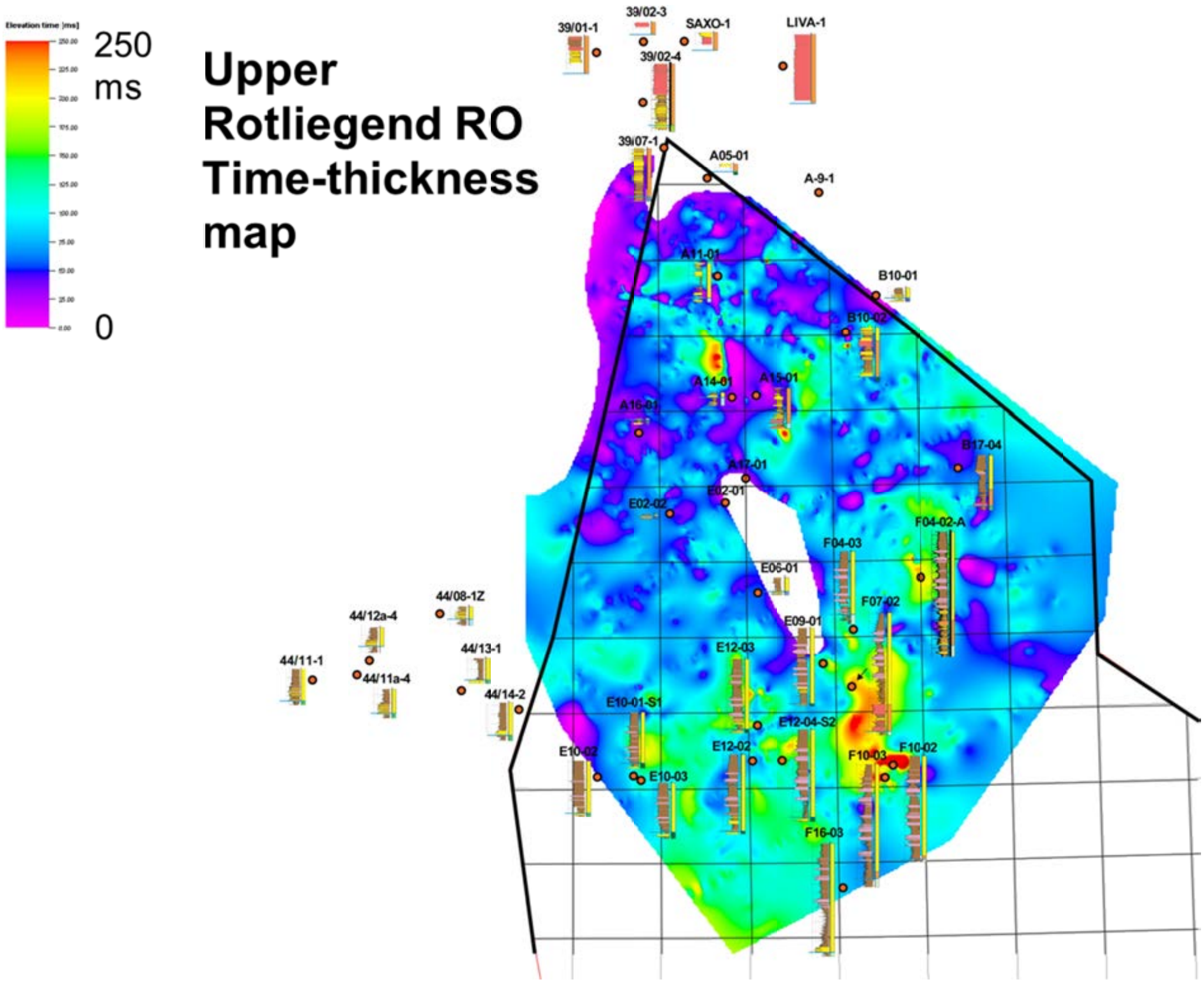


Figure 4.11: Time-thickness map of the Upper Rotliegend (RO)

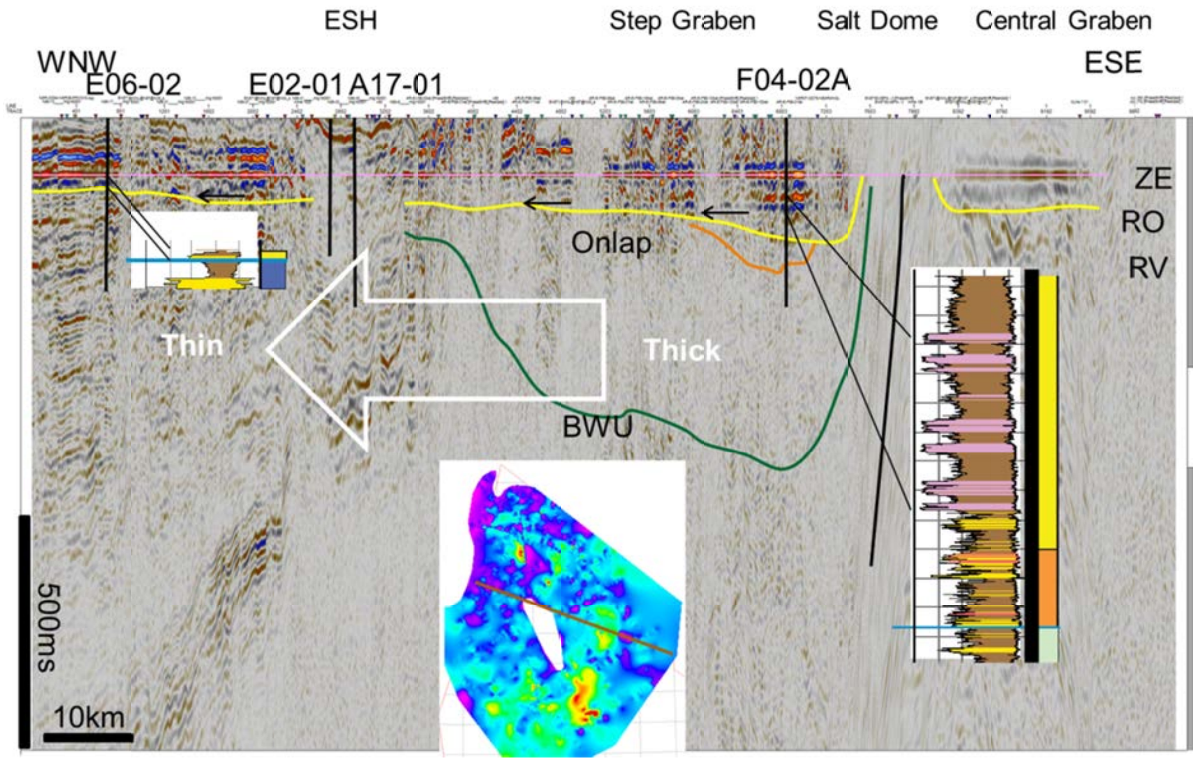


Figure 4.12: Flattened and highly vertically exaggerated seismic section showing the thickness variation and onlap configuration of the Upper Rotliegend. For larger image see appendix 4.25 and 4.26.

The stratigraphic relationship between the Lower and Upper Rotliegend is a seismically recognisable unconformity (Saalian Unconformity) (Figure 4.4, Figure 4.12 and Figure 4.13)

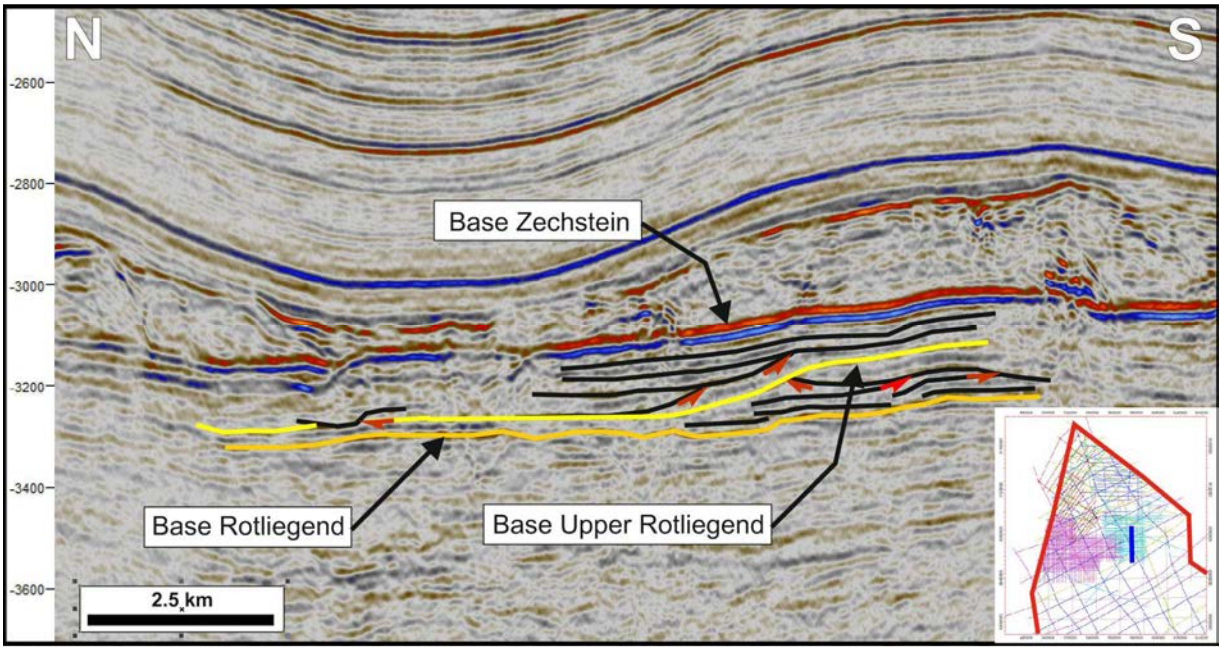


Figure 4.13: Seismic example of the intra-Rotliegend stratal complexity. The lower orange line represents the base of the Rotliegend.

4.2.5 Base Zechstein

The base Zechstein was interpreted as a top horizon. Since it is relatively easy to auto track, it was also interpreted in the available 3D seismic volumes (Figure 4.14 and Appendix 4.02).
Faults and fault trends are mapped on this surface (Figure 4.14 and Appendix 4.17).

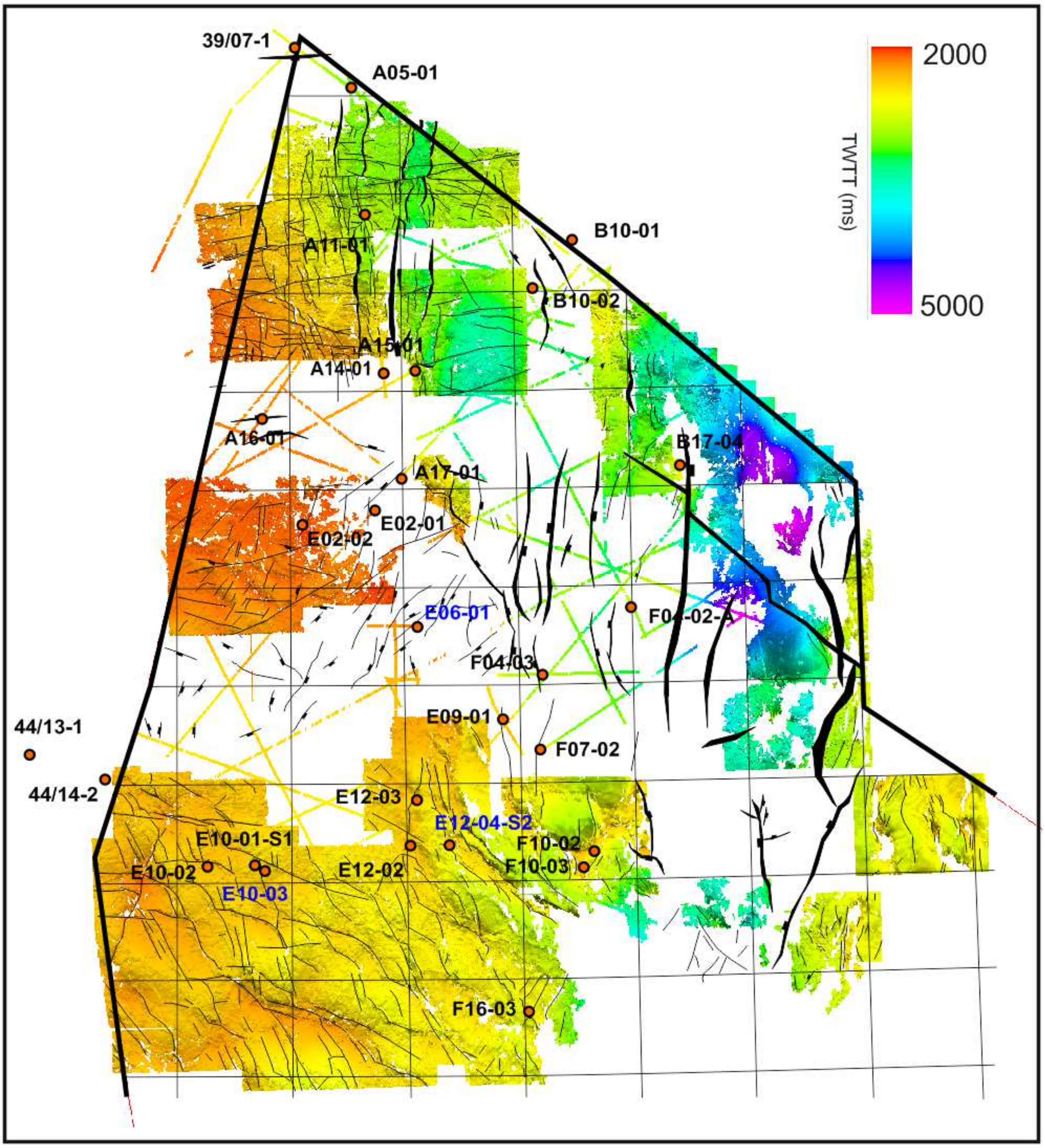


Figure 4.14: Base Zechstein time-structure map. The interpreted faults at this level are also shown.

Despite the limitation of seismic data quality, the seismic interpretation performed in this project was instrumental to unravel the tectono-stratigraphic history of this part of the North Sea during the Carboniferous and Permian. Even if this project scope did not include a seismic mapping exercise, the research team generated a vast amount of seismic-based results that are necessary to discuss the complex basin evolution.

4.3 Stratigraphy

The stratigraphic results obtained in this project are presented below. A new chronostratigraphic chart for the Dutch Northern Offshore is described as well as a new Base Permian subcrop map. The majority of the detailed stratigraphic results are focused on the Rotliegend, with a particular emphasis on the internal stratigraphic complexities of the Lower and Upper Rotliegend.

4.3.1 Chronostratigraphical chart

The chronostratigraphical chart (see Figure 4.15 and appendix 9) was constructed by combining the chronostratigraphical charts of the Carboniferous and Permian as published by Kombrink et al., (2010) and Glas et al. (2010) with the new stratigraphic results obtained in this study. This new chronostratigraphic chart is schematic and follows a North-South orientated transect in the Northern Dutch Offshore, extending to the north to the British and Danish sectors and to the F16 block in the south. The Permo-Carboniferous stratigraphy is described below:

- Old Red Group
  In the Southern Permian Basin the Old Red Group is composed of Devonian (Patch and Buchan Formations,) and Carboniferous (Tayport Formation) sediments (Geluk et al., 2007. Old Red Group is found in A17-01 and wells across the border in the UK (39/11-1, 38/10-1, 38/25-1, 38/24-1, 38/29-1). It is assumed to be present in the entire study area. In the border region (around the Mid North Sea High) it is directly underlying the Rotliegend (if present). This is represented in the northern part of the chart by the Saalian Unconformity.

- Farne Group
  In the Southern Permian Basin the Carboniferous Farne Group is composed of sediments of Dinantian-age (Cemenstone, Ellebog, and partly Yoredale Formations) and of Namurian-age (partly Yoredale and Epen Formations) (Geluk et al., 2007). In the study area, this group is mainly encountered in wells surrounding the Elbow Spit High (A14-01, A16-01, E02-01, E02-02 and E06-01) and just across the German border (B10-01). Around the Elbow Spit High the Farne Group is found directly underneath the Rotliegend (when present). This is represented in the middle section of the chart, by the Saalian Unconformity.

  The Scremerston Formation is not defined as a separate formation in the Netherlands. It is present in the Northern Permian Basin in the UK sector (e.g. 39/07-1) and is equivalent to the upper part of the Ellebog Formation is the Dutch sector. Note that coal layers are also encountered in the Elleboog Formation in the Netherlands, and could be the southern expression of the Scremerstone coal measures. The Scremerston Formation is one of the potential source rocks in our study area

- Limburg group
  The Limburg Group is composed of Namurian (Epen and Millstone Grit Formations), Westphalian (Klaverbank, Maurits, Hospital Ground and Step Graben Formations) age strata. By definition the Limburg Group includes Stephanian sediments but no Stephanian-age strata have been identified in the study area (see 4.4.3 section for detailed arguments). Below is a summary of the occurrences of Limburg Group strata in the project's wells:

  Epen Formation
  The Epen Formation was only found in A14-01 and E06-01. The base of the Epen Formation is the Geverik Shale, which could be a potential source rock.

  Millstone Grit Formation
  The Millstone Grit Formation was encountered below the Westphalian (B17-04, E09-01, E12-02, E12-03), directly below the Lower Rotliegend (A15-01) (caused by Hercynian erosion), and the Upper Rotliegend (A11-01 and A14-01) (caused by Saalian Unconformity).

  Klaverbank Formation (Approximately Westphalian A)
  The Klaverbank is the oldest Westphalian formation and is therefore more likely to be preserved than its younger counterparts (which had more extensive exposure to erosion of the Hercynian and Saalian erosion phases). The Klaverbank Formation is a potential source rock.

  Maurits Formation (Approximately Westphalian B)
  The Maurits formation is a well-known source rock, which has been encountered in the north of the study area (B17-04, F04-02A, and F07-02).

  Hospital Ground Formation (Approximately Westphalian C)
  The Hospital Ground Formation is a well-known reservoir, but it has only been encountered in the most southern well (F16-03) and is not present in towards the north.

  Step Graben Formation (Approximately Westphalian D)
  Towards the north it is not present and the Step Graben Formation directly overlies the Maurits Formation.

- *Lower Rotliegend Group*
  The Lower Rotliegend consists of the Grensen Formation in the North (UK sector), which corresponds to the Basal Rotliegend Clastics in the Netherlands. The age dating of the Lower Rotliegend is problematic, but it is most likely early Permian. The lower Rotliegend consist primarily of volcanics and volcanoclastics in the western part of the Danish Offshore and of clastics, volcanoclastics and volcanics in the Netherlands (Lower Rotliegend Volcanics Formation).

- Upper Rotliegend Group
  The Upper Rotliegend consists of the Auk Formation in the UK, which correspond to the Slochteren Formation in the Netherlands. The Slochteren Formation is

defined in the Southern Fringe of the Southern Permian Basin, and the same terminology was used in this project to describe the sandy part of the Upper Rotliegend along the Northern Fringe (northern basin margin). In the southern part of our study area the Silver Pit Formation is predominant, that is the low net-to-gross lateral equivalent of the Slochteren Formation (basin axis). The Upper Rotliegend onlaps from the SE towards the NW along the northern margin of the basin.

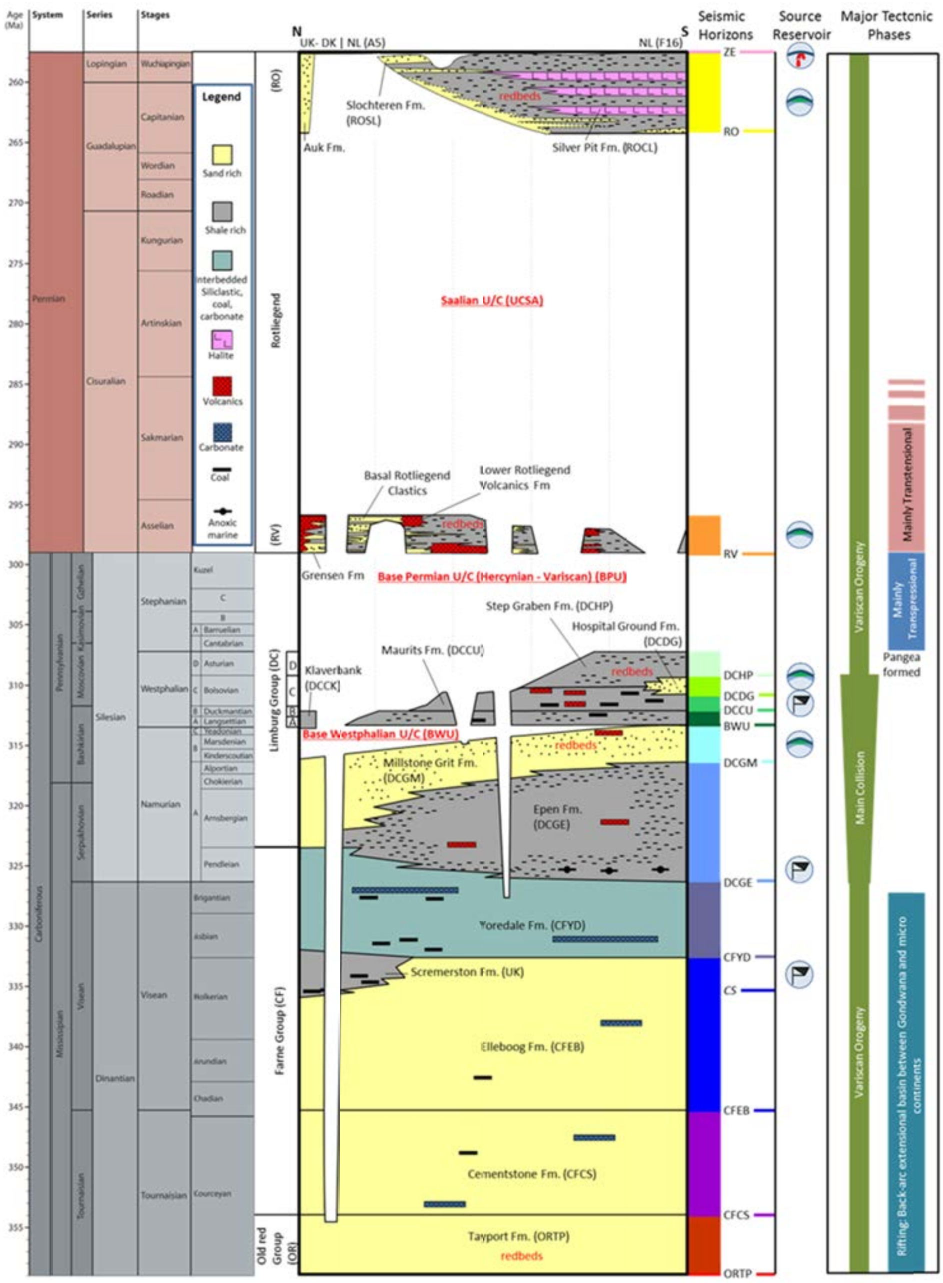


Figure 4.15: Chronostratigraphical chart of the Carboniferous and Permian in the study area

4.3.2 Subcrop map

A new Base Permian subcrop map (see Figure 4.17 and Appendix 7.01) has been constructed in this study for the Dutch northern Offshore. This new map, partially based on the previously published subcrop map by Mijnlieff (2002) (Figure 4.16), incorporate seismic and well interpretation results from the present projects.

Many zones within the study area show a different age than previously published. One of the main differences is in the northern part of the Step Graben where Westphalian-age strata (Klaverbank and Maurits Formations) have now been interpreted below the Base Permian Unconformity. The geometry of the subcrop in the middle of the Step Graben suggests an anticlinal geometry with Millstone Grit Formation at the core, also shown on seismic in Figure 4.5. North of the Elbow Spit High an area is kept blank since seismic interpretation along the UK/NL boundary suggests the presence of Carboniferous rocks, while several UK wells (38/24-1, 38/25-1 and 38/29-1) show Old Red Group just across the border. This issue was planned to be resolved as part of Theme 3, but due to budget cuts this was cancelled.

This new subcrop map has been used in this study during the basin modelling activity.

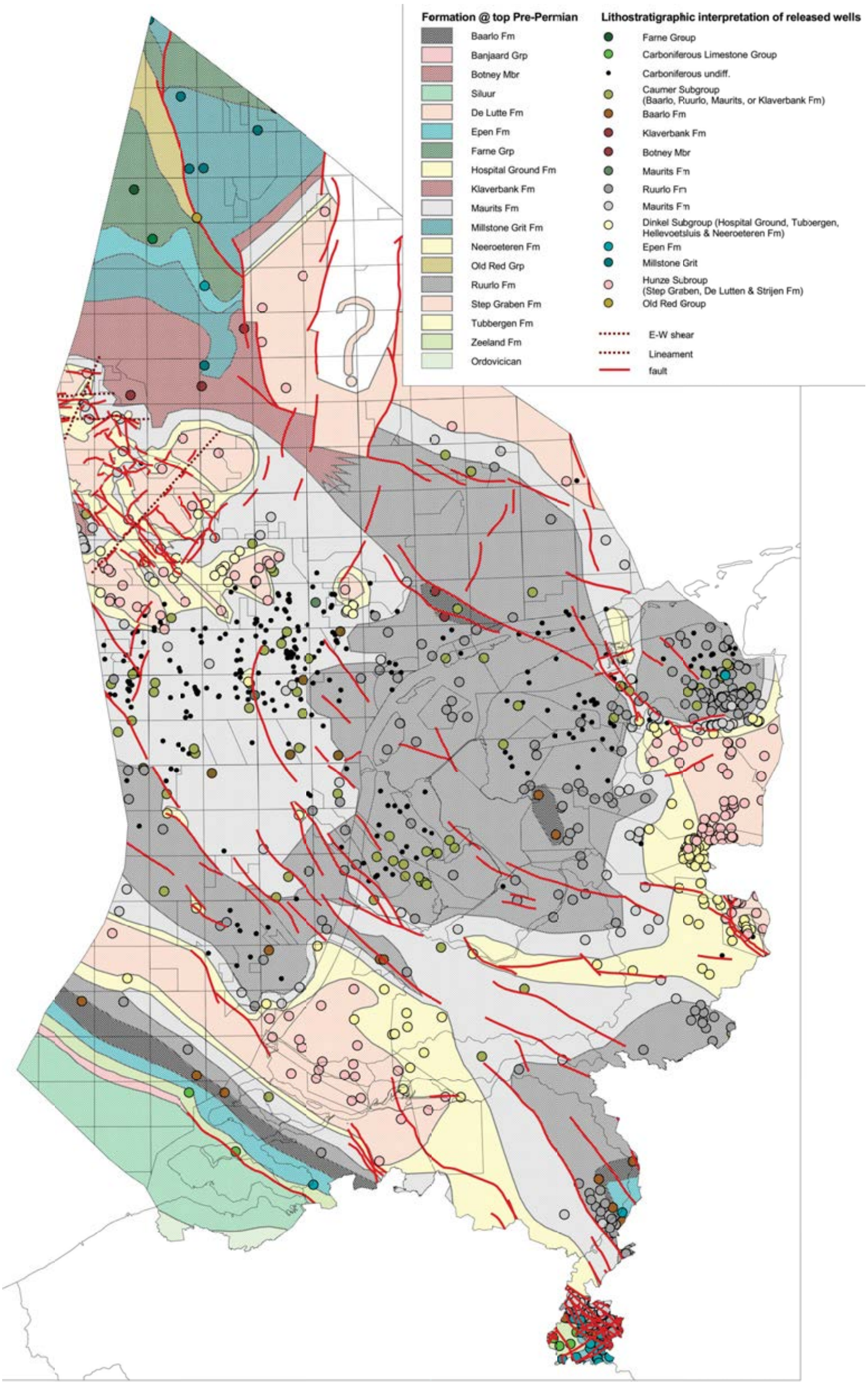


Figure 4.16: Top Pre-Permian distribution map (or Base Permian Subcrop map) from Mijnlieff (2002)

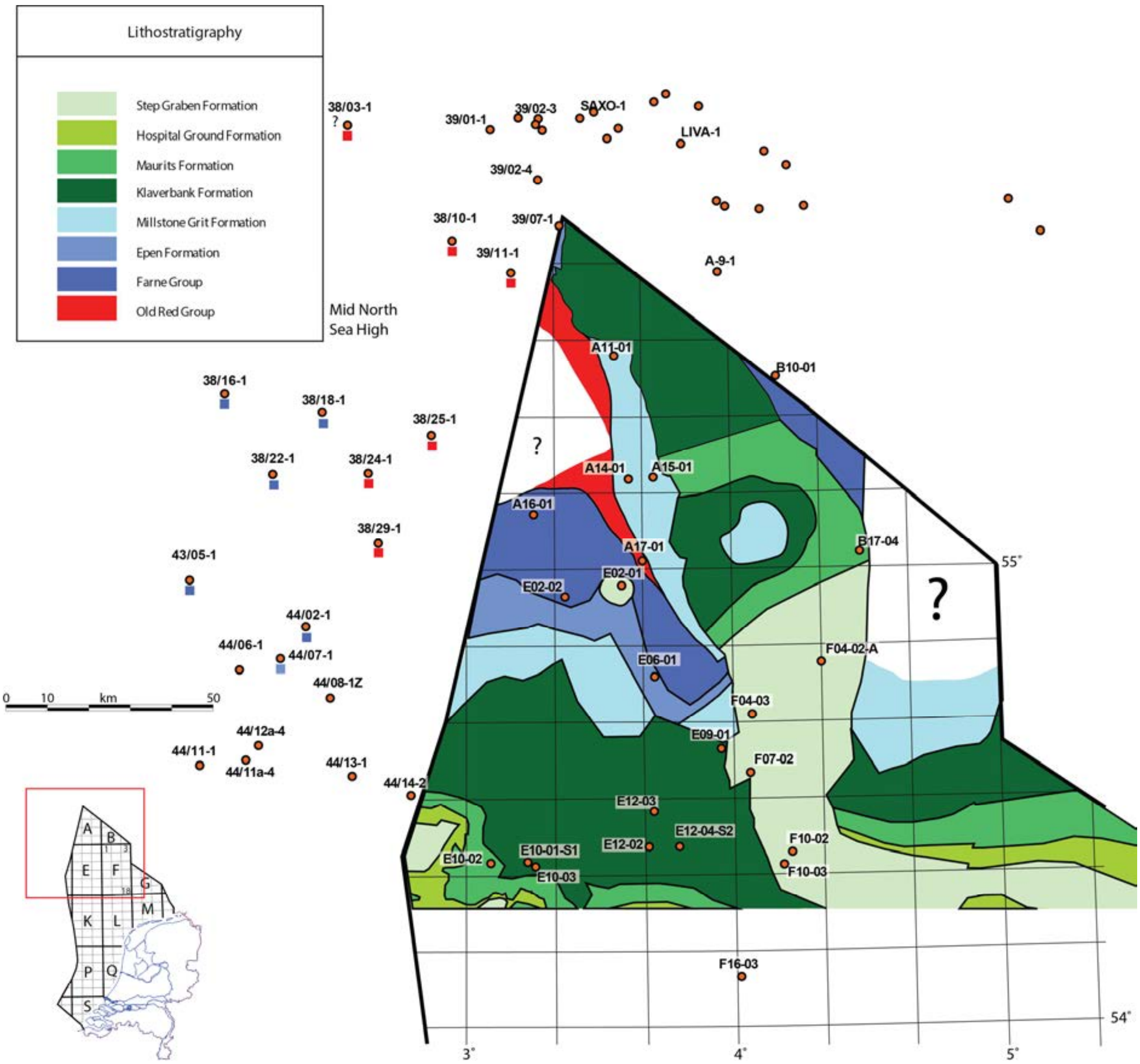


Figure 4.17:New Base Permian subcrop map. Note that the age of subcropping strata in the Dutch Central Graben has not been resolved in this study to the greater present-day depth of the Permian in this area and the low seismic data quality in this part of the basin. See also Appendix 7.01

4.3.3 Rotliegend Stratigraphy

The Rotliegend stratigraphy is complex due to the vertical and lateral variability in depositional settings, systems, thicknesses and lithologies. In this section, the main results concerning the stratigraphy of the Rotliegend as a depositional unit will be summarised, followed by specific sub-sections on the stratigraphy of the Lower and Upper Rotliegend Groups.

Lithological information, in the form of electrofacies classes, has been extracted from the well database for the Rotliegend interval. Figure 4.18 and Figure 4.19 summarize the electrofacies results for the Rotliegend in the study area. Only two wells have no Rotliegend preserved, i.e. E02-02 and A17-01 (Figure 3.5). The Rotliegend is primarily composed of shales (70%) with some halites (13%), sands (10%) and volcanics (5-8%). Less than 0.1 % of limestones are observed. The large amount of shales in the Rotliegend stratigraphy is mainly due to the, often thick, low net–to-gross deposits of the Silver Pit Formation (Silver Pit palaeo-lake) that are located in the southern part of the study area. Most of the reservoir facies are located along the margins of the basin to the south and north of the study area, on the margins of the successive Silver Pit lake depo-centres.

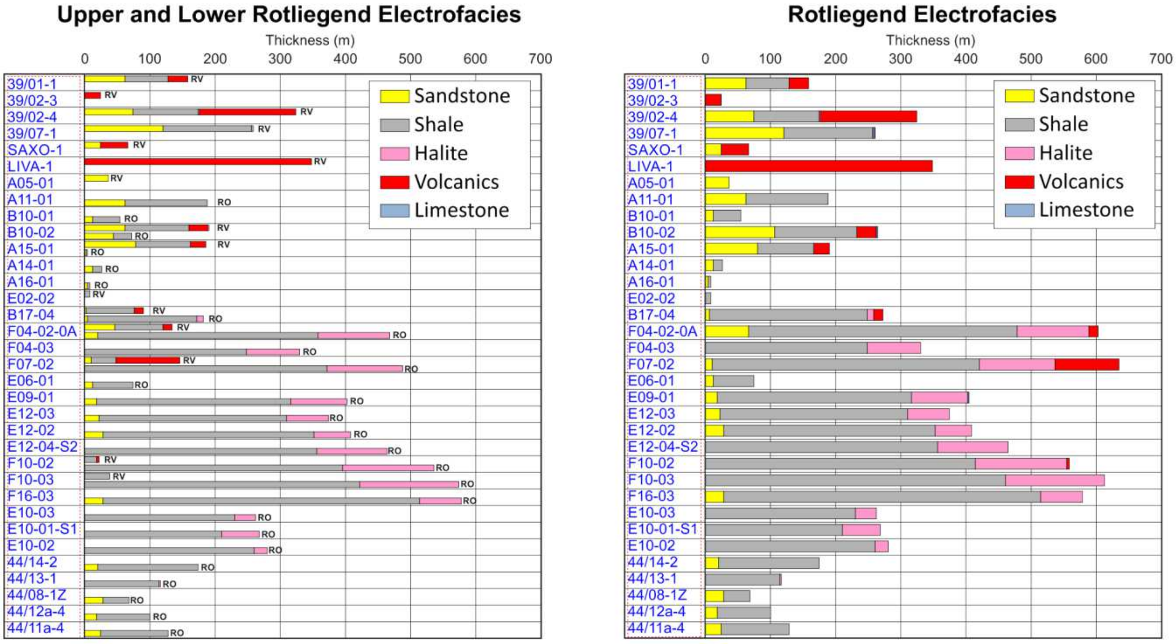


Figure 4.18: Electrofacies results of the Rotliegend for all the wells located in the study area. 1) To the left: differentiated for the Upper and Lower Rotliegend for each well, and 2) to the right: for the entire Rotliegend for each well. The Rotliegend electrofacies thicknesses measured in the well are not corrected for deviation since no major deviated wells have been used in this study. RO= Upper Rotliegend, RV= Lower Rotliegend. Location of wells shown in Figure 3.2.

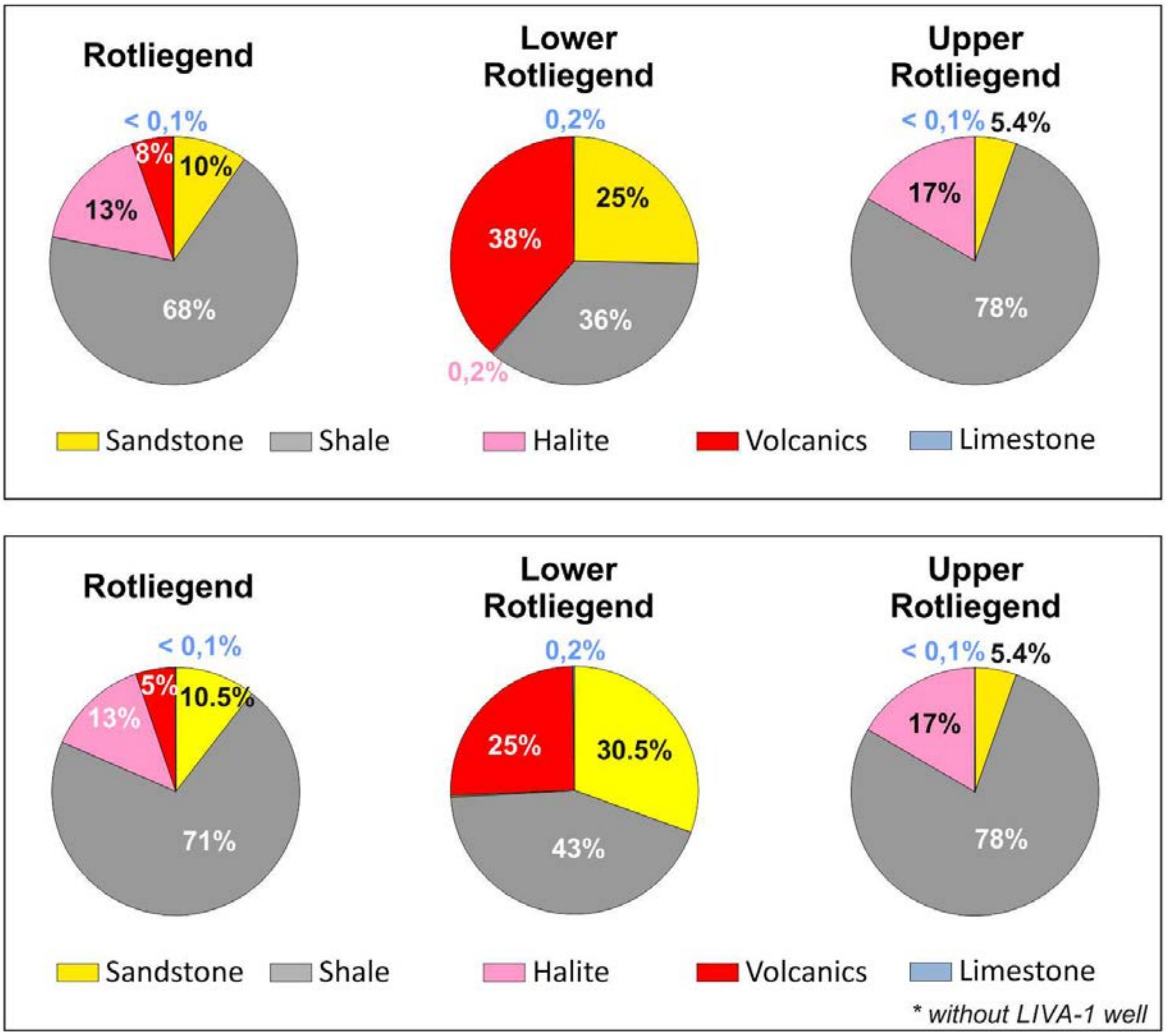


Figure 4.19: Pie-charts documenting the relative proportion of the Rotliegend electrofacies. The entire database for the first row, and for the second row, all wells but one (* i.e. well LIVA-1, which is located in Denmark and consists of volcanics in the Rotliegend). Note that the amount of carbonate lithology in the Rotliegend is very low (less than 0.1% overall.

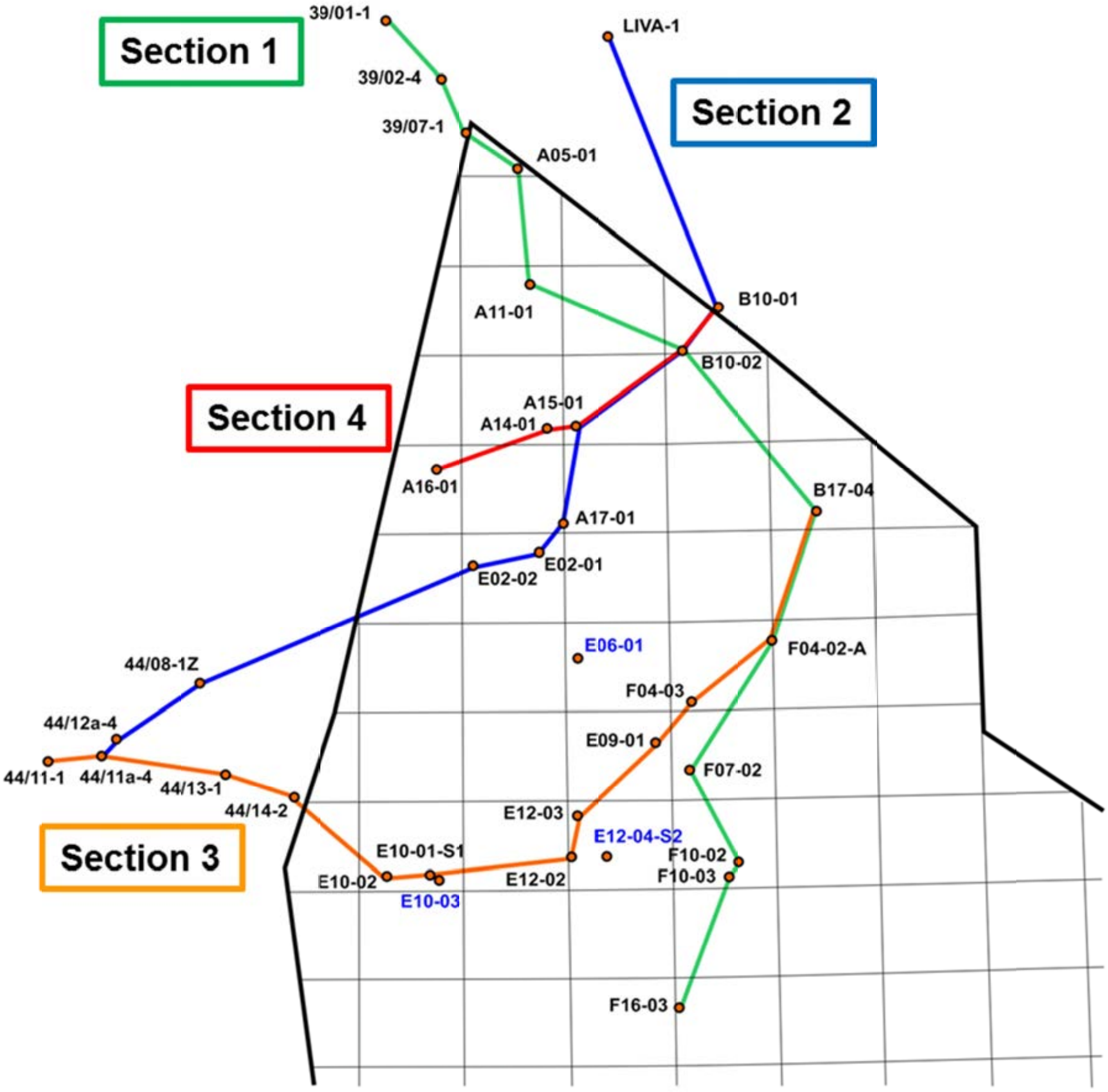


Figure 4.20: Location map of the stratigraphic correlation panels.

4.3.3.1 Lower Rotliegend

During Permo-Carboniferous times, when the Lower Rotliegend was deposited, volcanic activity took place throughout North Western Europe. Figure 4.21 summarizes attempts to evaluate the ages of the major basaltic events from Norway to Scotland in relation to North Sea Volcanism. The results indicate that most basaltic and rhyolitic events are straddling the boundary between Carboniferous and Permian (i.e. from 320 to 280 Ma). Ages younger than 280 Ma have been reported in a few publications only (Larsen, 1975). The latter typically occur in older publications only, when age-dating techniques were often less reliable.

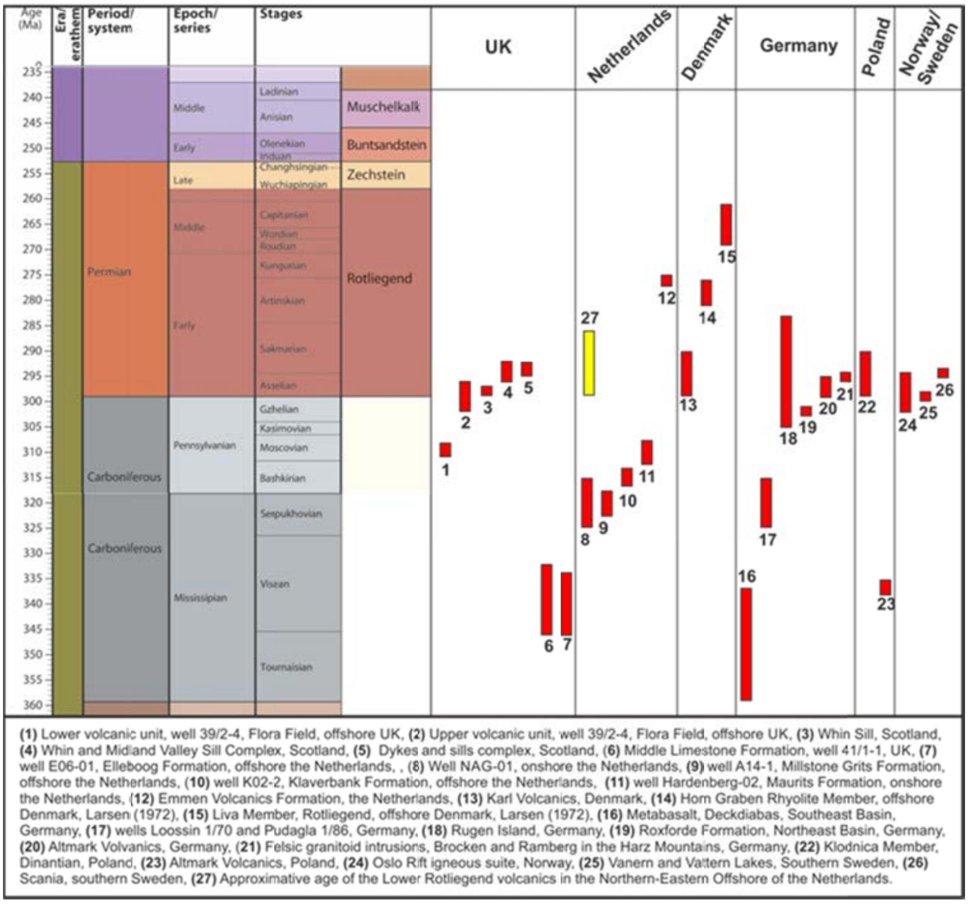


Figure 4.21: Compilation of results on the ages of volcanic units in the North Sea and surrounding areas. Compiled from SPBA, Martin et al. (2002) and Heeremans et al. (2004).

Intra Lower Rotliegend stratigraphical correlation is challenging due to its complex depositional setting and reduced preservation potential as a result of the subsequent Saalian erosional event(s), (Figure 4.13). However, in order to better illustrate and understand the vertical and lateral stratigraphic changes within the Lower Rotliegend, a vertical subdivision into three individual units was applied (Figure 4.22 and Figure 4.23). The subdivisions are based on lithology, especially correlatable and recognizable thick sandy or shaly intervals are used. In the more challenging wells (e.g. LIVA-1 Figure 4.22) where no clear stratigraphical breakdown into these units was feasible, a proportional subdivision (division into three equally thick intervals) has been applied. The stratigraphical units of the Lower Rotliegend are referred to as RV1, RV2 and RV3. They have been correlated across the eleven wells that contain Lower Rotliegend strata. Figure 4.22 and Figure 4.23 also show that certain wells are lacking some or even all three units.

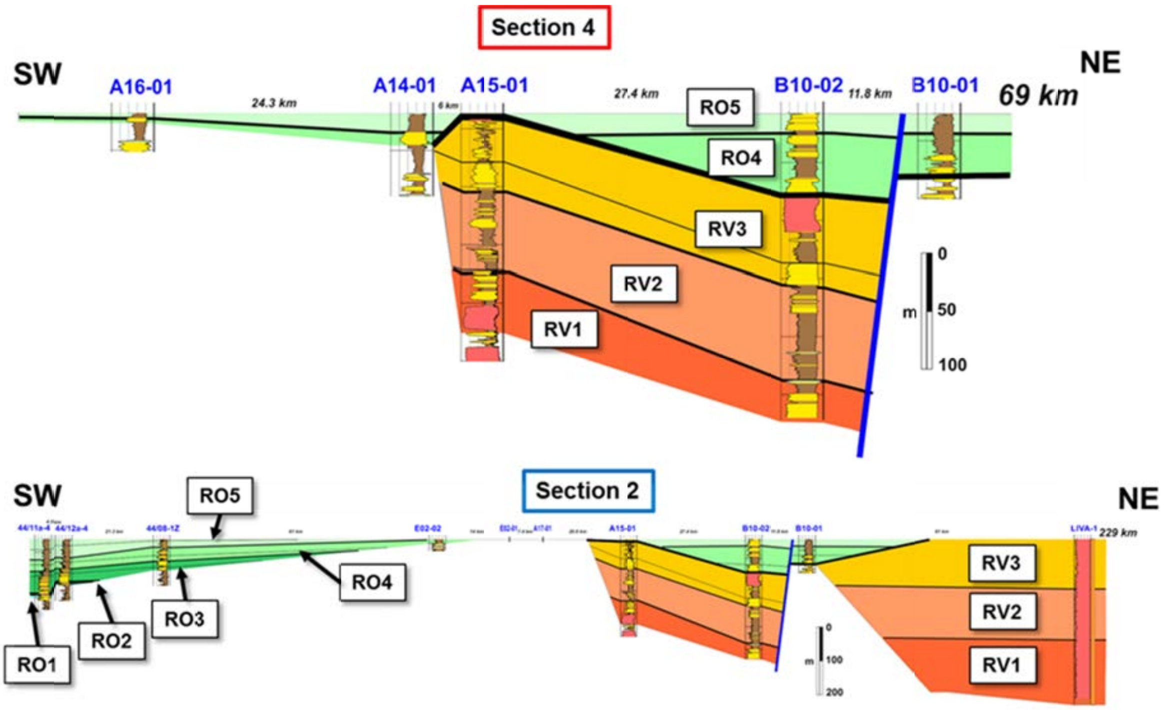


Figure 4.22:Stratigraphical correlation panels illustrating the intra Lower and Upper Rotliegend subdivisions (part1). RV1-RV3 refer to three intra Lower Rotliegend subdivisions and RO1-5 refer to Upper Rotliegend subdivisions. See Figure 3.2 for location.

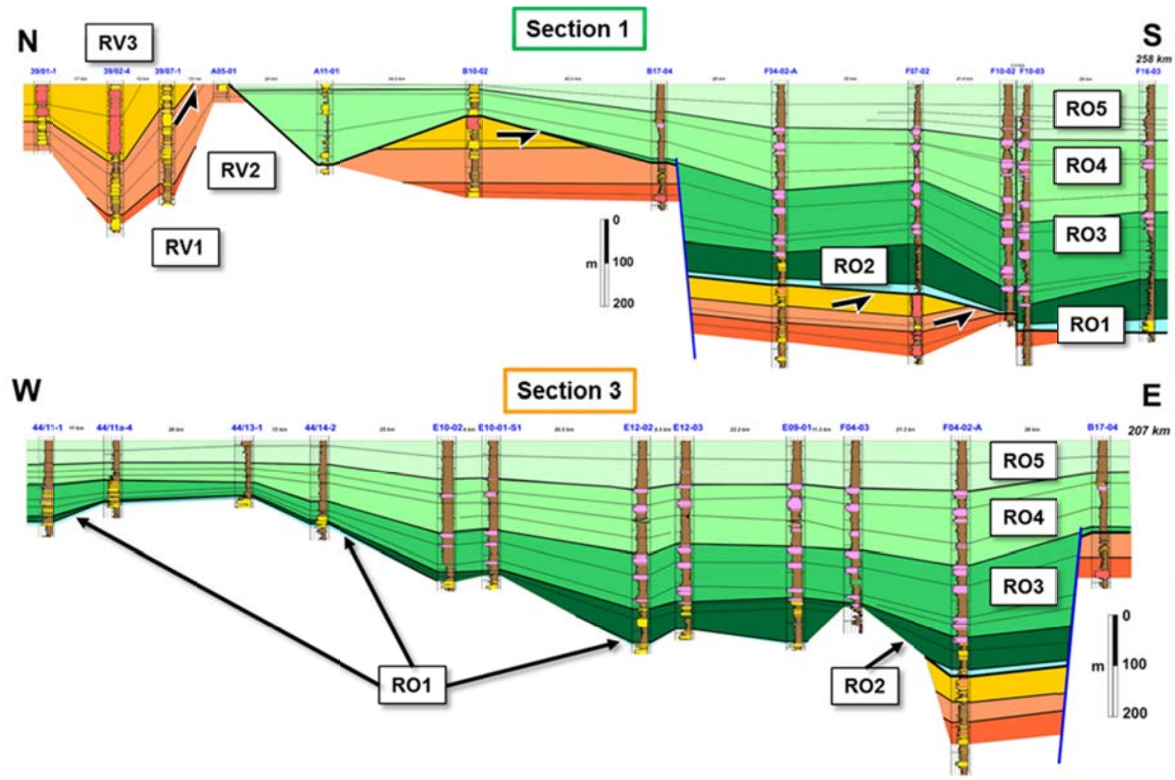
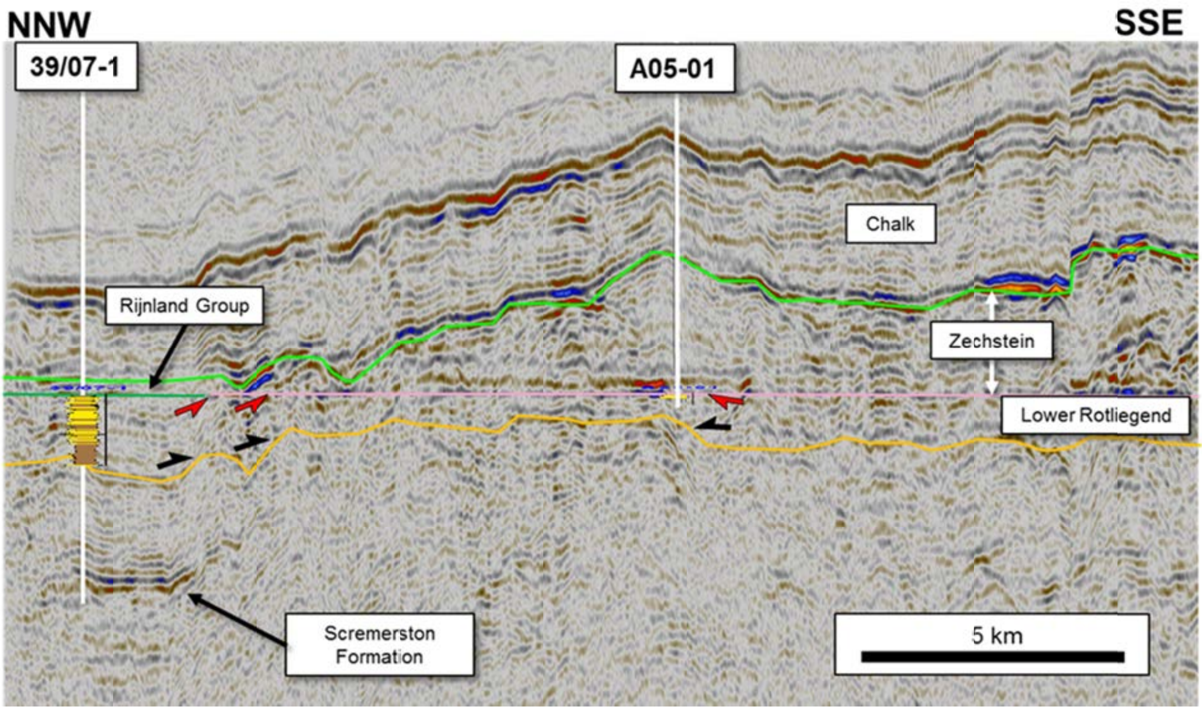


Figure 4.23:Stratigraphical correlation panels illustrating the Intra Lower and Upper Rotliegend subdivisions (part 2). RV1-RV3 refer to three intra Lower Rotliegend subdivisions and RO1-5 refer to Upper Rotliegend subdivisions. Main truncations are highlighted with black arrows. See Figure 4.20 for location.

Subsequently three maps were constructed for the Lower Rotliegend, each illustrating the lateral extents and palaeo-depositional distribution of the main lithofacies (electrofacies) per unit (Figure 4.24). A total of six different lithofacies associations were recognised within the three stratigraphic sub-divisions of the Lower Rotliegend. The four most common ones are referred to as 1) predominantly sand, 2) sand, silt and shale interfingering, 3) predominantly shales, and 4) volcanoclastics and volcanics. Note that the distribution of Lower Rotliegend sediments is restricted to the north-eastern part of the study area, with the exception of a small sliver in the central part of the area i.e. in wells F07-02, F10-02 and F10-03 (Figure 4.23). The absence of Lower Rotliegend in the remainder of the study area can be explained by subsequent erosion rather than by non-deposition. This topic will be further discussed in section 5.2.1. The base of the Upper Rotliegend is the regionally significant Saalian Unconformity, which locally truncates the lower Rotliegend e.g. between wells B10-02 and B17-04 and between wells F07-02 and F10-02 (Section 1, Figure 4.23).

Each of the three Lower Rotliegend units will be described below (from old to young):



- Figure 4.25. The oldest Lower Rotliegend unit is locally confined within basin structural lows (e.g. between wells 39/01-1 and A05-01, Figure 4-25) and displays lateral lithofacies variations. An area of non-deposition, in which well A05-01 is located, is represented as a hiatus in Figure 4.24 (grey checker textured zone). This hiatus area truly represents a non-depositional area rather than an erosional zone (as seen for the younger Lower Rotliegend intervals described below). This zone is also illustrated on the interpreted seismic line in Figure 4.25 (between the black arrows representing onlap onto the topographic high). A zone composed of volcanoclastics and volcanics lithofacies is located in the northern and central part of the preserved depositional area. Two zones contain reservoir sands (represented by the “predominantly sand” lithofacies association) are found in the extreme northwest (Zone A), and in the central eastern part of the preserved area (Zone B). Finer-grained lithofacies associations (i.e. the ‘sand, silt and shale interfering’, and ‘predominantly shales’ lithofacies associations) are also deposited during this period (in Zone C). The latter mixed lithofacies associations were identified on the southern edges of the main preserved Lower Rotliegend area and are locally bounded by a large NW-SE oriented normal fault (i.e. Fault 1).

- RV2: Middle Unit of the Lower Rotliegend (see Figure 4.23 to Figure 4.24). The middle unit is mainly composed of the ‘Sand, silt and shale interfingering’ lithofacies associations. ‘Volcanoclastics and volcanics’ lithofacies associations are limited to the north eastern part of the area, located in the Danish and German offshore sectors. Each well that contains RV2 strata shows one or two coarsening-up sequences and an overall coarsening-up trend for the entire interval. Rare thin ‘Carbonates’ lithofacies associations are observed in the northern part of the area, in wells 39/02-04 and 39/07-1. The depositional map (Figure 4.24) for this interval shows a NW-SE trend in the distribution of the main lithofacies. The NW/SE trending ‘Predominantly sand’ zone (Zone D) borders the SW edge of the ‘Volcanoclastic and volcanics’ zone. Farther to the southwest and parallel to the sandy Zone D, a more extended zone of lower net-to-gross (referred to as “sand, silt and shale inter-fingering”) is observed (Zone E). The south-western limit of depositional zone E is truncated and therefore the palaeo-extent of this interval is unknown. Finally, to the extreme south a low net-to-gross deposition area (i.e. ‘predominantly shales’) is observed.

- RV3: Upper Unit of the Lower Rotliegend (see Figure 4.23 to Figure 4.24). This upper (=youngest) unit of the Lower Rotliegend is locally eroded and therefore has a more limited geographic extent than the two older units (i.e. RV1 and RV2). Two eroded zones are identified (i.e. Zones F and G). In Zone F the RV3 unit is eroded between wells 39/07-1 and A05-01 (Figure 4.25) at base Zechstein and is missing in the position of well A05-01. Zone G is located on the up thrown side of Fault 1. In contrast to the older two Lower Rotliegend units, RV3 shows a different distribution of the ”predominantly sand” lithofacies associations with these sandy facies located along the south-western edge of the area (Zone H), where it is locally fault-bounded (Fault 1).

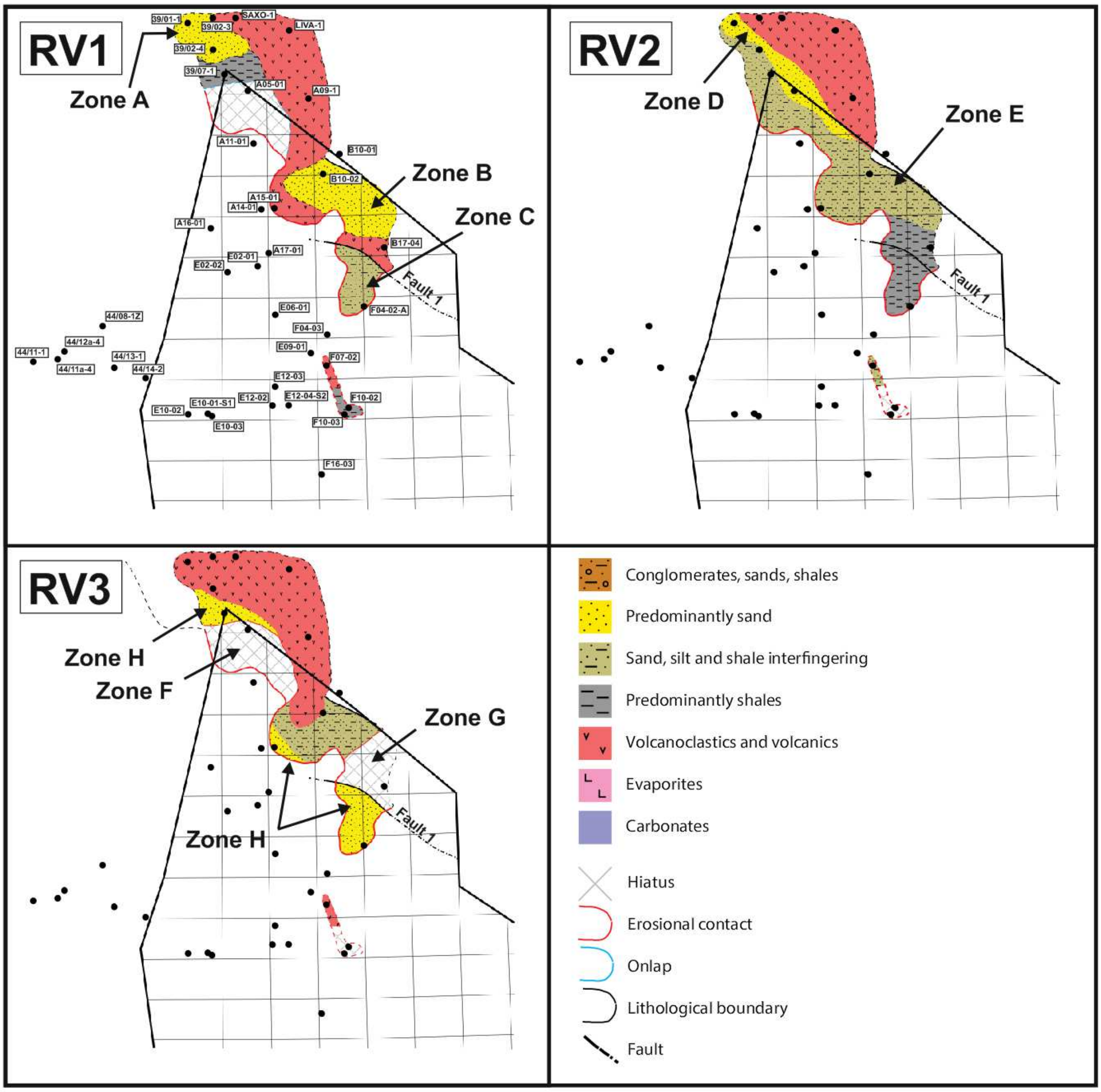


Figure 4.24: Depositional maps of the preserved three units of the Lower Rotliegend. Seven lithofacies associations have been identified at well locations and extrapolated across the wells. Seismic data was used to map the aerial extent of each sub-division and to characterise the boundaries of each lithofacies (i.e. eroded, onlapping or laterally transitioning to other lithofacies associations).

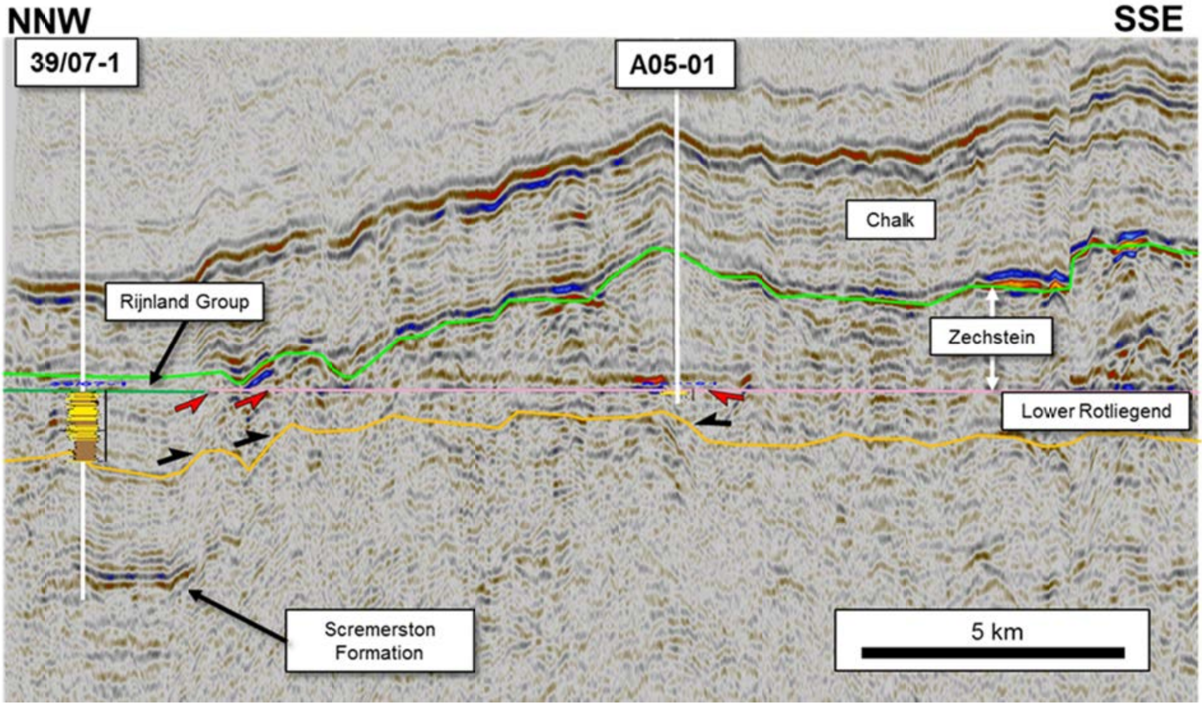


Figure 4.25: Seismic line between wells 39/07-1 and A05-01. The line is flattened on base Zechstein (ZE). In absence of the Zechstein, the base of the Rijnland Group (KN) was used. Note the onlap configuration (black arrows) highlighting the presence of a topographic high during the lower part of the Lower Rotliegend at this location.

4.3.3.2 Upper Rotliegend

The stratigraphical correlations carried out in this project for the Upper Rotliegend are more robust than the ones for the Lower Rotliegend. This is principally due to 1) its larger geographical extent, compared with the more restricted Lower Rotliegend and 2) the complex and heterogeneous nature of the Lower Rotliegend, compared to the lateral homogeneous lithofacies encountered in the Upper Rotliegend (e.g. the ‘Evaporites’ lithofacies). This greatly contributed to a more robust detailed correlation within the southern part of the study area and a better constrained seismic interpretation for this stratigraphic interval. Figure 4.22 and Figure 4.23 illustrate the stratigraphical correlation of the Upper Rotliegend, which has been subdivided into five individual stratigraphical units (RO1 to RO5) for this study. Figure 4.26 shows the map-view distribution of the successive Upper Rotliegend depositional units. Note that the Upper Rotliegend distribution is confined to the southern half of the study area for the three oldest units (i.e. RO1-RO3). The two youngest units (i.e. RO4-RO5) extend farther north, almost covering the entire study area.

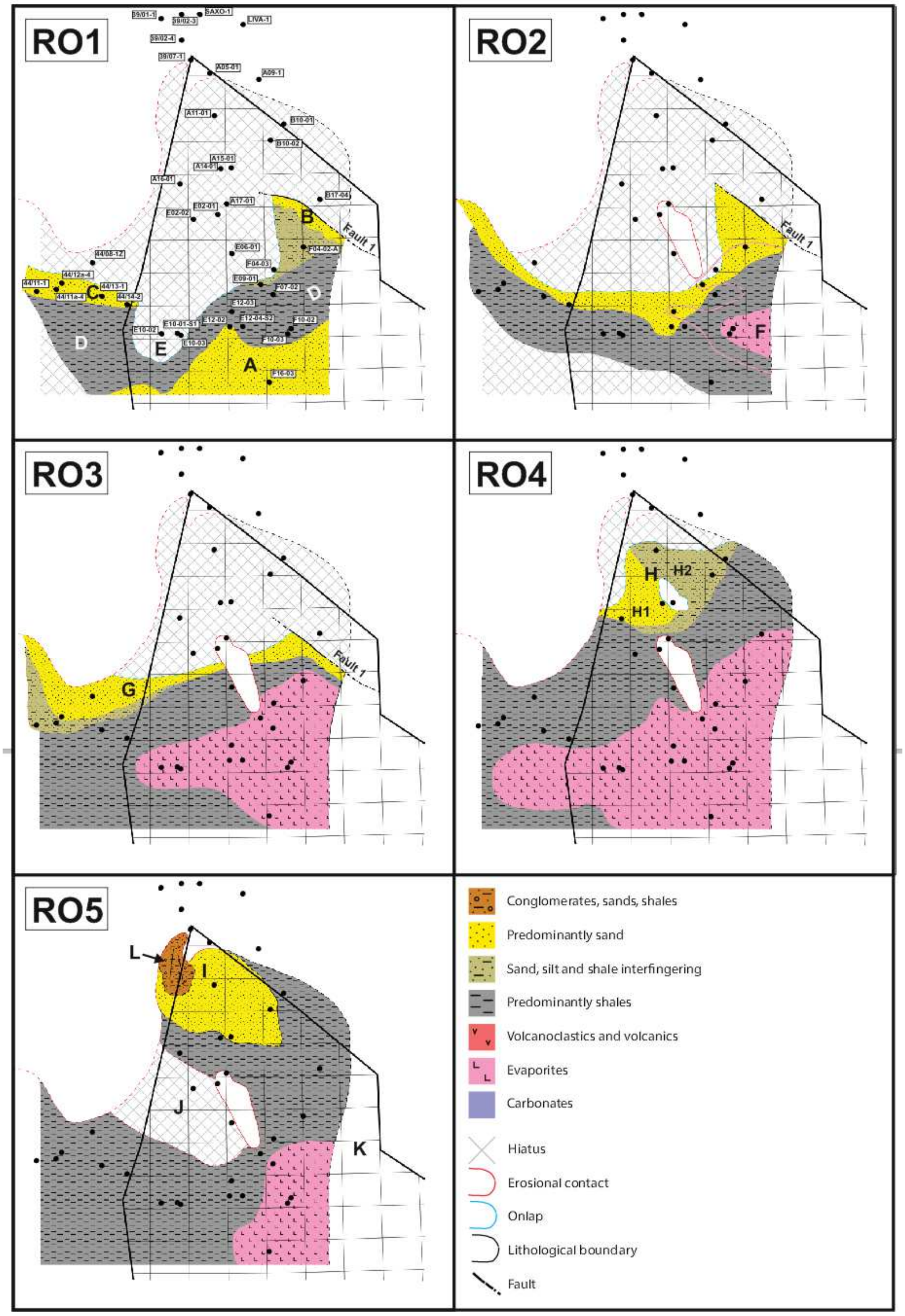


Figure 4.26: Depositional maps of the preserved five units of the Upper Rotliegend. Seven lithofacies associations have been identified at well locations and have been extrapolated across wells. Seismic data was used to map the aerial extent of each unit and to characterise the boundaries of each lithofacies (i.e. eroded, onlapping or laterally transitioning to other lithofacies associations).

Each of the five successive Upper Rotliegend units will be described below (from old to young):

- RO1, first Upper Rotliegend Unit (see Figure 4.26 to Figure 4.30). The oldest stratigraphic unit is, overall, relatively thin (i.e. up to a max. of 28m in well F16-03). The unit is composed of three main lithofacies: i.e. Predominantly sand', 'Sand, silt and shale interfingering' and 'Predominantly shale'. The 'Predominantly sand' lithofacies is situated to the south (i.e. Zone A) and is observed at well F16-03. It is also found in the central and western parts of the study area, i.e. respectively Zones B and C. They are separated by an E-W oriented low net-to-growth zone (i.e. 'Predominantly shale' facies, Zone D). No halite is observed in this unit.
  Locally RO1 pinches out onto older strata in northerly direction, in the western part of the study area (Zone C). At those locations RO1 is mainly composed of sandstones intercalated with thin low net-to-gross strata. RO1 is not present around the E10 block (Zone E), which contrasts with the younger Upper Rotliegend strata (see following maps). No Upper Rotliegend strata of that age are present in the entire northern half of the study area. To the northeast, the depositional limit of RO1 is controlled by the same fault (i.e. Fault 1), as previously observed.
  It is important to note that the southern 'predominantly sandy' facies (i.e. Zone A) is only observed in RO1 and correspond to the Lower Slochteren Mb that extends outside of the study area toward the south (Figure 2.6 and Figure 4.15). The younger units (i.e. RO2-5) only contain low net-to-gross strata in this part of the study area, which are more axial basinal setting within the Silver Pit Paleo-Lake.

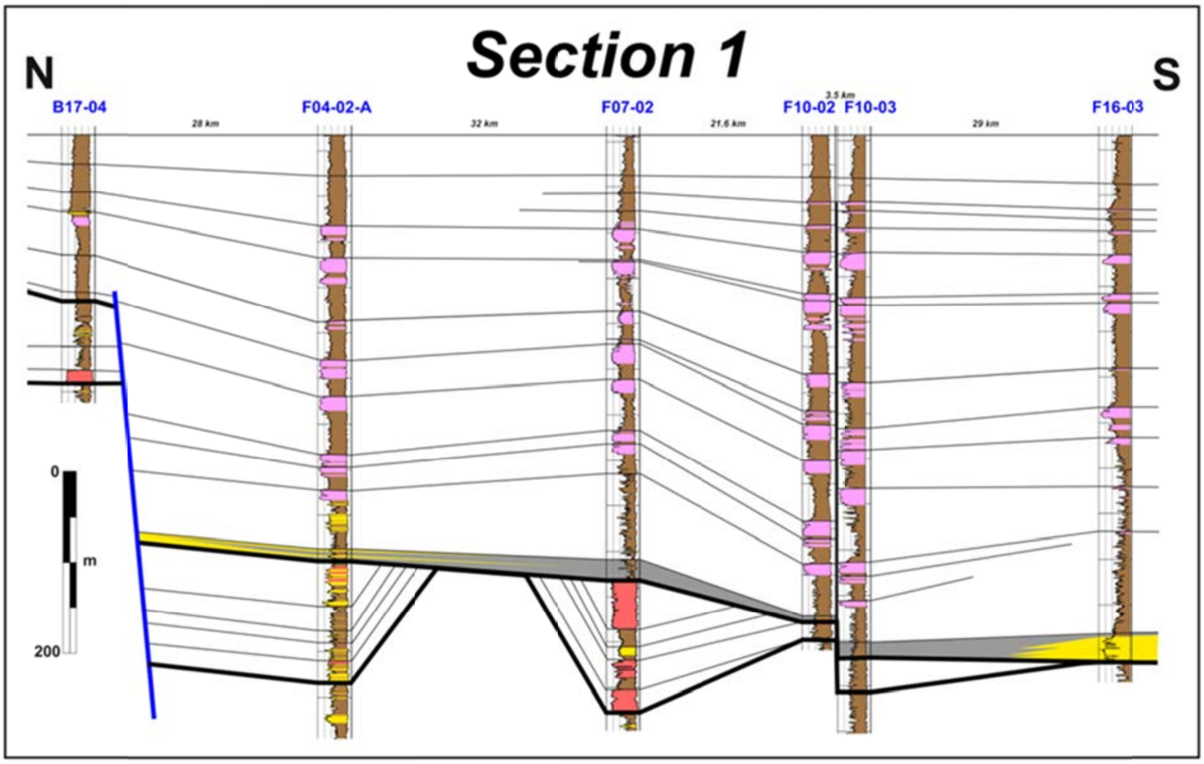


Figure 4.27: Internal stratigraphy of the oldest unit of the Upper Rotliegend (RO1). Southern part Section 1, a N/S oriented well correlation panel. The RO1 interval is represented by the coloured interval. Figure 4.20 for location.

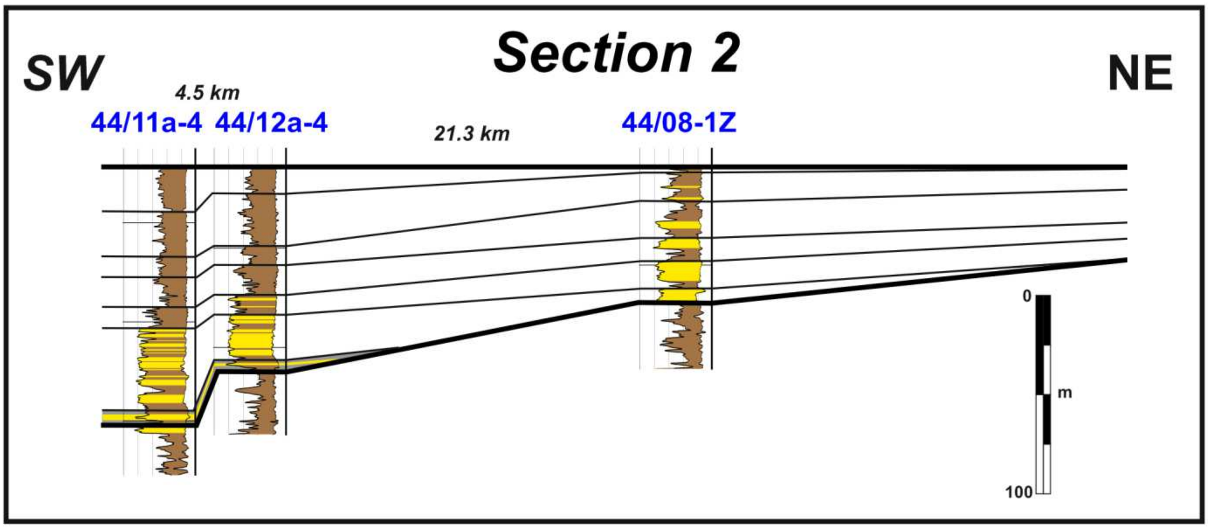


Figure 4.28: Internal stratigraphy of the oldest unit of the Upper Rotliegend (RO1). South western part of Section 2, a NE/SW oriented well correlation panel. The RO1 interval is represented by the coloured interval. Figure 4.20 for location.

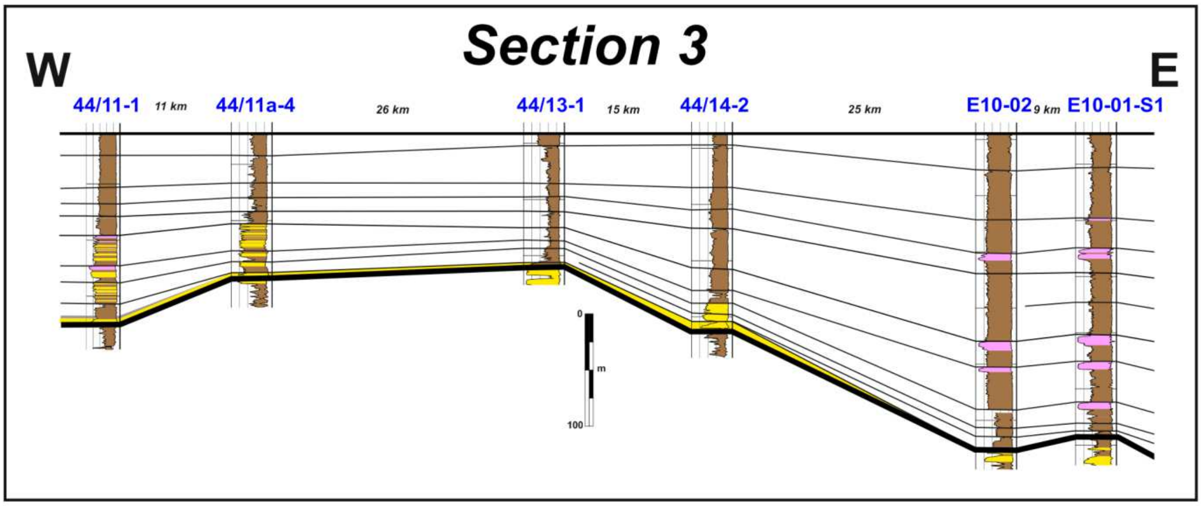


Figure 4.29:Internal stratigraphy of the oldest unit of the Upper Rotliegend (RO1). Western part of Section 3, an E/W oriented well correlation panel. The RO1 interval is represented by the coloured interval. Figure 4.20 for location.

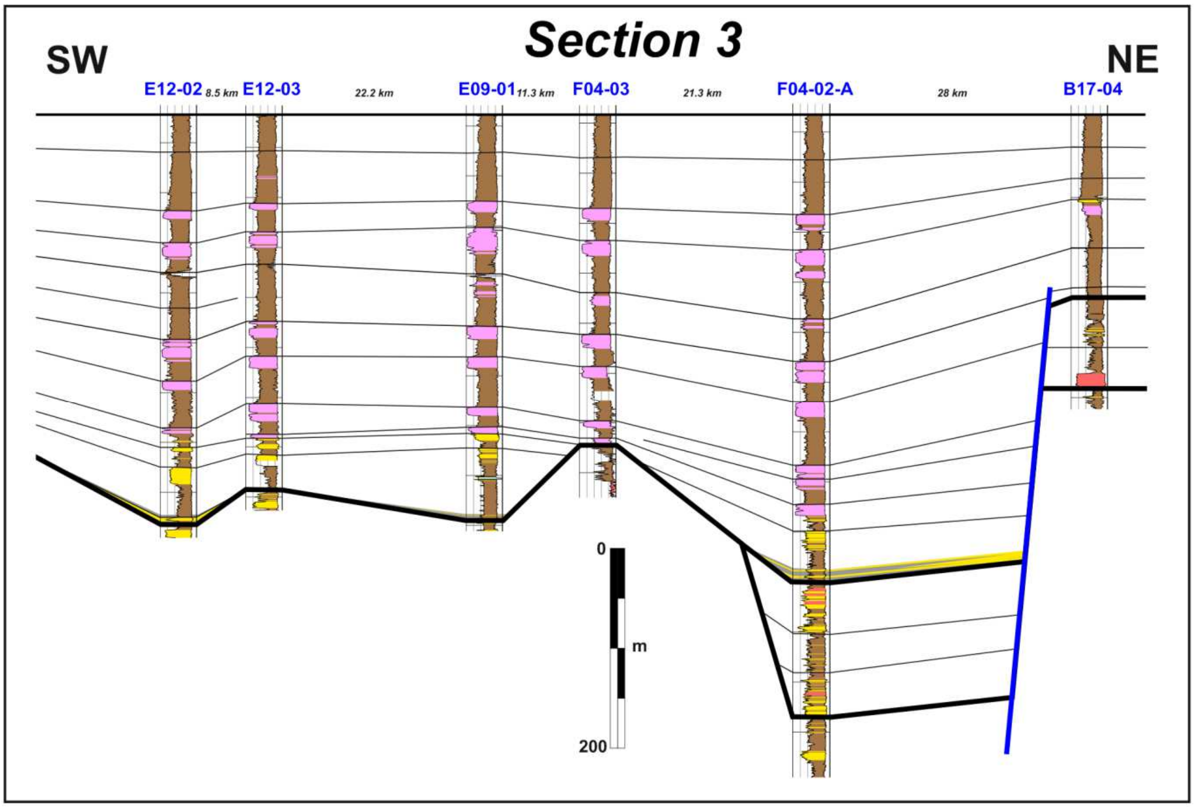


Figure 4.30:Internal stratigraphy of the oldest unit of the Upper Rotliegend (RO1). Eastern part of Section 3, an E/W oriented well correlation panel. The RO1 interval is represented by the coloured interval. Figure 4.20 for location.

- RO2, second Upper Rotliegend Unit (Figure 4.26 and Figure 4.31 to Figure 4.33). This stratigraphic unit shows some similarities with the previous unit (i.e. RO1) but also some major differences. Its similarities with RO1 are summarised as follows:
  1) Both distributions are restricted to the southern part of the study area,
  2) Both distributions are E-W oriented, arc-shaped and have a northern sandy edge.
  3) Both are fault bounded (i.e. by Fault 1) in the northeast, and
  4) Both pinch out to the north along a low angle palaeo-relief.

  The differences with RO1 are:
  1) RO2 unit is overall thicker (up to 94m),
  2) RO2 unit contains halite toward the top of the interval, and
  3) RO2 unit lacks the southern sandy facies (i.e. Zone A equivalent).

  Halite rich strata of the Silver Pit Formation are found toward the south east of the area (Zone F). The maximum extent of a single halite interval is shown as a pink line in Figure 4.26.

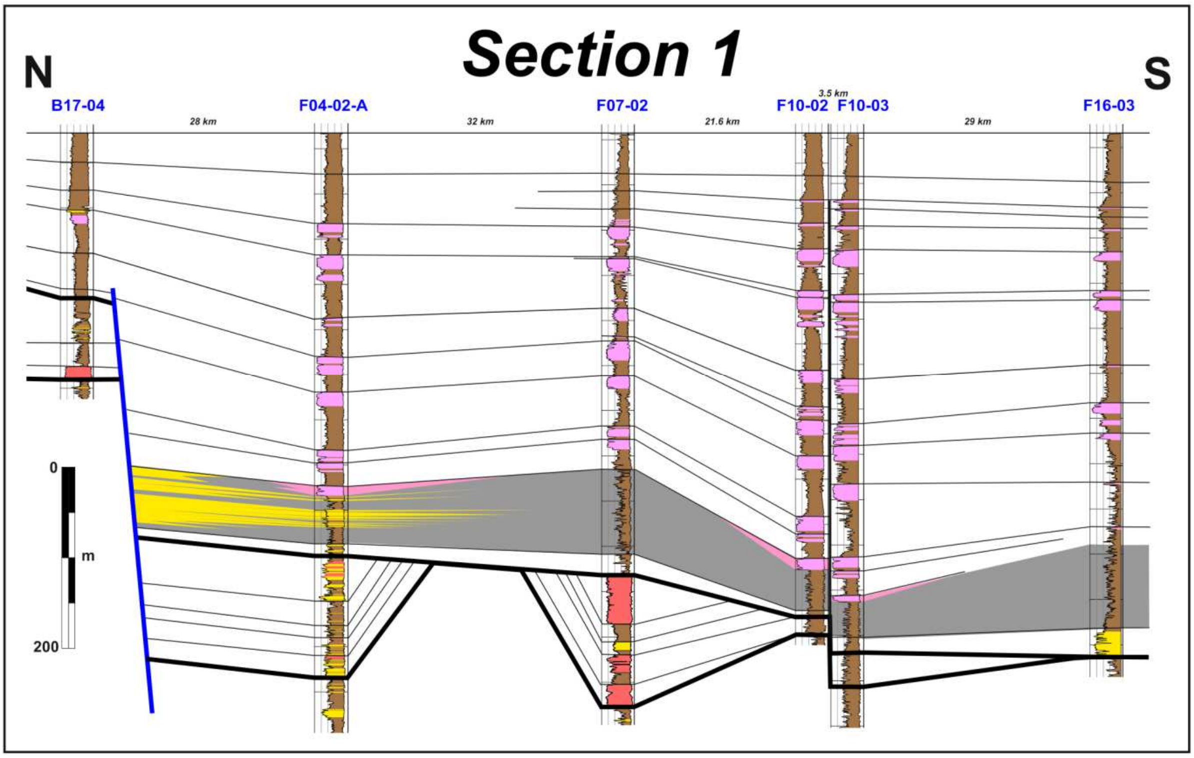


Figure 4.31:Internal stratigraphy of the second unit of the Upper Rotliegend (RO2). Southern part of the Section 1, a N/S oriented well correlation panel. The RO2 interval is represented by the coloured interval. Figure 4.20 for location.

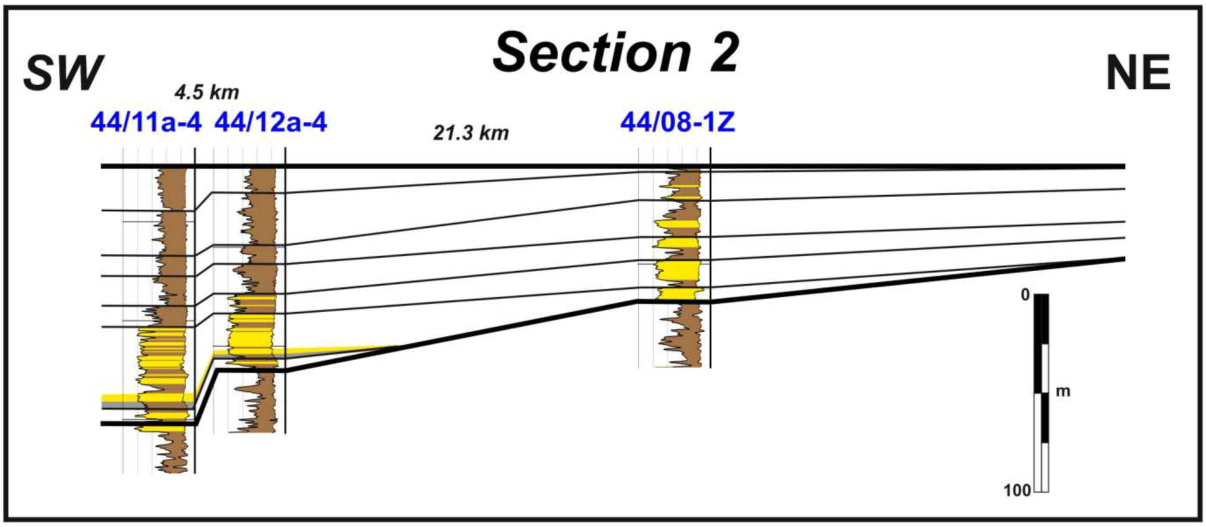


Figure 4.32:Internal stratigraphy of the second unit of the Upper Rotliegend (RO2). South western part of the Section 2, a NE/SW oriented well correlation panel. The RO2 interval is represented by the coloured interval. Figure 4.20 for location.

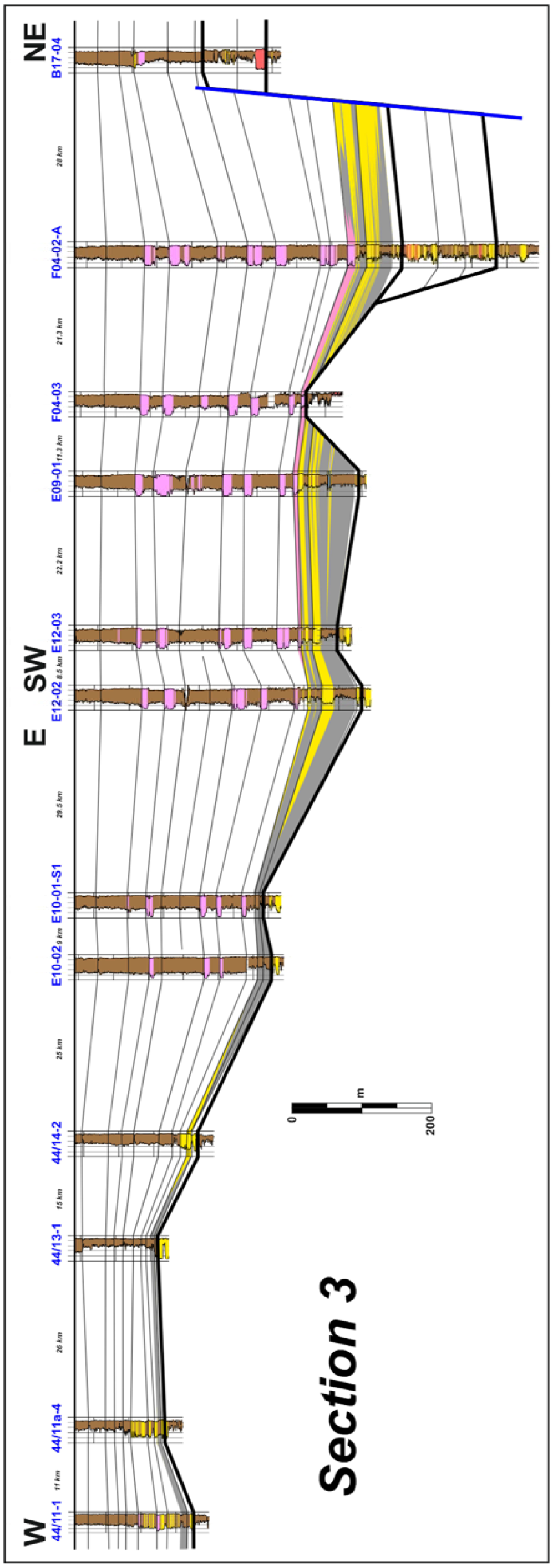


Figure 4.33:Internal stratigraphy of the second unit of the Upper Rotliegend (RO2). Section 3, a W/E and SW/NE oriented well correlation panel. The RO2 interval is represented by the coloured interval. Figure 4.20 for location.

- RO3, third Upper Rotliegend Unit (Figure 4.26 and Figure 4.34 to Figure 4.36). RO3 is thicker than the previous units, with the thickest area around wells F10-02 and F10-03 (190m). Lithofacies and overall distribution of this interval is similar to RO2. However, its overall areal extent is larger. The shape of the high net-to gross 'Predominantly sand' facies (i.e. Zone G) is also different from RO2, with an inferred bend to the northwest in the UK sector as a result of the seismically interpreted basin margin edge during this period. The halite rich zone extent in the basin axis is wider compared with RO2. The north-eastern edge is again fault-bounded (i.e. by Fault 1), but the topmost part of RO3 strata oversteps the fault and is deposited on the footwall side of the fault (Figure 4.34). The cross section (Figure 4.35) shows the overall E-W thickness trend and illustrates the thinning above the pre-existing topographic high corresponding to the south-western edge of the Elbow Spit High.

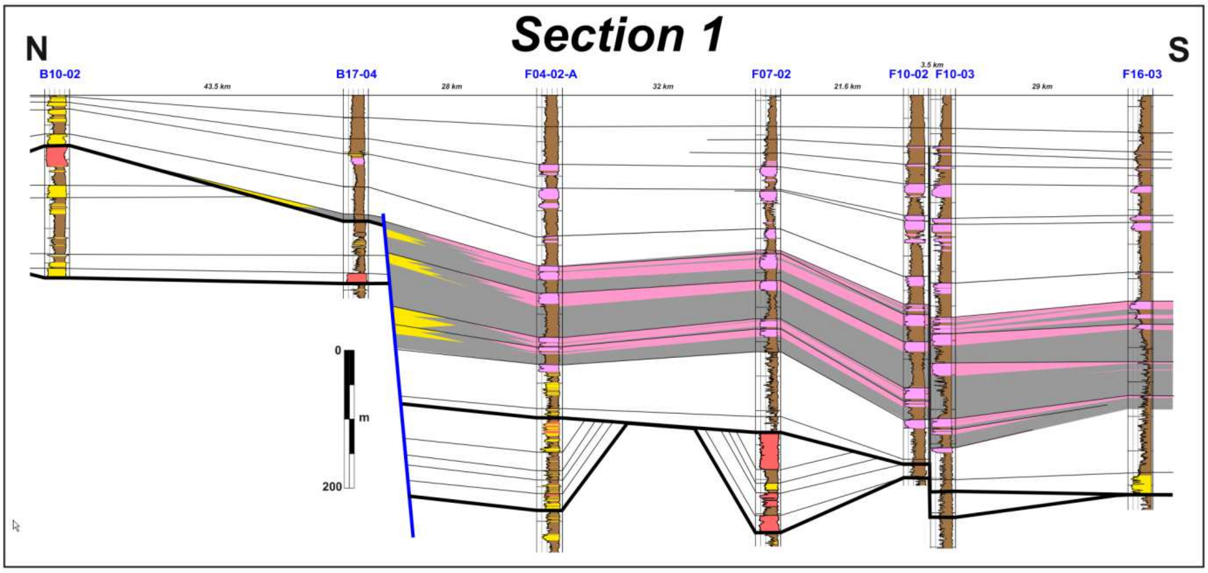


Figure 4.34:Internal stratigraphy of the third unit of the Upper Rotliegend (RO3). Southern part of Section 1, a N/S oriented well correlation panel. The RO3 interval is represented by the coloured interval. Figure 4.20 for location.

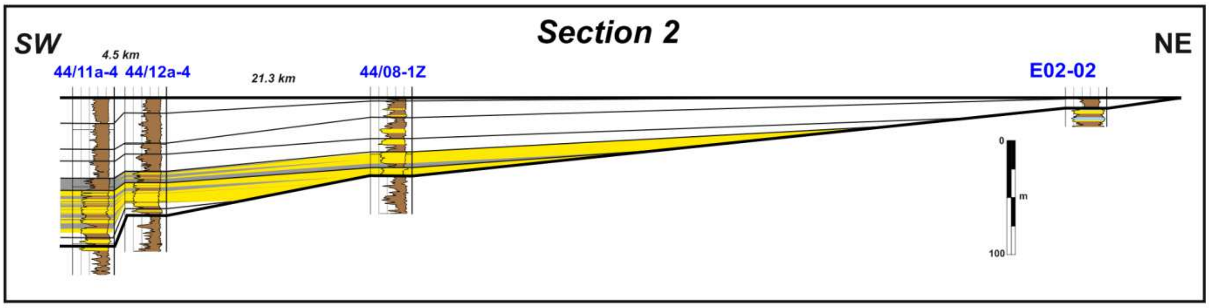


Figure 4.35:Internal stratigraphy of the third unit of the Upper Rotliegend (RO3). South western part of Section 2, a SW/NE oriented well correlation panel. The RO3 interval is represented by the coloured interval. Figure 4.20 for location.

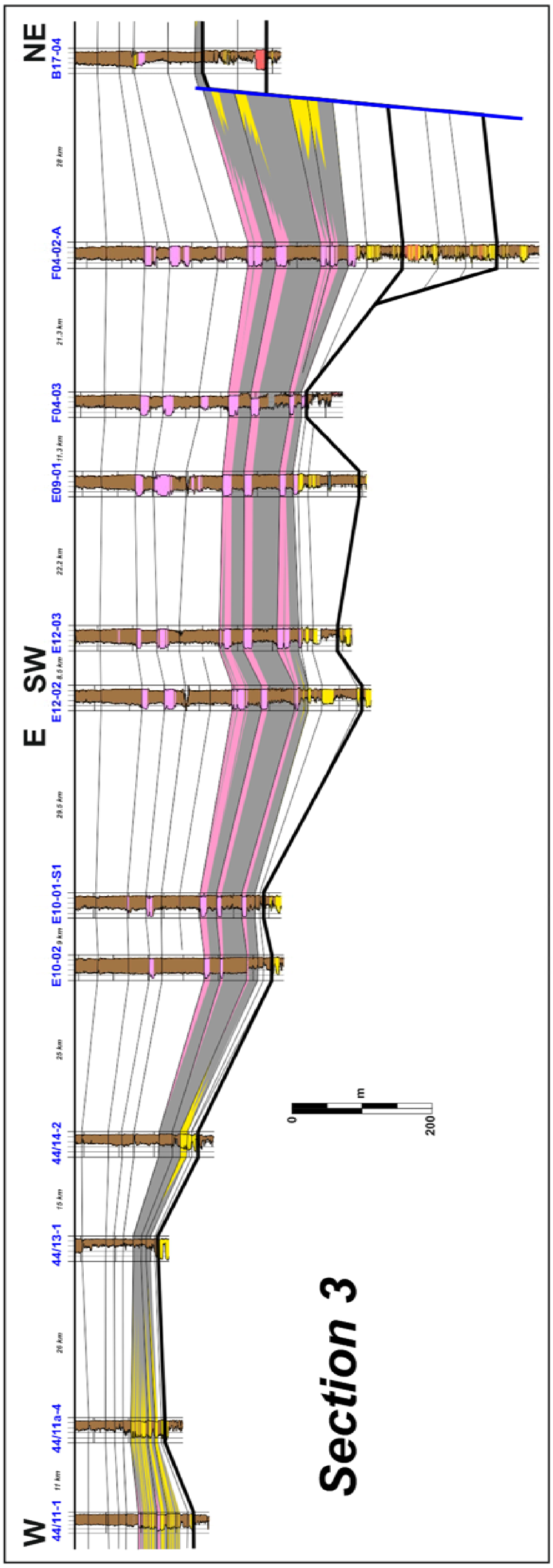


Figure 4.36:Internal stratigraphy of the third unit of the Upper Rotliegend (RO3). Section 3, a W/E oriented well correlation panel. The RO3 interval is represented by the coloured interval. Figure 4.20 for location.

- RO4, fourth Upper Rotliegend Unit (Figure 4.26 and Figure 4.37 to Figure 4.41). The Upper Rotliegend Unit RO4 shows two main depo-centres. One to the south around wells F10-02 and F10-03 (maximum measured thickness is 192m at well F10-03) and one to the north, around well A11-01 (185 m thick) (see Figure 4.37), with the latter is much sandier. In map view the northern margin of the Silver Pit paleo-lake moved northward compared with RO3 (i.e. Zone H). This can also be observed in Figure 4.38, with the Lower Rotliegend strata reaching well E02-02. The extent of the 'Predominantly sand' facies (Zone H) is smaller than in RO3 and is located north of the Elbow Spit High, within a confined topographic low. This sand-rich zone is divided into a high net-to gross western area (Zone H1) and a slightly lower net-to gross zone to the east (Zone H2).
  The areal extent of the halite units is larger than for previous intervals with an inferred western extent into the UK sector. Fault 1 does not appear to be any more active during this period. RO3 and RO4 display similar E-W thickness trends in the southern part of the study area, with a thinning over the south-western edge of the Elbow Spit High (i.e. wells 44/13-1 and 44/11a-4). It is important to note that RO4 is not present in well A15-01.

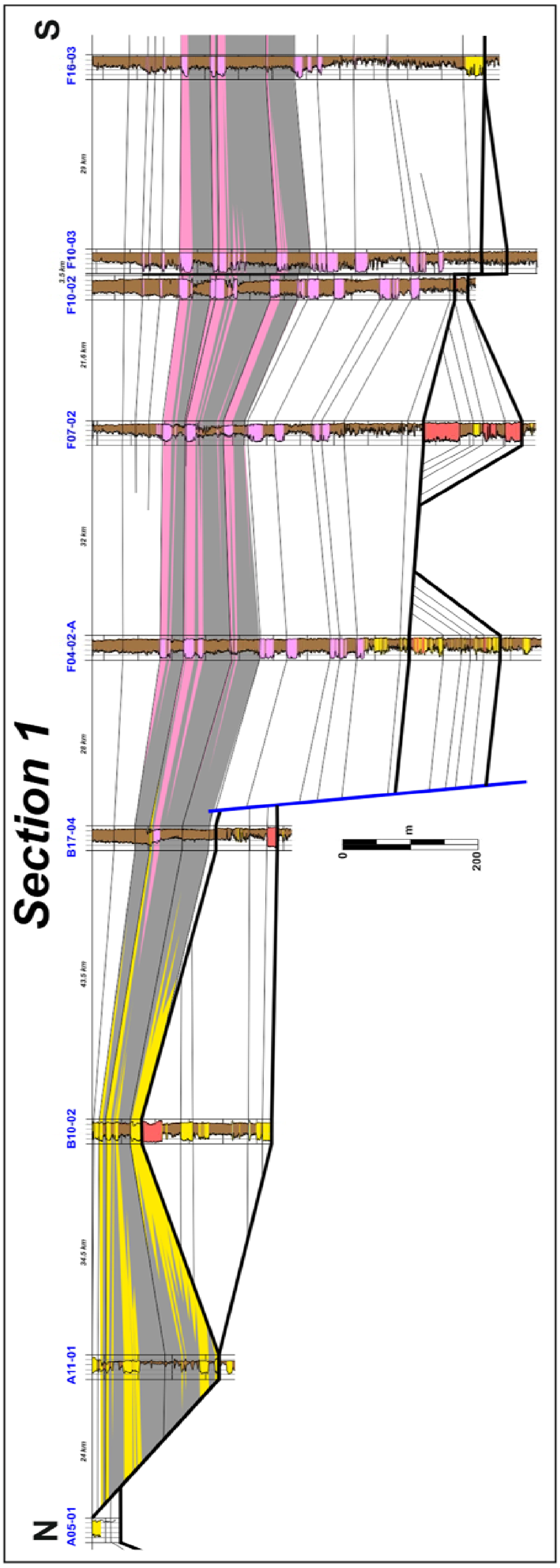


Figure 4.37:Internal stratigraphy of the fourth unit of the Upper Rotliegend (RO4). Section 1, a N/S oriented well correlation panel. The RO4 interval is represented by the coloured interval. Figure 4.20 for location.

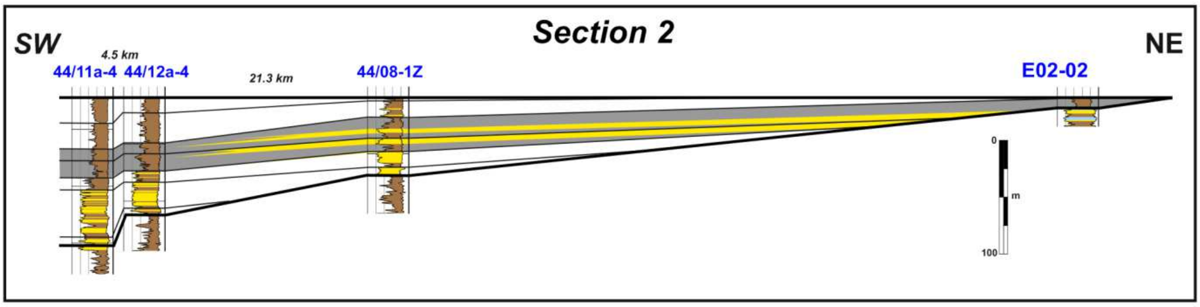


Figure 4.38:Internal stratigraphy of the fourth unit of the Upper Rotliegend (RO4). South western part of Section 2, a SW/NE oriented well correlation panel. The RO4 interval is represented by the coloured interval. Figure 4.20 for location.

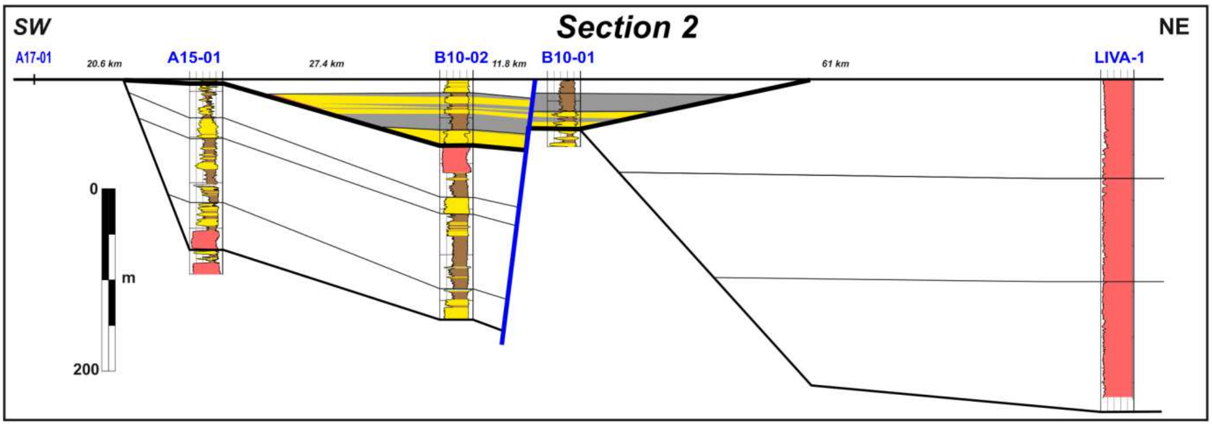


Figure 4.39:Internal stratigraphy of the fourth unit of the Upper Rotliegend (RO4). North Eastern part of Section 2, a SW/NE oriented well correlation panel. The RO4 interval is represented by the coloured interval. Figure 4.20 for location.

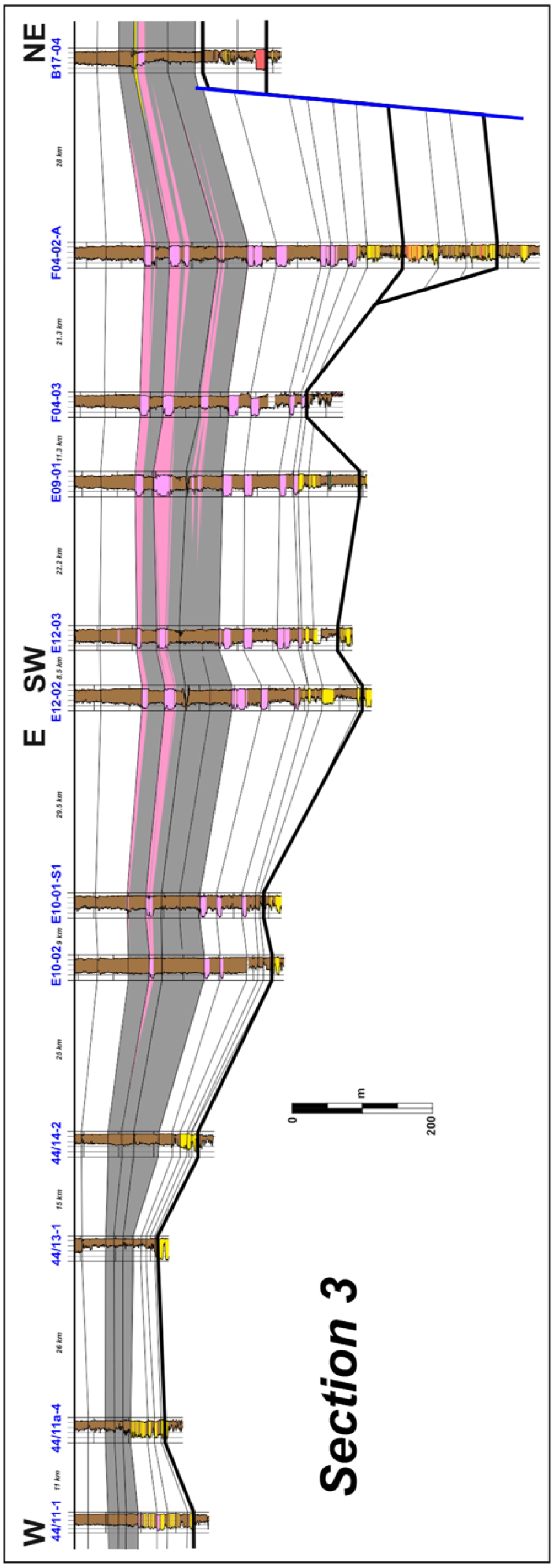


Figure 4.40:Internal stratigraphy of the fourth unit of the Upper Rotliegend (RO4). Section 3, an E/W oriented well correlation panel. The RO4 interval is represented by the coloured interval. Figure 4.20 for location.

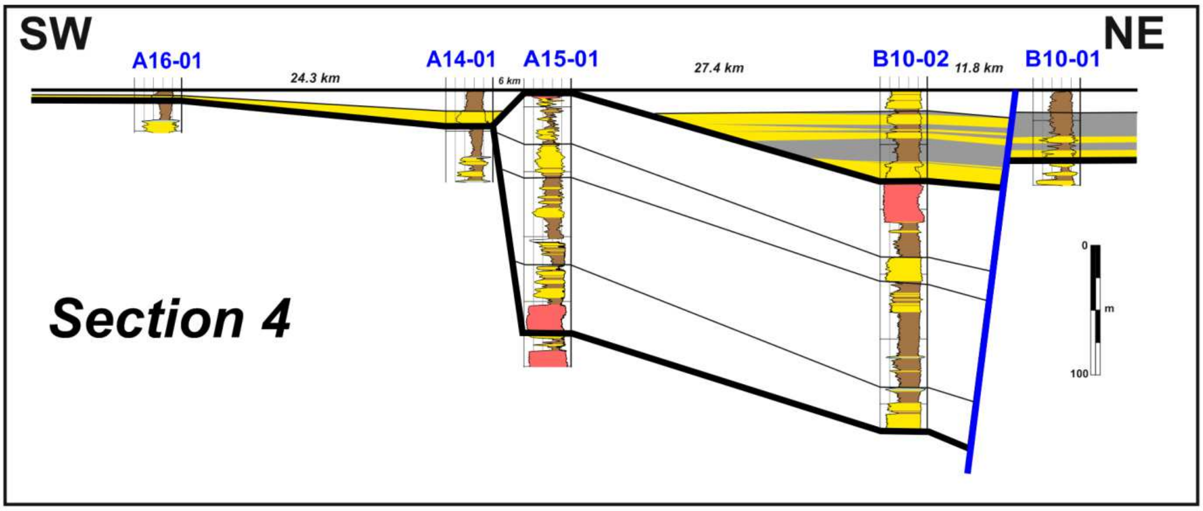


Figure 4.41:Internal stratigraphy of the fourth unit of the Upper Rotliegend (RO4). Section 4, a NE/SW oriented well correlation panel. The RO4 interval is represented by the coloured interval. Figure 4.20 for location.

- RO5, youngest Upper Rotliegend Unit (Figure 4.26 and Figure 4.42 to Figure 4.46). The youngest Upper Rotliegend unit covers most of the study area. However, in three zones no occurrence of RO5 sediments could be demonstrated.
  1) The first zone is located in the northernmost part of the Dutch offshore and in the UK sector. RO5 sediments are absent in this area because the northern depositional edge has not reached this far.
  2) The second zone is Zone J that is located to the west of the Elbow Spit High and is related to erosion of the shallowest part of the Upper Rotliegend.
  3) The last zone is Zone K, which is located within the Dutch Central Graben. Data available to us (i.e. well and seismic) could not unambiguously demonstrate the presence of Rotliegend in this zone.

  A zone of conglomerates, sands and shales (Zone L) is inferred to the northern edge of the study area based on well 39/11-1 where Upper Rotliegend conglomerates have been identified from cuttings information. It is worth noting that the amount and the aerial extent of the halite intervals within RO5 are more limited in comparison to the previous stratigraphic unit (i.e. RO4). RO5 shows an overall thinning to the north (i.e. leaving only 15-20m of sand rich strata). The stratal configuration of RO5 in the north is still confined within topographic lows with a sand-rich western zone around well B10-02 and two low net-to-gross areas around well B10-01 and around wells A14-01 and A16-01. These three different depositional areas are separated by a fault (blue fault, Figure 4.44) and a topographic high around well A15-01 (Figure 4.46).

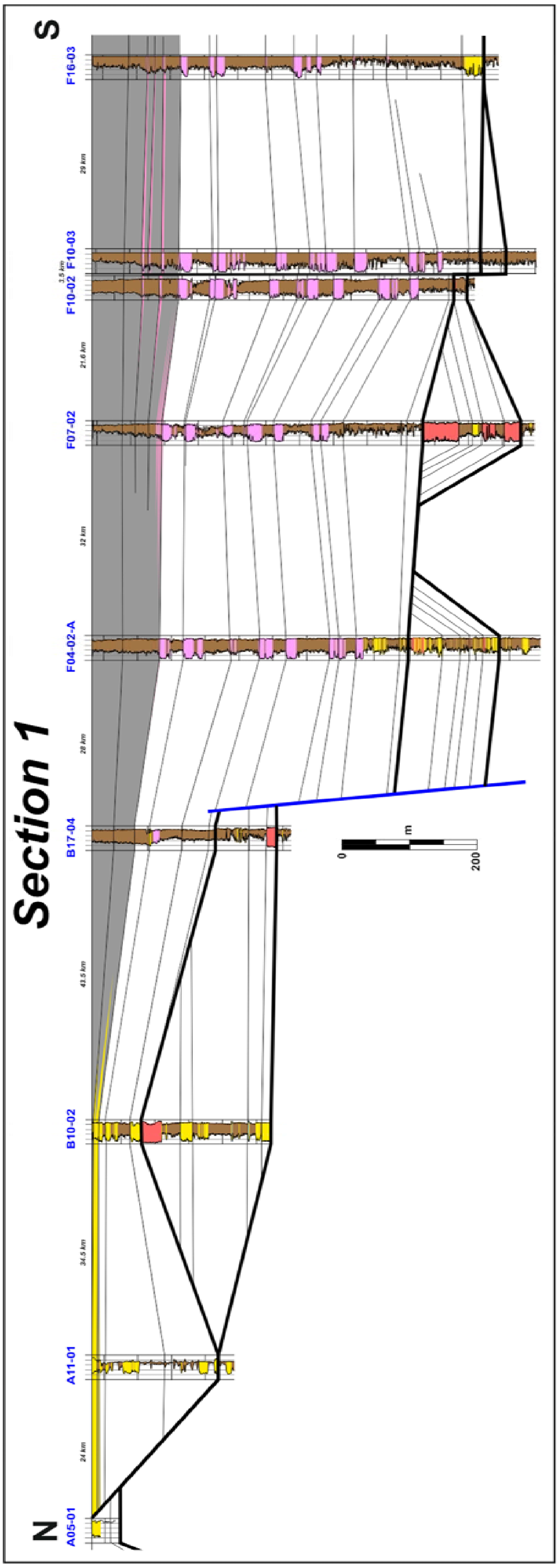


Figure 4.42:Internal stratigraphy of the youngest unit of the Upper Rotliegend (RO5). Section 1, a N/S oriented well correlation panel. The RO5 interval is represented by the coloured interval. Figure 4.20 for location.

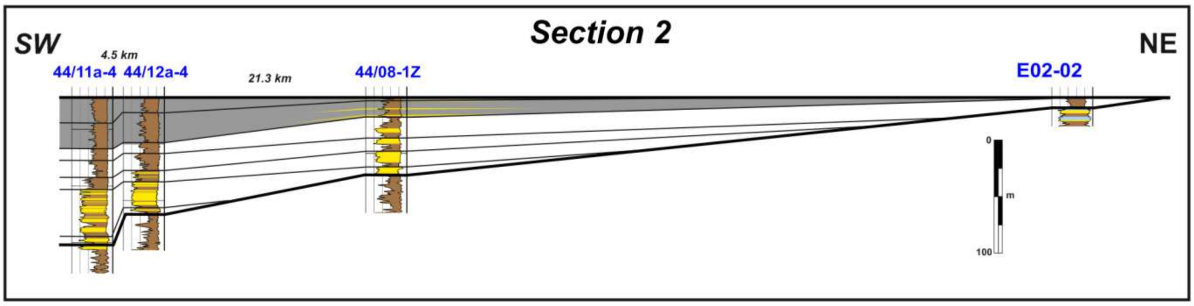


Figure 4.43: Internal stratigraphy of the youngest unit of the Upper Rotliegend (RO5). South western part of Section 2, a SW/NE oriented well correlation panel. The RO5 interval is represented by the coloured interval. Figure 4.20 for location.

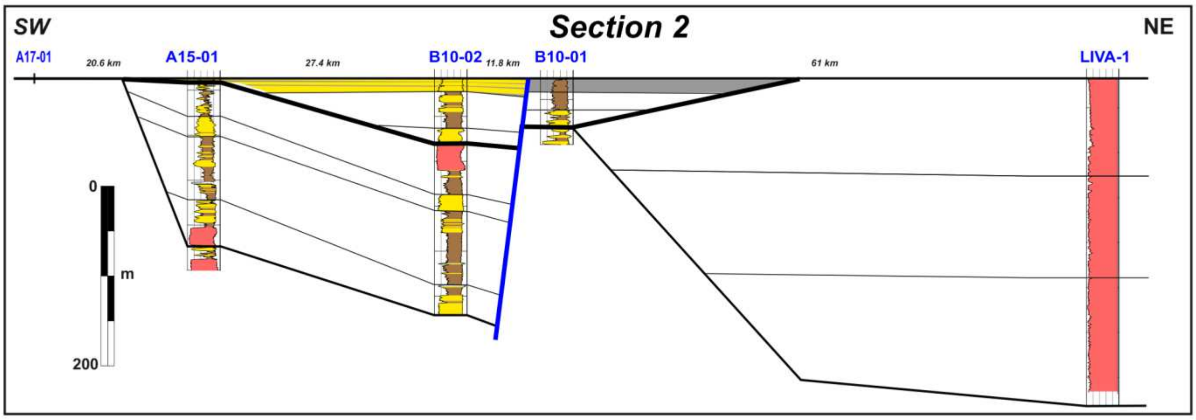


Figure 4.44: Internal stratigraphy of the youngest unit of the Upper Rotliegend (RO5 North Eastern part of Section 2, a SW/NE oriented well correlation panel. The RO5 interval is represented by the coloured interval. Figure 4.20 for location.

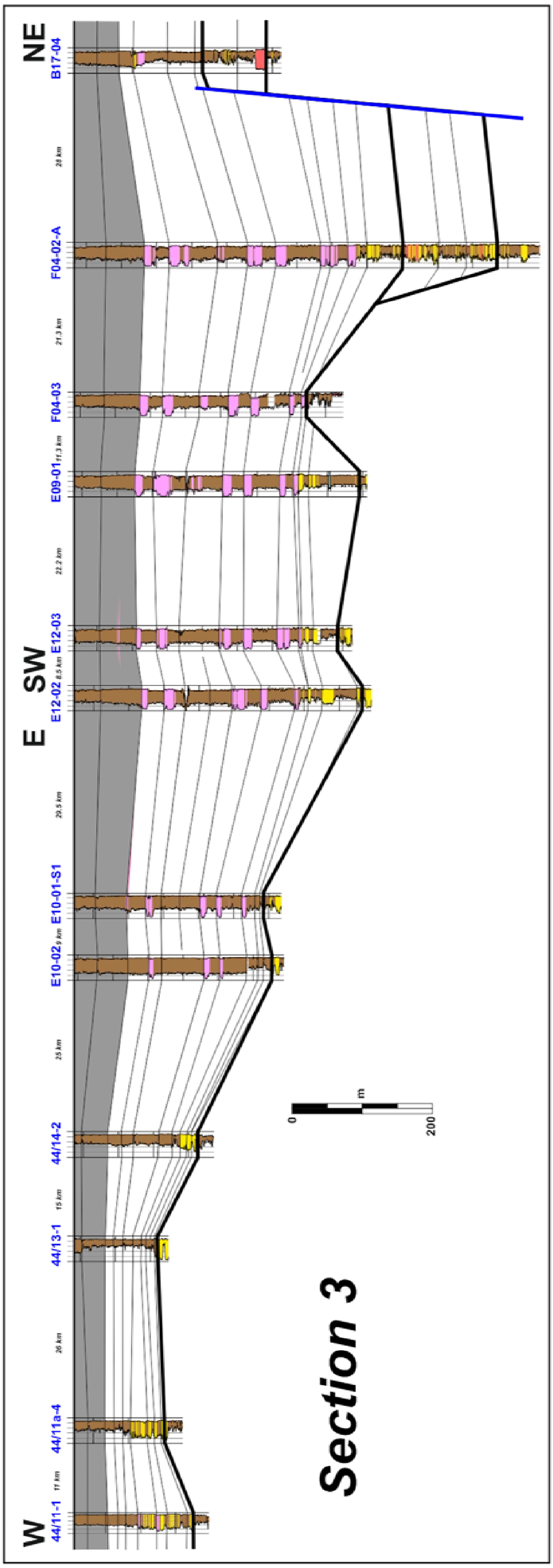


Figure 4.45:Internal stratigraphy of the youngest unit of the Upper Rotliegend (RO5). Section 3, a W/E and SW/NE oriented well correlation panel. The RO5 interval is represented by the coloured interval. Figure 4.20 for location.

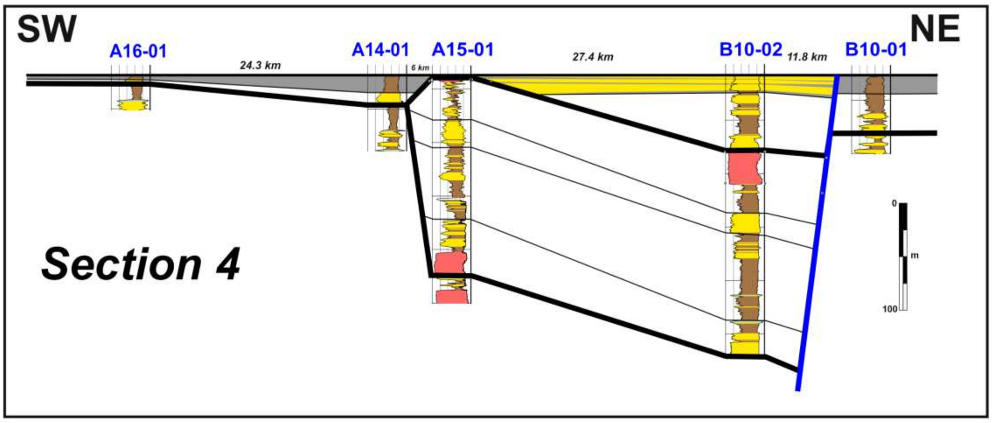


Figure 4.46:Internal stratigraphy of the youngest unit of the Upper Rotliegend (RO5). Section 4, a SW/NE oriented well correlation panel. The RO5 interval is represented by the coloured interval. Figure 4.20 for location.

The detailed stratigraphic analysis of the Rotliegend in the study area greatly decreased uncertainties in the reservoir potential of this part of the Dutch Offshore. The new paleogeographic results open new possible play concepts along the northern basin margin of the Southern Permian Basin in the Netherlands and beyond, to the east and west.

4.3.4 Reservoir quality of the Upper and Lower Rotliegend

A comprehensive petrophysical evaluation of the Upper and Lower Rotliegend Groups was beyond the scope of work of this study. However, a quick look at the well logs revealed some interesting facts.

- The wells from the Cygnus Field (44/11 and 44/12) have moderate to good reservoir properties in Upper Rotliegend zones RO1 to RO3. Porosities are reasonable (10-20%) and permeabilities are in the millidarcy range, occasionally reaching tens of millidarcies. Some intervals (notably those around the BPU) are heavily cemented and have permeabilities lower than 1mD.
- This reservoir trend can be partly traced eastward to the Dutch sector. Well A16-01(see Figure 4.46) for example, shows sonic values of 80 to 82 us/ft, corresponding to porosities of some 20% in a sandstone matrix. Core measurements confirm this and yield permeabilities of several hundred millidarcies. On the other hand, the Cygnus sands are interpreted as being in RO1-RO3 units and likely extend eastward into the Dutch E blocks. Wells E12-02 and E12-03 have tight sands with porosities estimated from the sonic log of 5-8%.
- As for the volcanic and volcaniclastic deposits of the Lower Rotliegend (RV1-RV3), a petrophysical interpretation is highly speculative and should be treated with care. However, if the volcaniclastics behave like normal sedimentary sandstone, the sonic log shows some interesting intervals with apparent porosities of around 25% (e.g. in well B10-02 at a depth of 3767md). These high porosity zones are usually found overlying basaltic layers, and might represent weathered zones.

4.4 Biostratigraphy

The biostratigraphic results obtained in this study contributed to the new stratigraphic framework and locally help validating some of the detailed stratigraphic correlations.

4.4.1 Legacy data

Results of the literature survey for biostratigraphical legacy data are depicted in Appendix 3.3

4.4.2 New analyses

Analyses from the selected intervals from wells A14-01 and A15-01 confirmed a Westphalian age for both intervals in line with other findings in this study. The legacy data revealed that palynological data is present in the Lower Rotliegend interval of B10-02, but this is most likely due to Zechstein caving.

4.4.3 Stephanian or Westphalian?

The initial hypothesis that was formulated at the beginning of this project proposed that Stephanian deposits could be preserved in the study area, and could be a possible source rocks in the deeper parts of the Step Graben (F10-02) and a reservoir in the shallowest part (well K02-02). Based on the seismic interpretation, new biostratigraphical insights and the literature review it was concluded that it is highly unlikely that there are any Stephanian deposits deposited or at least preserved in this part of the basin. The sand and conglomerates found in K02-02 have never been dated but assumed to be Stephanian in age because they are located stratigraphically below the (upper) Rotliegend and above the Westphalian. A more logical explanation for these coarse deposits at well K02-02 would be to attribute them to the Lower Rotliegend Clastic (Grensen Formation). No evidence has been found to support the hypothesis of a preserved Stephanian in the study area and therefore it is discarded. Regarding the age of the high TOC sediments found in well F10-02, this study concludes that they are not of Stephanian age (as originally postulated) but of likely Westphalian-age.

The biostratigraphical evidence of the presence of Stephanian in F10-02 was originally based on the presence of *Vittatina costabilis*. In numerous zonations this taxon is given a Permian to latest Carboniferous (i.e. Stephanian) affinity. In F10-02, the co-occurrence of this taxon with clear Westphalian taxa was postulated to resemble a wetland refugia where coal-forest species survived in a more xerophytic Stephanian plant community. However, this interpretation depended on a strict first occurrence date of *Vittatina costabilis* in the Stephanian.

In recent years numerous publications have questioned the applicability of first occurrence dates of xerophytic elements like *Vittatina costabilis* as a biostratigraphical marker (e.g. Falcon-Langet al., 2009; van Hoof et al., 2013, Looy et al., 2014). This is due to the fact that a more palaeoecological approach in Carboniferous biostratigraphy led to the insight that upland elements (typical for Stephanian and early Permian biotas) already migrated into the basin during Westphalian lowstands. As biostratigraphical zonations for the Carboniferous are commonly based on coal deposits, there is an existing bias in the zonations that needs to be resolved.

In the current project we used the recently studied Dutch De-Lutte-06 (van Hoof al., 2013) and its neighbouring well Norddeutschland -8 in Germany. The correlation between both those wells indicates that *Vittatina costabilis* is found within the (palaeobotanically controlled) Westphalian D strata instead of the previously interpreted Stephanian age strata. Therefore the significance of *Vittatina costabilis* as a marker restricted to the Stephanian was discarded.

4.5 Isotope correlations

In order to test the correlation of barren sands just below the Zechstein in wells A15-01 and B10-02, a pilot study on stable isotope stratigraphy was performed on both wells. However, during the projects detailed seismic and lithostratigraphical analyses showed that these sands were found to belong to different stratigraphic units altogether (i.e. Upper Rotliegend in B10-02 and Lower Rotliegend in A15-01). Consequently they are non-correlatable. Conclusions based on average values of delta ^{13}C confirmed these results (Figure 4.47).
In order to further test the applicability of this technique for distinguishing intra-Rotliegend units, a third well (i.e. F04-02) was added to the pilot study. F04-02 was chosen since both the Upper and Lower Rotliegend were encountered in this well. The goal was to test if this well could be correlated to the A15-01 and B10-02 wells with stable isotope analysis, in order to test whether a higher resolution correlation could be reached within the Rotliegend.

Results from stable carbon isotope analyses are depicted in Figure 4.47. Trends are visible within each well, which indicates that it is possible to obtain enough organic matter from these barren red-beds to enable carbon isotope stratigraphy.

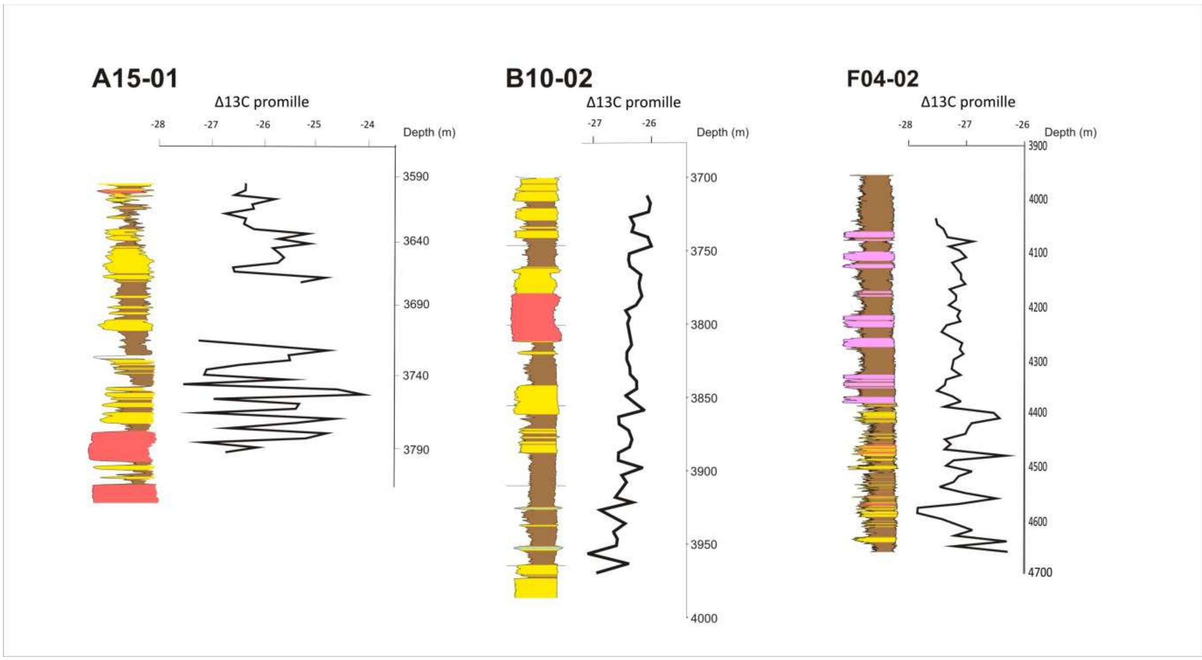


Figure 4.47:Carbon isotope results, shown per well

Based on average values and trends, the results of the carbon isotope study on wells A15-01 and B10-02 support the conclusions of the seismic study that the top ("fringe") sands in both wells actually belong to separate stratigraphic units (i.e. RO and RV) (see Figure 4.48). A sudden break in average values and the form of the isotope signal at 4400m in F04-02 coincides with the boundary between RV and RO and indicates that stable isotope stratigraphy can be used to distinguish these units. Furthermore the difference in trends between B10-02 and F04-02 suggests that younger section of RO is preserved in F04-02 which is supported by the results of the seismic and stratigraphic studies.

As the results of the present pilot study confirmed the concepts developed in the seismic stratigraphy study, this technique is believed to be a promising correlation tool even on a sub-unit level. Furthermore, when a better control on organic facies overprint (by using phytolith facies control and increasing the number of wells) and a regional standard curve are developed, this technique can lead to a solid chronostratigraphical backbone for future seismic stratigraphic models.

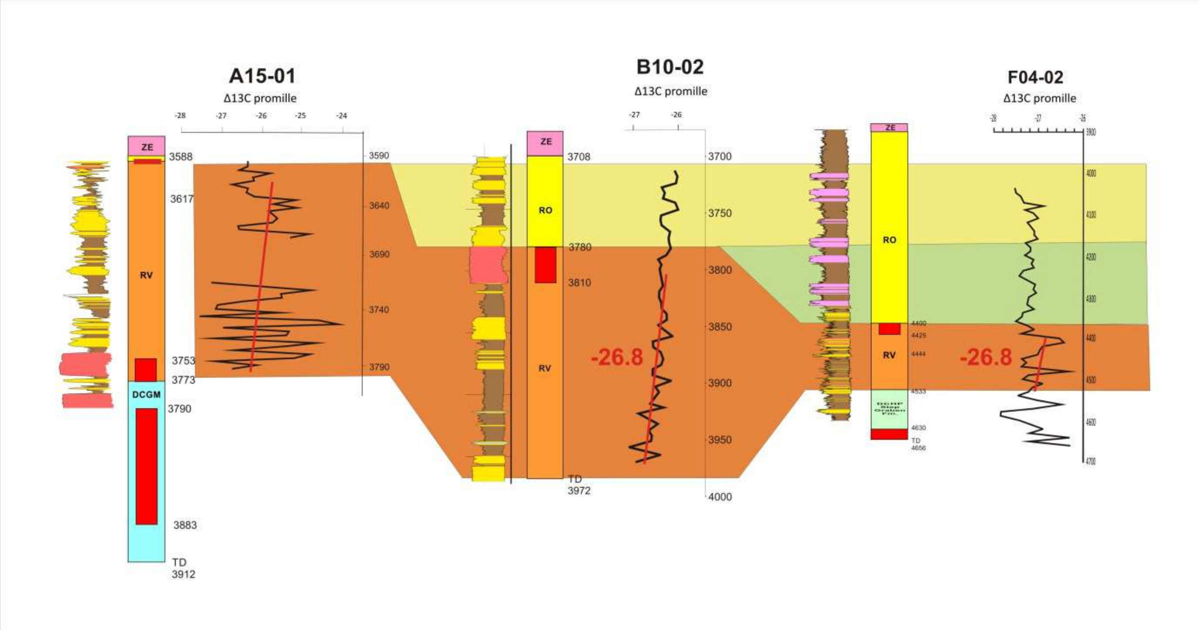


Figure 4.48:Carbon isotope trends depicted against the stratigraphic model developed during this study

4.6 Basin Modelling

The selected wells for modelling could be put into two categories

- Wells where Westphalian source rocks area present (including Maurits and Klaverbank Formations),
- Wells where the Dinantian Scremerston Formation has been identified or anticipated (Figure 4.49 and Table 4-1).

The results of the modelling are presented below for each modelled well separately. The main inputs and the assigned source rocks properties are explained in chapter 3.6.

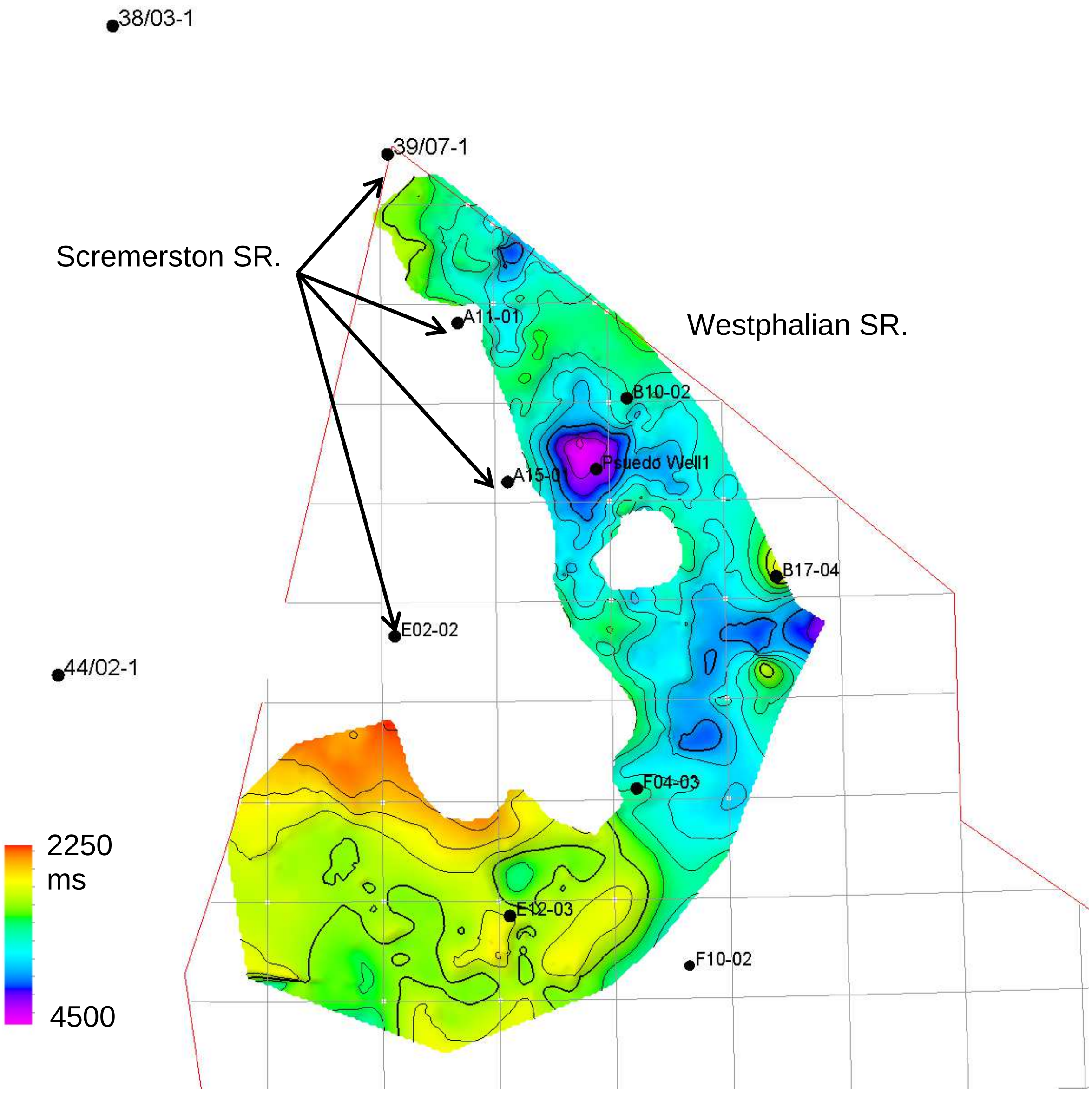


Figure 4.49:Location of modelled wells and the included source rock for maturity modelling. Westphalian time structure map is shown in rainbow colours.

4.6.1 Well B10-02

The well is located in the Step Graben and reached TD (Total Depth) in the Lower Rotliegend (RV). No source rocks were encountered by the well. Based on the results of the extensive seismic and well correlation exercise, described above, a Westphalian section is present below the well's TD. This section was included in the modelling exercise and was given a total thickness of 850m, the upper 200m of which were considered belonging to the Maurits Formation (DCCU). The latter is assumed to be a source rock of kerogen type III (Table 3-2 and Table 3-3). The modelled burial history in well B10-02 shows that the deepest burial is reached at present-day and the Maurits source rock is in the gas window (Figure 4.50). The modelled history indicates that hydrocarbon generation and expulsion (i.e. generation and expulsion rates) from the source rock took place since the Eocene and continues to present-day (Figure 4.51). Two peaks of generation and expulsion are also observed in the Early Triassic and Late Jurassic. Modelled transformation ratio reflects these generation phases and shows that only 40% of the organic matter in the source rock has been converted to hydrocarbons at the location of this well. Modelled present-day temperature shows a good fit with measured temperatures at the location of B10-02 well (Figure 4.51).

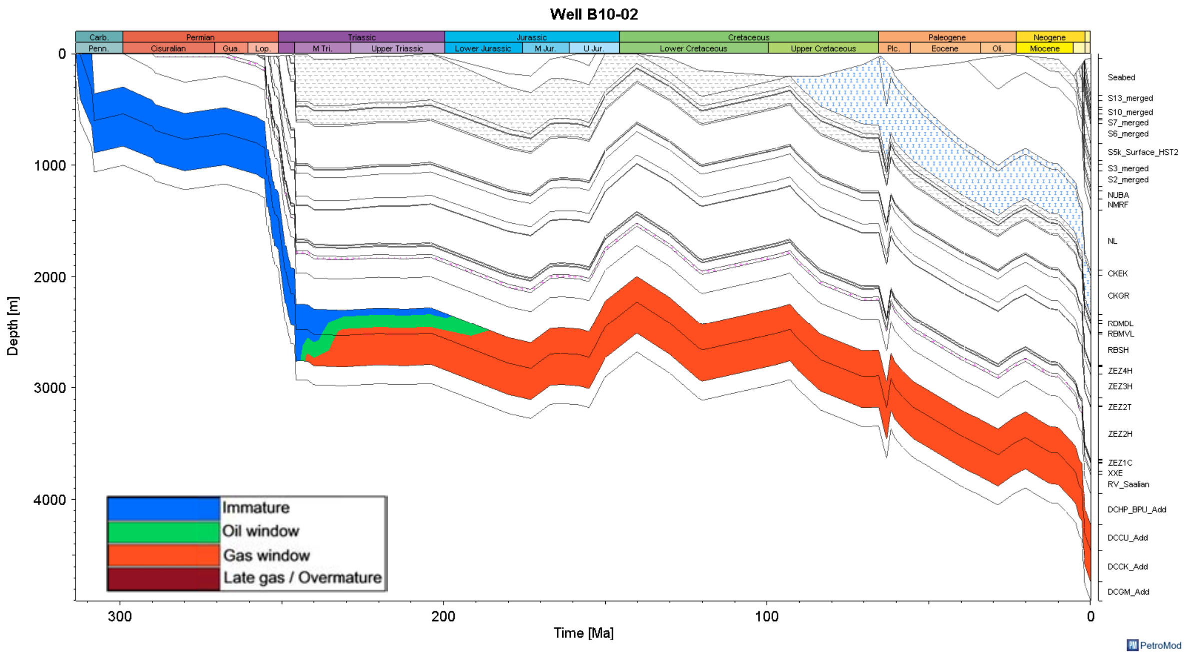
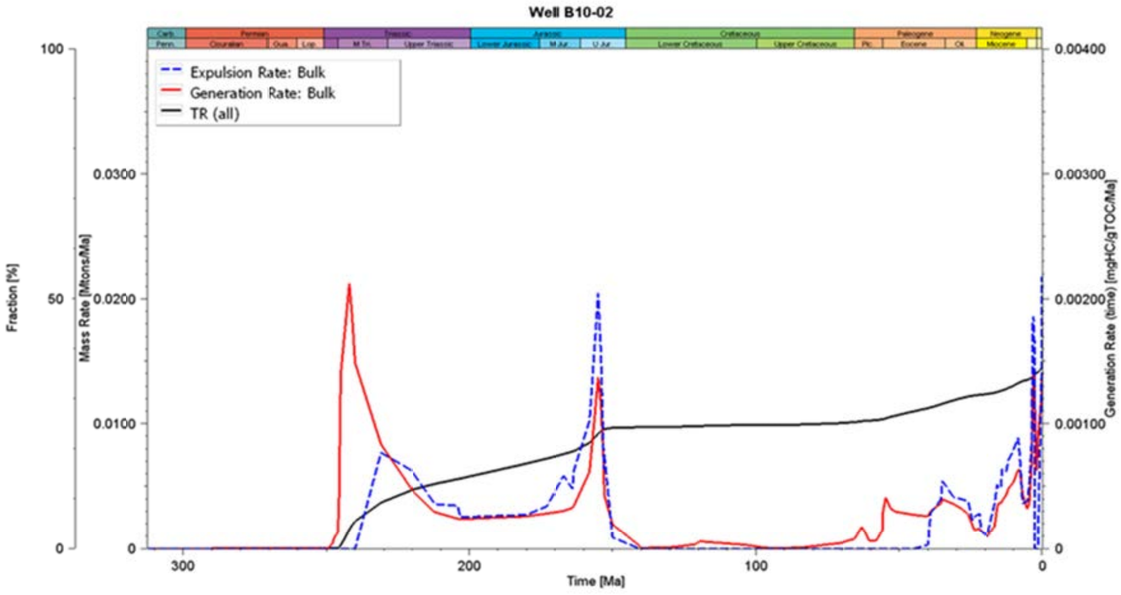
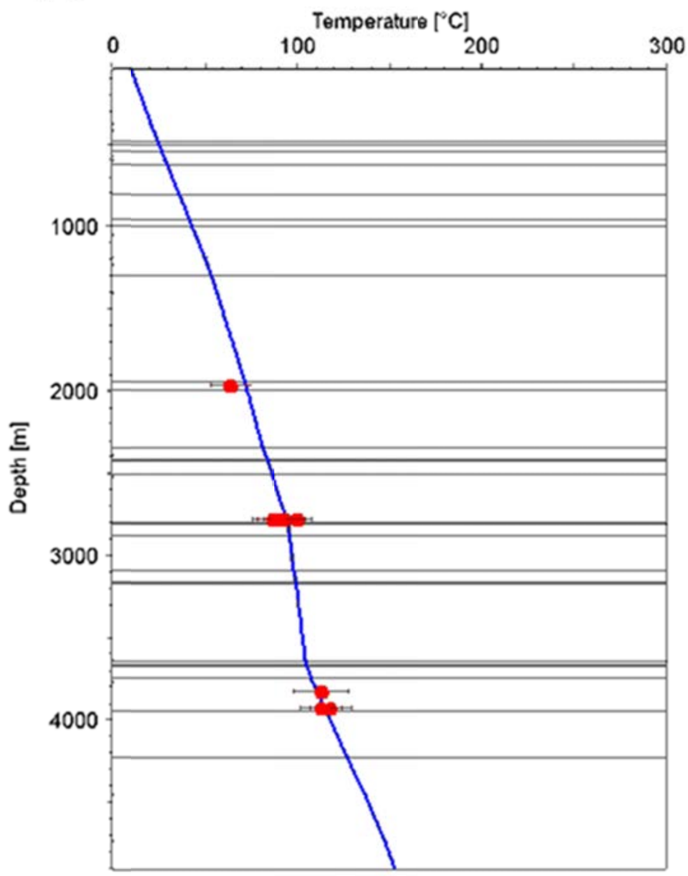


Figure 4.50:Modelled burial history and maturity of the Maurits Formation (DCCU) at well B10-02.



(A)



(B)

Figure 4.51:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the source rock (A). Results of model calibration to present-day temperature (B) in well B10-02.

4.6.2 Well B17-04

The well is located at the border between the Step Graben and the Central Graben. The well reaches TD in the Namurian Millstone Grit Formation (DCGM). The Westphalian Maurits Formation was defined as a source rock of kerogen type III (Table 3-2 and Table 3-3). The well is located on a salt structure and therefore we accounted for the salt movement during the geologic history.
The modelled deepest burial is reached at present-day and the Maurits source rock appears to be in the gas window (Figure 4.52).
The modelled rates of hydrocarbon generation and expulsion from the Maurits Formation indicate that the main phase of hydrocarbon generation and expulsion was in the Early Miocene (Figure 4.53). Generation declined from the Miocene onward but is still going on at present-day. Modelled transformation ratio shows that up to 60% of the transformable organic matter in the Maurits source rock has been converted to hydrocarbons at the location of this well. Modelled present-day temperatures and maturity could not directly match the measured values in this well (Figure 4.53).

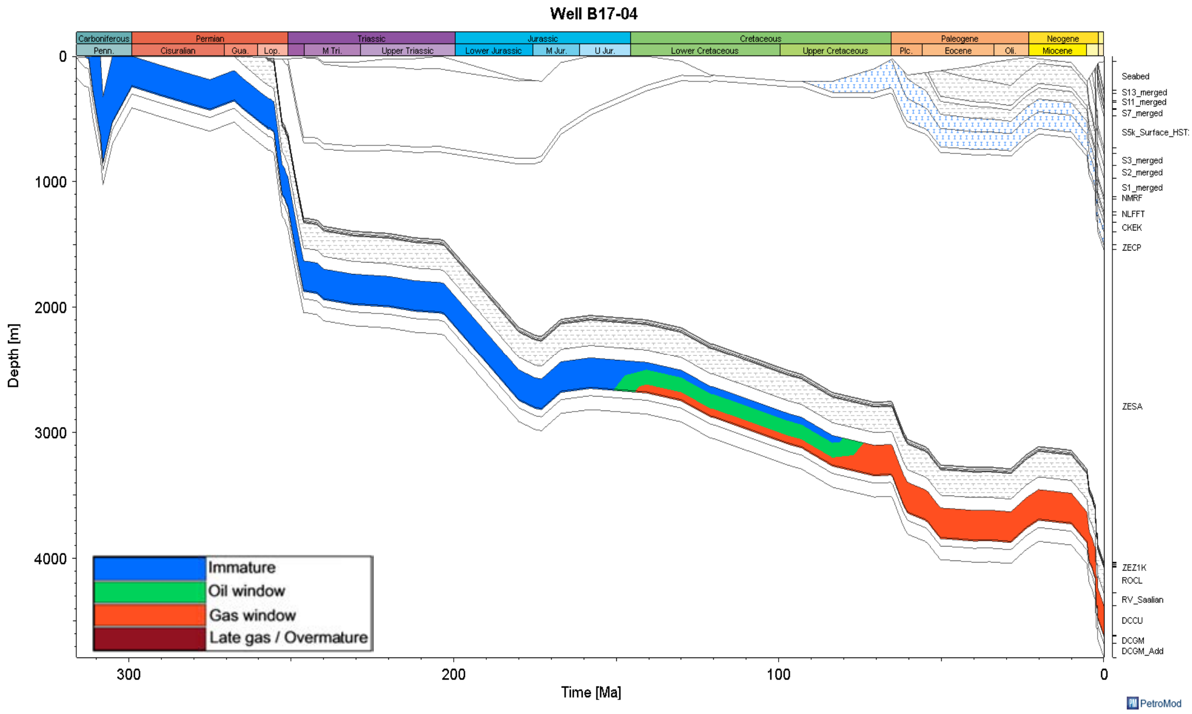


Figure 4.52:Modelled burial history and maturity of the Maurits Fm. (DCUU) at well B17-04.

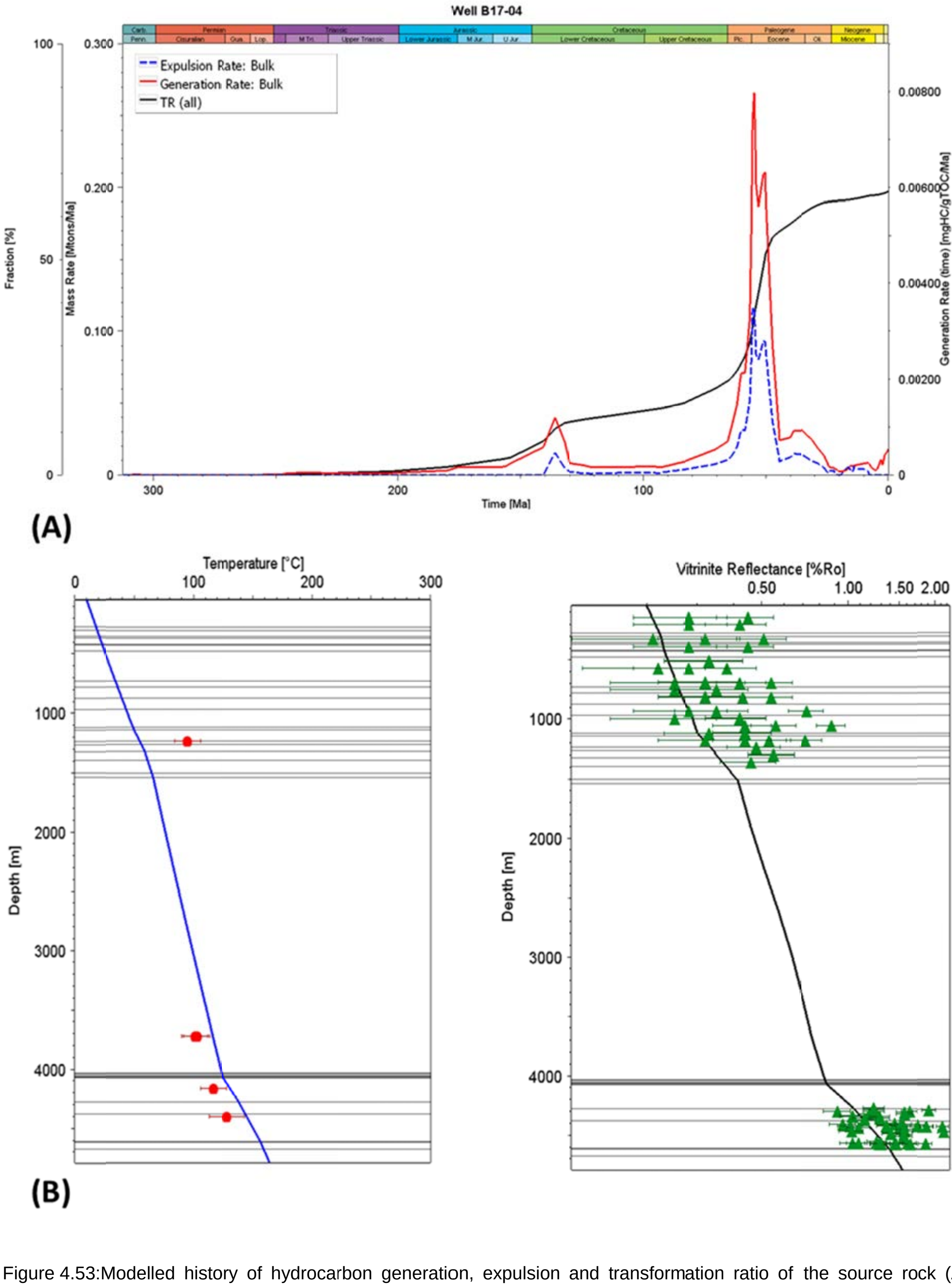


Figure 4.53:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the source rock (A). Results of model calibration to present-day temperature and Vitrinite Reflectance (B) at well B17-04.

4.6.3 Well F04-03

The well is located in the Step Graben. It reaches TD in the Maurits Formation (DCCU) which was defined as a source rock of kerogen type III in the model (Table 3-2 and Table 3-3). The modelled deepest burial is reached at present-day and the Maurits source rock appears to be in the gas window (Figure 4.54).
The model shows that hydrocarbon generation started in the Early Triassic and continued to the Palaeocene. The major phase of generation and expulsion from the Maurits Formation took place in the Tertiary (Palaeogene and Neogene) (Figure 4.55). Hydrocarbon generation and expulsion declined from the Miocene onward. Modelled transformation ratio shows that up to 70% of the transformable organic matter in the Maurits source rocks have been consumed. A good fit is achieved between modelled present-day temperatures, maturities and the measured values in this well (Figure 4.55).

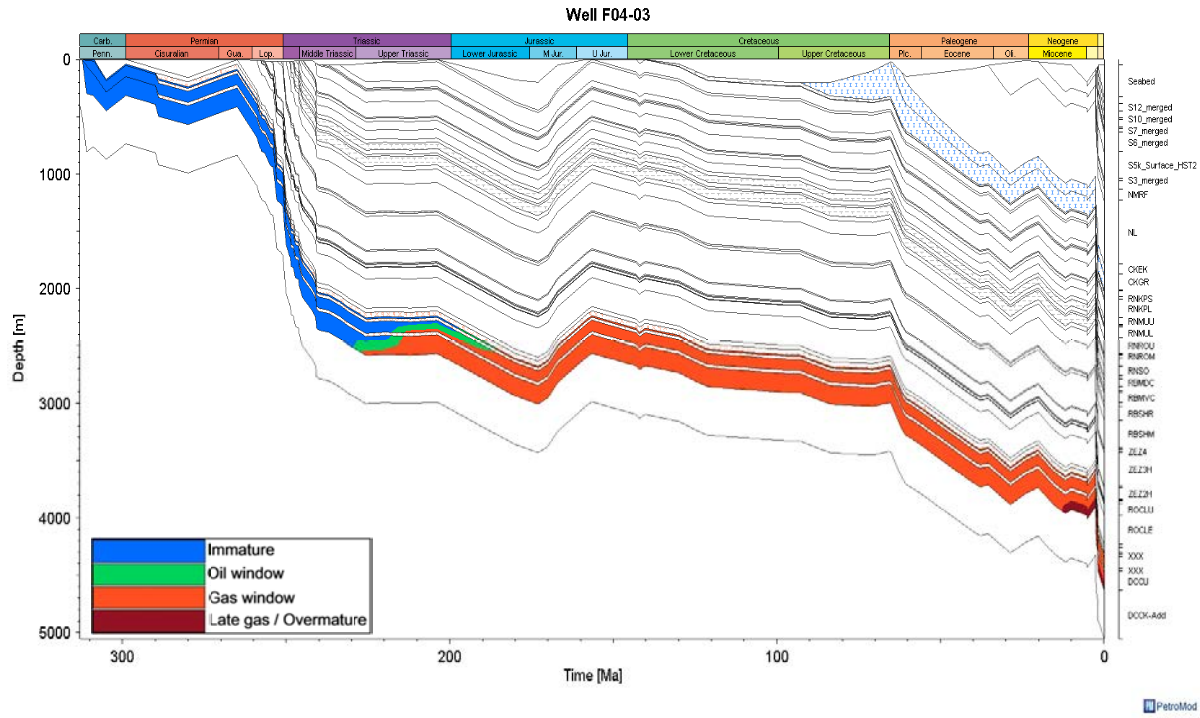
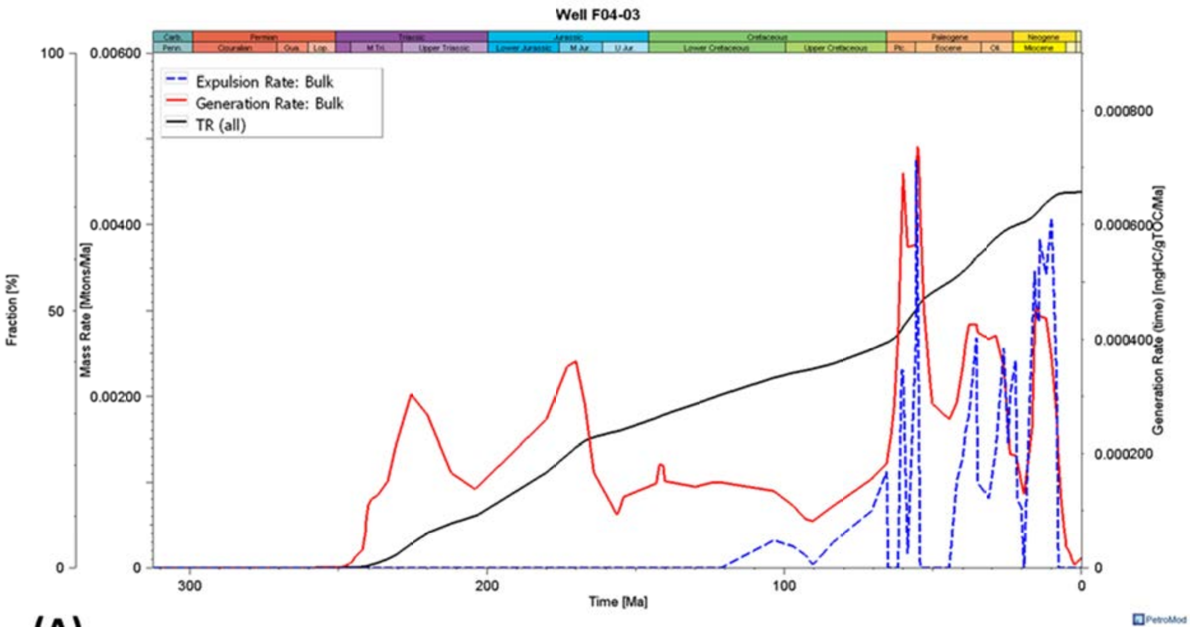


Figure 4.54:Modelled burial history and maturity of the Maurits Fm. (DCCU) at well F04-03.



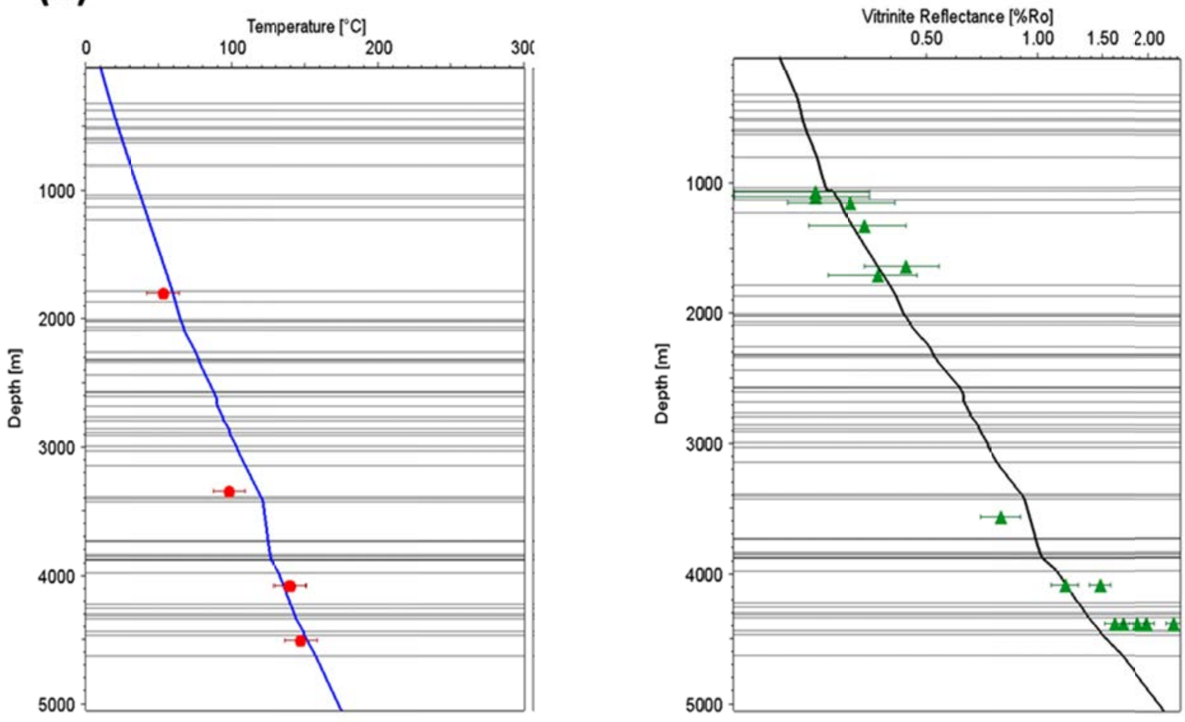


Figure 4.55:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the source rock (A). Results of model calibration to present-day temperature and Vitrinite Reflectance (B) at well F04-03.

4.6.4 Well F10-02

The well is located in the Step Graben. It reaches TD in the Step Graben Formation (DCHP). Based on the interpreted seismic sections, a thickness of 488m was included in the stratigraphy of the well to represent the Westphalian source rock (Table 3-2 and Table 3-3). The deepest burial is reached at present-day which is about 5000m at the bottom of the added Westphalian layer (Figure 4.56). The modelled maturity indicates that the Maurits source rocks are in the gas window, especially in the upper parts.
The model also shows that the main phase of hydrocarbon generation and expulsion was in the Early to Mid-Triassic. A limited amount of hydrocarbons were generated and expelled from the Westphalian rocks during the Miocene (Figure 4.57). Up to 80% of the transformable organic matter in the source rock has been consumed as suggested by the model. A good fit is achieved between modelled present-day temperatures values in this well (Figure 4.57).

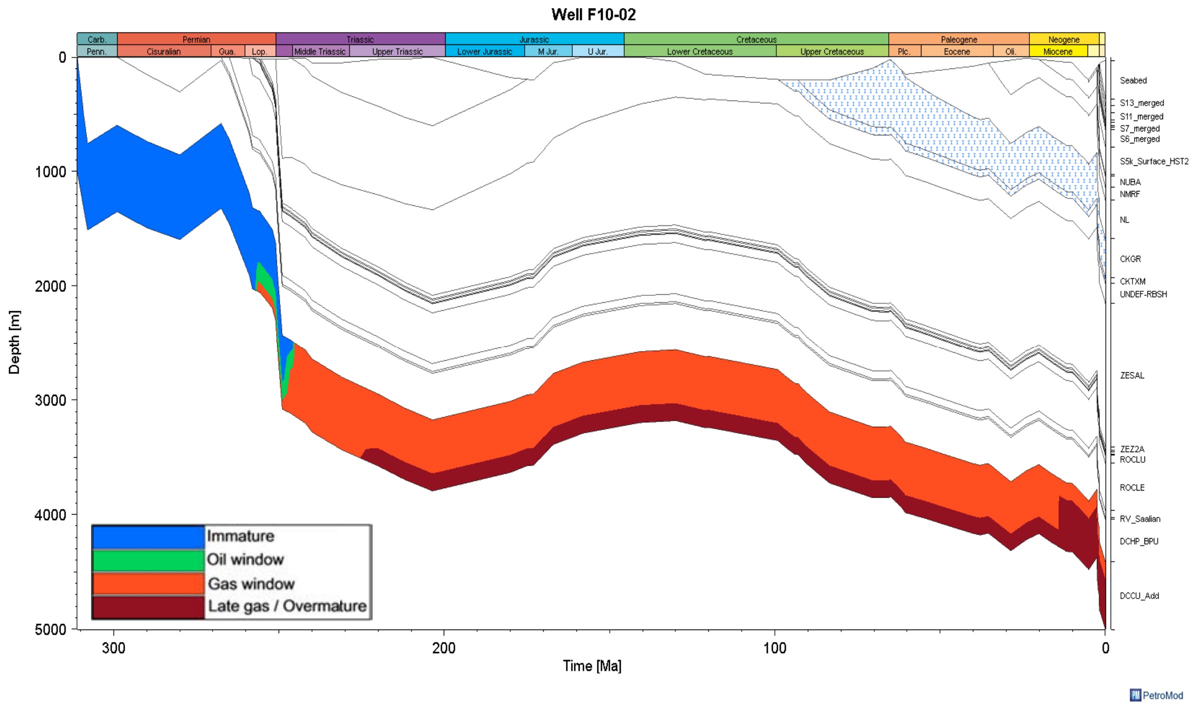
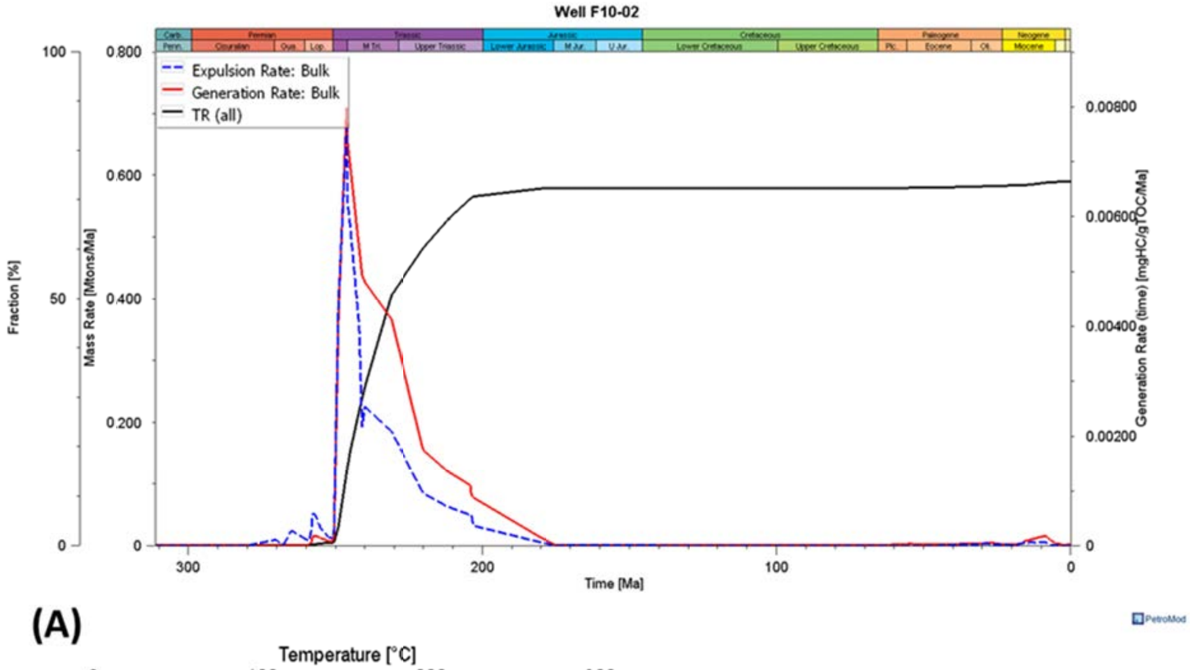


Figure 4.56:Modelled burial history and maturity of the annexed Maurits Fm. (DCCU) at well F10-02.



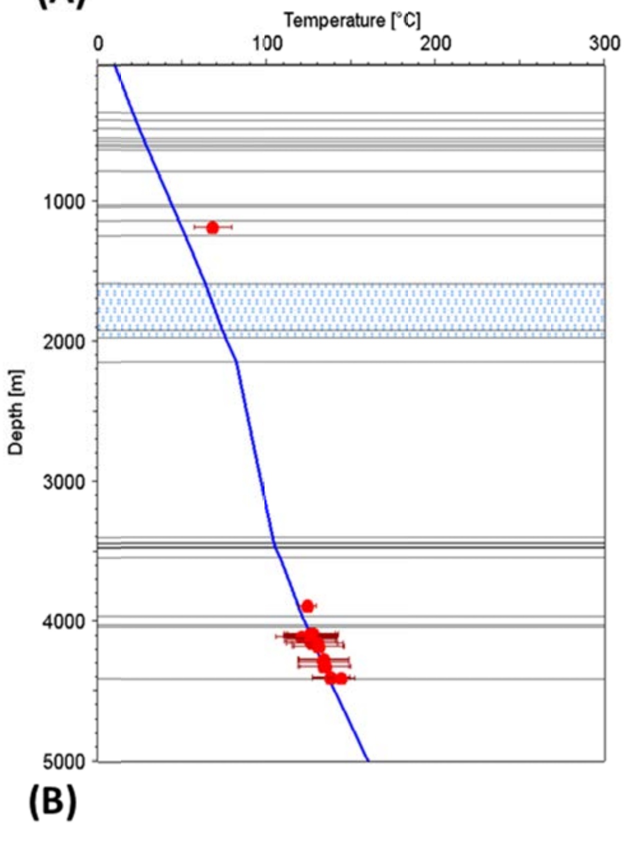


Figure 4.57:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the source rock (A). Results of model calibration to present-day temperature (B) at well F10-02.

4.6.5 Well Pseudo Well_1

The selected pseudo well _1 is located in the Step Graben where the mapped Westphalian is the deepest (Figure 4.58). The seismic line that crosses the location of the pseudo well shows some evidence of gas chimneys that can be traced down to the interpreted Westphalian layer (Figure 4.58). The Westphalian source rock (Maurits Formation) was given a thickness of 243m for the modelling (Table 4-1). The model shows that the deepest burial is reached at present-day (ca. 7000 m) at bottom of the Westphalian layer (Figure 4.59). The modelled maturity indicates that the Maurits source rocks are in the late gas to overmature window (especially in the deepest parts of the layer).
The model also shows that the main phase of hydrocarbon generation and expulsion was in the Early to Mid-Triassic and continued to Late Jurassic. A small amount of hydrocarbons were generated and expelled from the Maurits Formation in the Late Cretaceous and the Tertiary (Figure 4.60). The transformation ratio curve shows that almost 90% of the transformable organic matter in the source rock have been consumed.

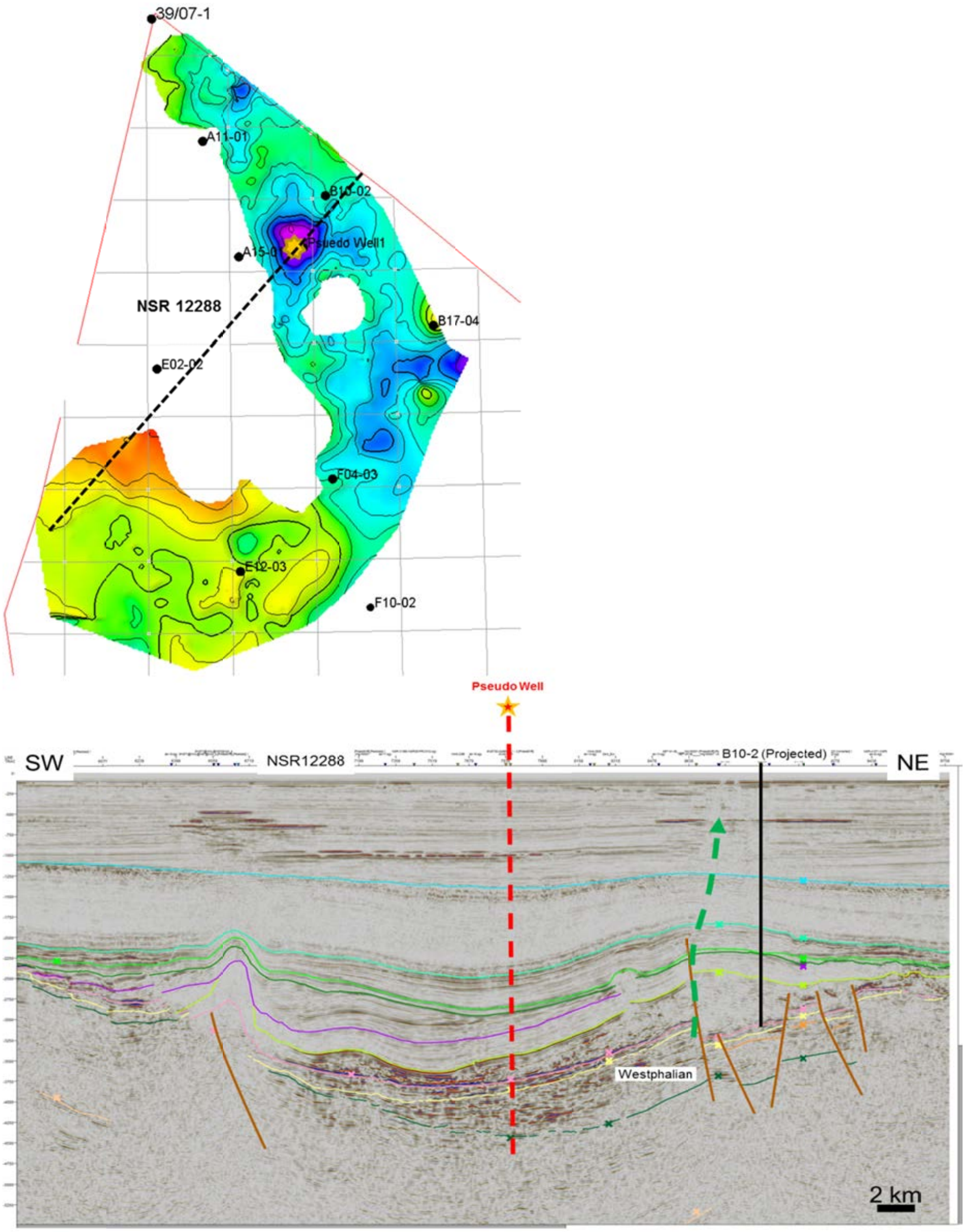


Figure 4.58:Seismic-based depth map of the Westphalian (in time) showing the location of the selected Pseudo Well_1 and seismic line (NSR 122888) (Top).

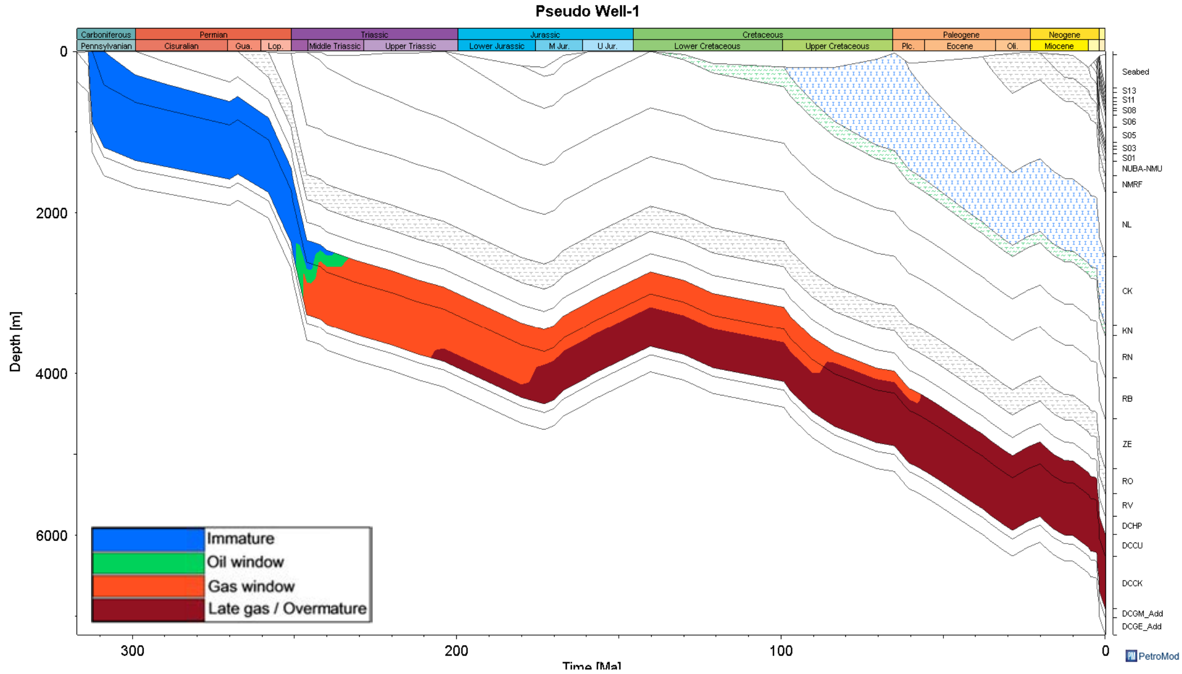


Figure 4.59:Modelled burial history and maturity of the Maurits Fm. (DCCU) at the location of the Pseudo Well_1.

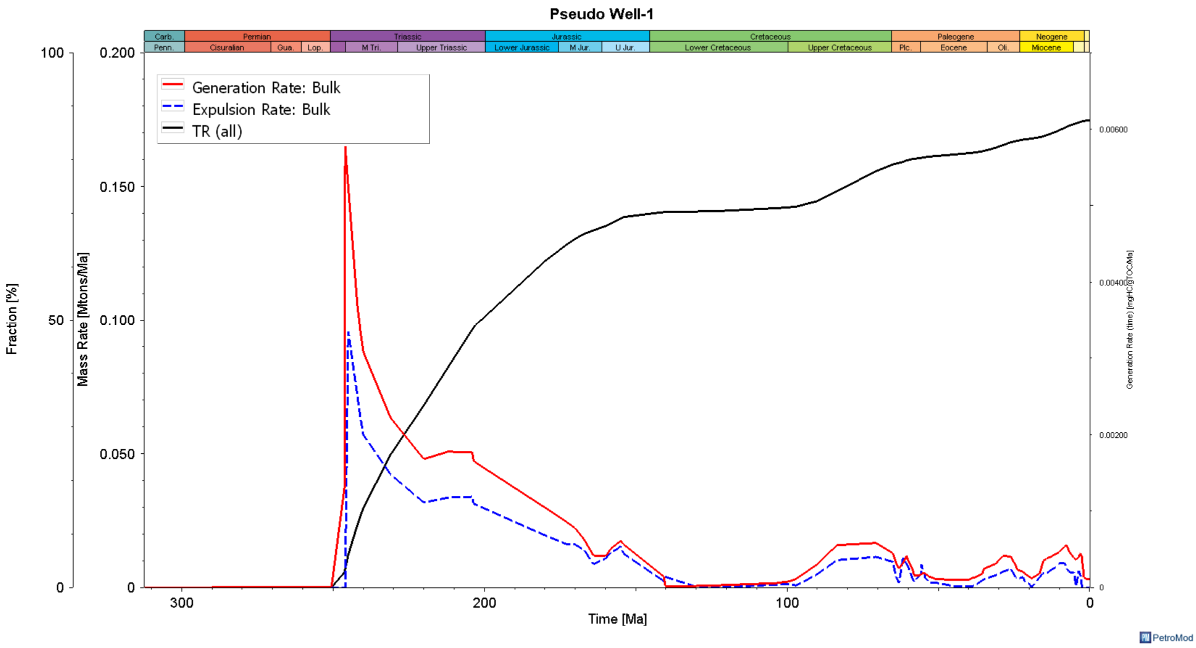


Figure 4.60:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the Maurits Fm. in the Pseudo Well_1.

4.6.6 Well 39/07-1

This well is located in the UK offshore section. According to the new interpretation as presented in this report the Westphalian and Namurian sections are not present (Figure 4.3). The well penetrates the Dinantian Scremerston Formation (Asbian-Brigantian age) which has also been identified on seismic at the location of this well. The coal-rich Scremerston Formation was considered as the source rock in this well and it was given the properties of a gas prone source rock (Table 3-2; Table 3-3). Although the Scremerston coals form only part of the Farne Group section, for modelling purposes we have assumed the entire Asbian section to be the source rock.

The formations have reached their deepest burial at present-day which reaches about 4000m at lowest section of the well. The modelled maturity shows that the Scremerston section is in the gas generating window since the Eocene (Figure 4.61). The model also shows that the main phase of hydrocarbon generation and expulsion from the source rock was during the Eocene and continued to present-day (Figure 4.62). Up to 30% of the organic matter in the source rock has been consumed and the source rock is therefore still rich in organic matter and able to generate hydrocarbons.

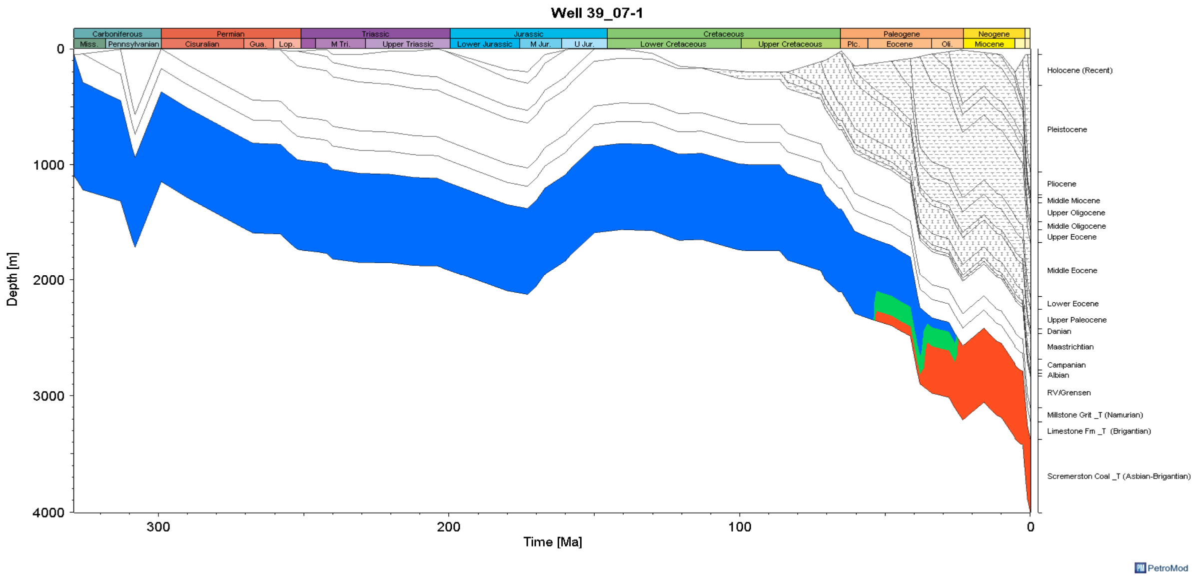


Figure 4.61:Modelled burial history and maturity of the Dinantian Scremerston Fm. at the location of well 39_07-1.

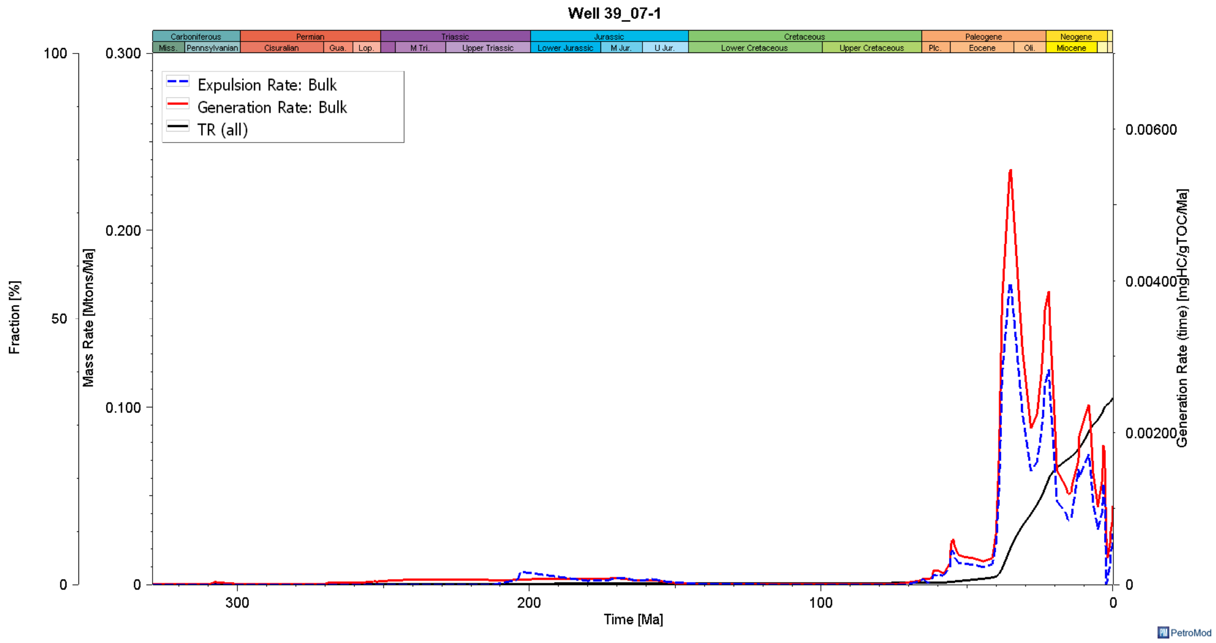


Figure 4.62:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the Dinantian Scremerston Fm at the location of well 39_07-1.

4.6.7 Well A11-01

This well is located in the Netherlands Step Graben (Figure 4.49). The well reaches the Namurian Millstone Grit Formation (DCGM) which is not considered to be a source rock. The Westphalian is missing due to erosion. Deeper sections were added to this well based on the information available from the adjacent well A14-01. The Dinantian Scremerston Formation was added to this well based on the information available from the adjacent well A14-01 was considered a type III source rock (Table 3-3).

The model shows that the Dinantian source rocks in the well entered the gas generation window during the Jurassic and are still in the gas window (Figure 4.63). Although some hydrocarbon generation and expulsion took place in the Mid-Jurassic, the main peak of generation and expulsion occurred during the Eocene. The generation decreased afterward and remained limited at present-day (Figure 4.64).The history of transformation ratio also reflects the peak in hydrocarbon generation in the Miocene. According to the model, about 60% of the organic matter has been consumed by generation. The model shows a good calibration with present-day temperatures and maturities (vitrinite reflectance) (Figure 4.64).

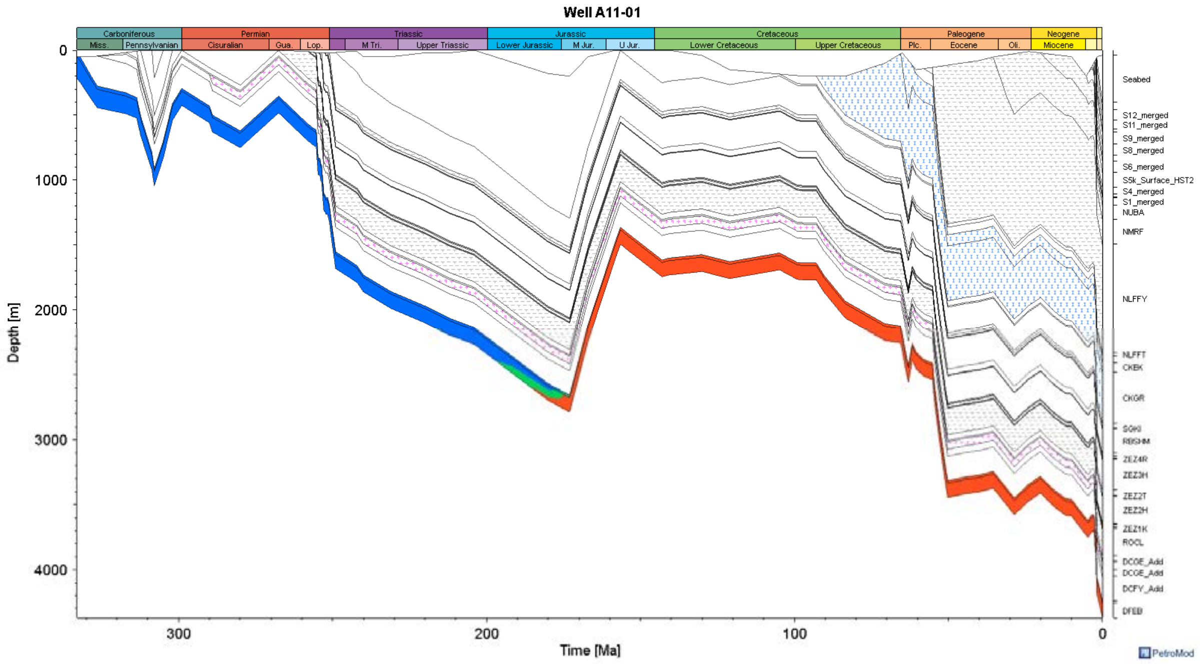
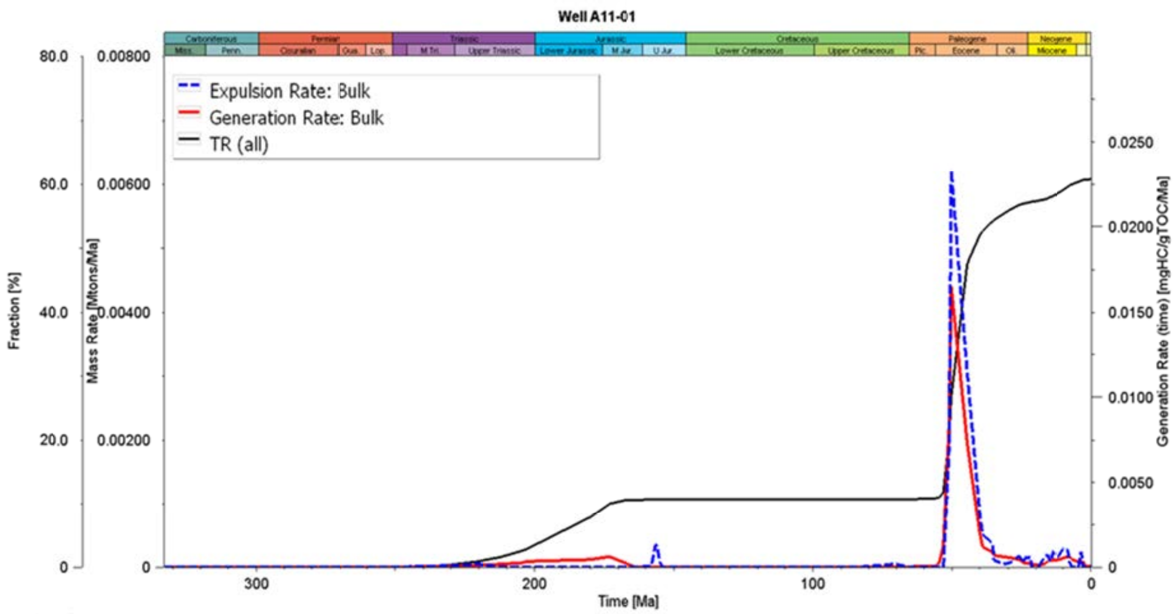
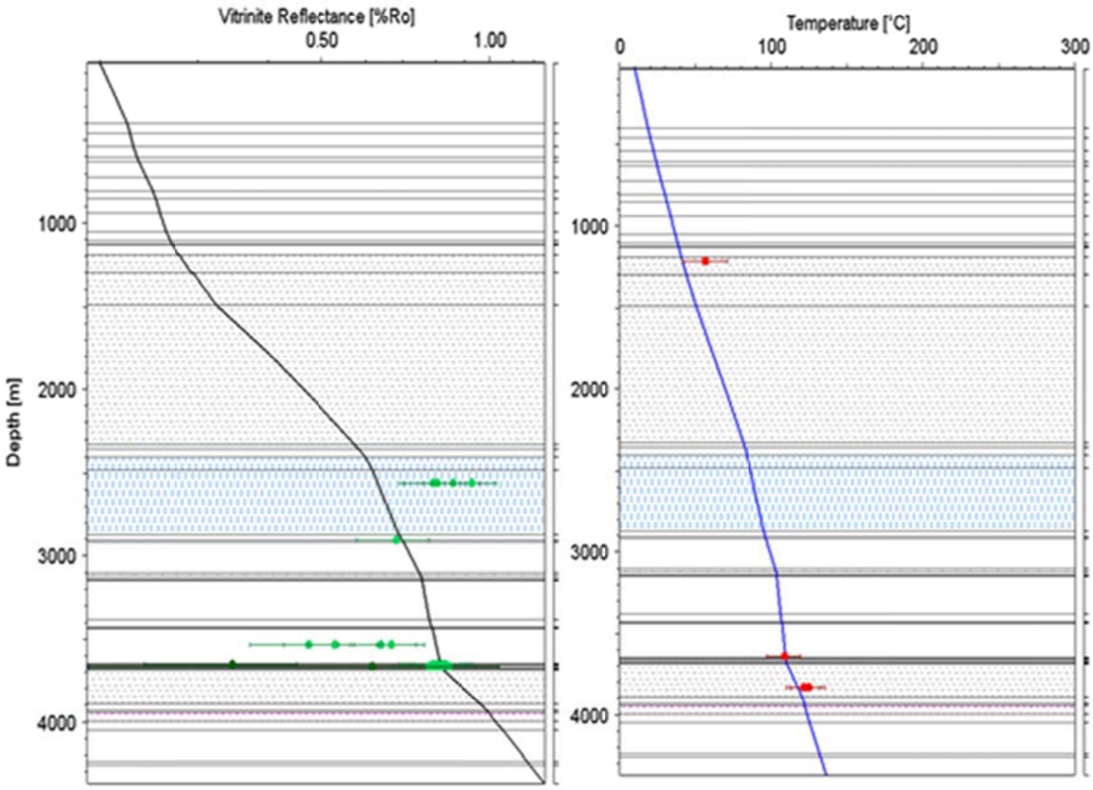


Figure 4.63:Modelled burial history and maturity of the Dinantian Scremerston Formation at the location of well A11-01.



(A)



(B)

Figure 4.64:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the source rock (A). Results of model calibration to present-day vitrinite reflectance and temperature (B) at well A11-01.

4.6.8 Well A15-01

The well is located in the Netherlands Step Graben on the eastern edge of the Elbow Spit High (Figure 4.49). The true vertical depth of the well reaches the Namurian Millstone Grit Formation (DCGM). The Westphalian section is not present in this well and therefore deeper sections were added based on neighbour well A14-01. The annexed Dinantian Scremerston Formation was considered to be the source rock in this well (Table 3-3).

Similar to other wells, the deepest burial is reached in this well at present-day. The Dinantian source rocks in the well entered the gas generation window in the Jurassic and are still in the gas window (Figure 4.65).

The model shows that the Palaeogene was the main phase of hydrocarbon generation and expulsion from the Scremerston formation at this location. Generation continued in the Miocene to present day but with a lower rate (Figure 4.66). Although some hydrocarbon generation and expulsion took place in the Mid-Jurassic, the main peak of generation and expulsion was in the Eocene. The generation decreased afterward and remained limited at present-day (Figure 4.66).The modelled transformation ratio reflects the increasing generation during the Palaeogene. About 65% of the organic matter has been consumed by generation. While a good fit was achieved with the temperature data, especially from deeper layers, the modelled maturity trend did not fit the measured value in the well. However, since there is only one vitrinite reflectance value available from this well, it is difficult to use the calibration with the maturity and therefore we rely more on the calibration with the temperature.

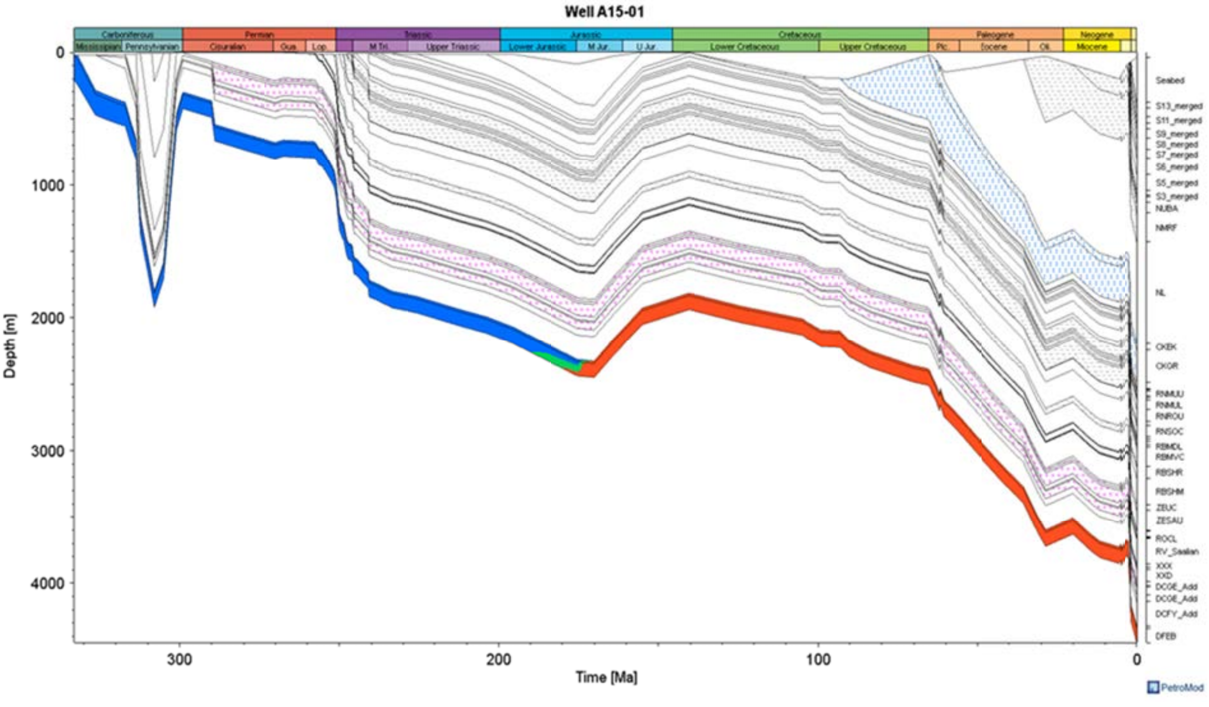


Figure 4.65:Modelled burial history and maturity of the Dinantian Scremerston Fm. at the location of well A15-01.

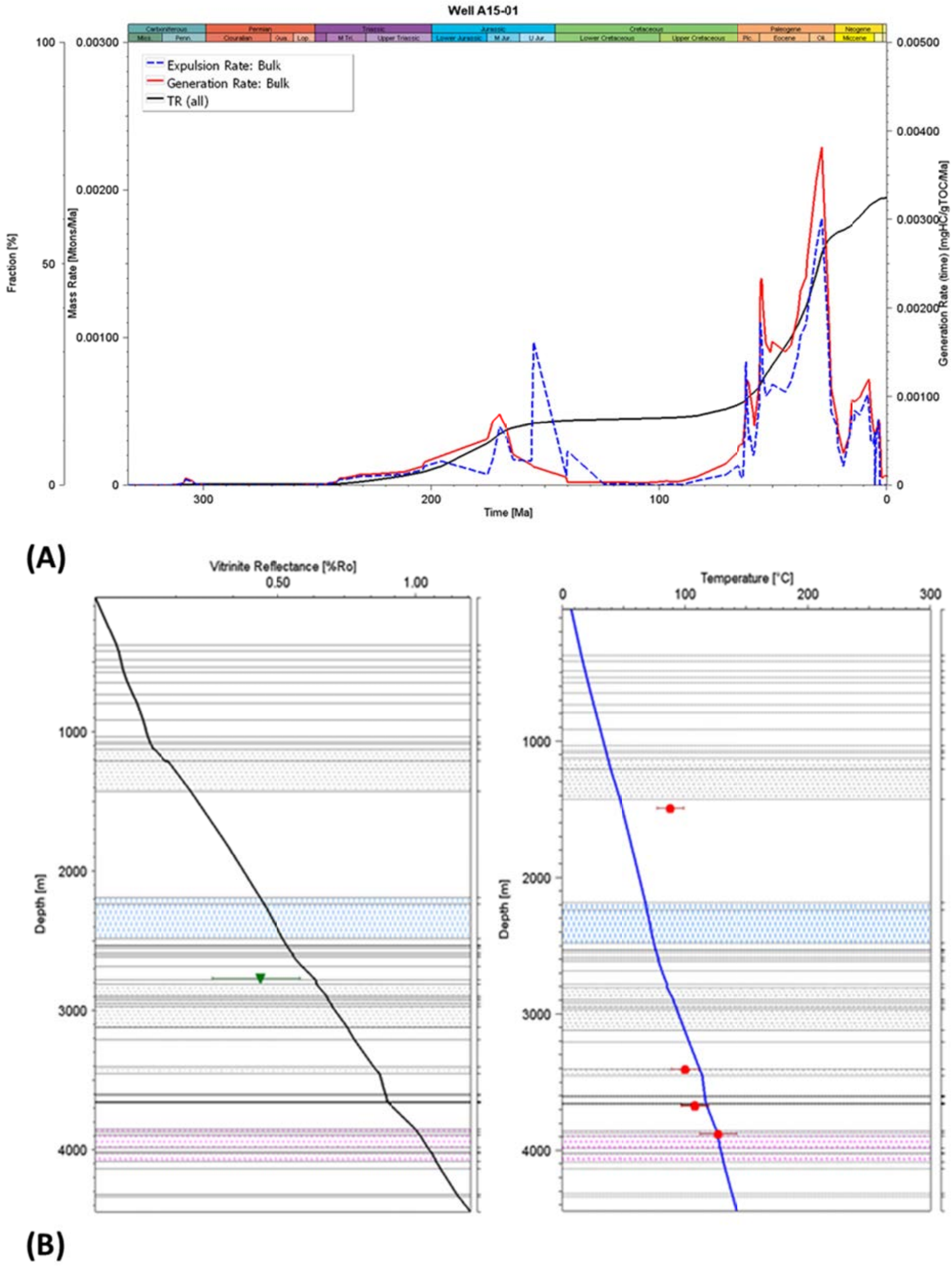


Figure 4.66: Modelled history of hydrocarbon generation, expulsion and transformation ratio of the source rock (A). Results of model calibration to present-day Vitrinite reflectance and temperature (B) at well A15-01.

4.6.9 Well E02-02

The well is located on the Elbow Spit High. The Westphalian and Namurian are not present in the section. A Dinantian section was annexed to the model where the Scremerston Formation is representing the potential source rock in this well (Table 3-3). The modelled burial history shows that the area was largely uplifted in the Late Jurassic but the rapid sedimentation since the Pliocene has resulted in deepest burial at present-day. The model also shows that the Dinantian source rock is thermally immature which mainly caused by the relatively shallow burial of the formations. History of hydrocarbon generation and expulsion indicate that limited amounts of hydrocarbons have been generated from the Scremerston Formation with the major peak being in the Mid-Jurassic. This is also supported by the modelled transformation ratio which indicates a value of less than 5% (Figure 4.68).
The modelled temperatures fit with the measured values at present-day. Modelled maturities however are less consistent with the measured vitrinite reflectance data, but a relatively better fit could be achieved in case less Jurassic erosion is assigned to the model (Figure 4.68). This however will not change the maturity of the Dinantian source rock.

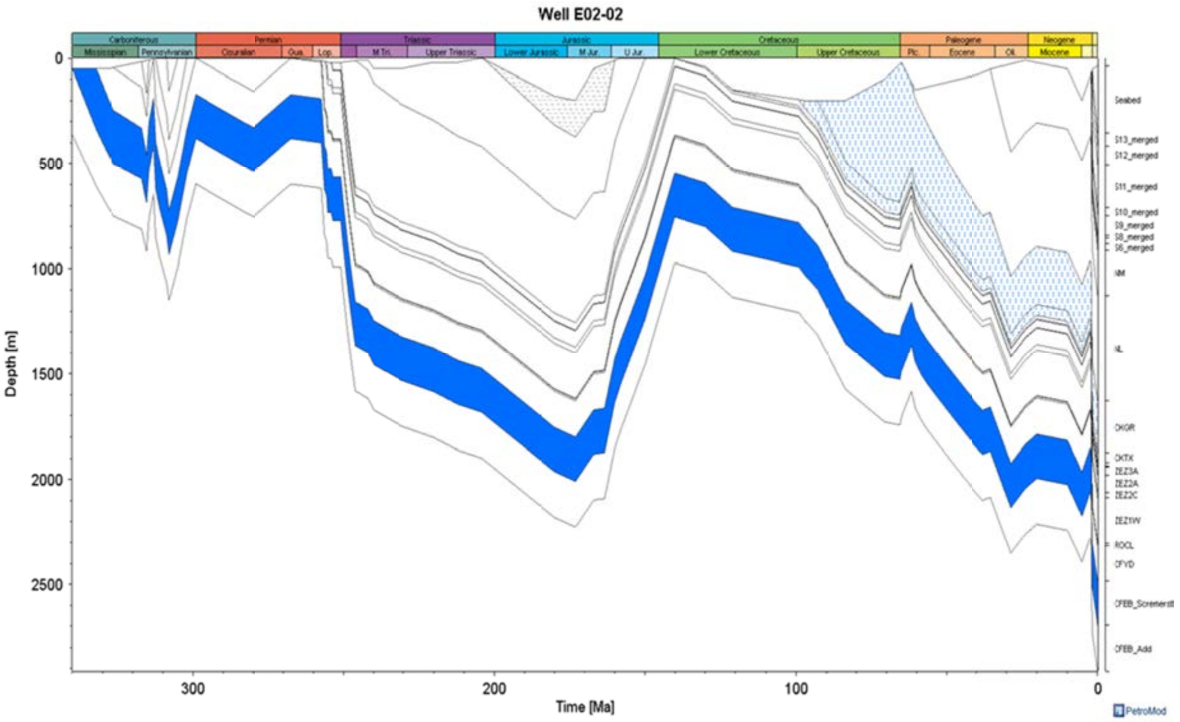
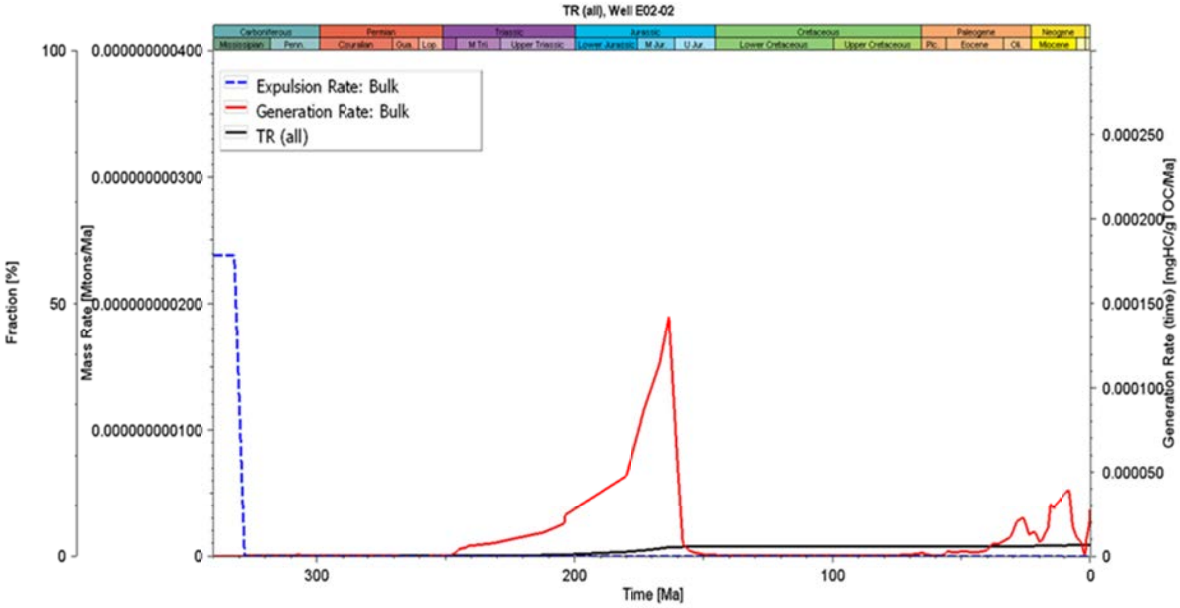
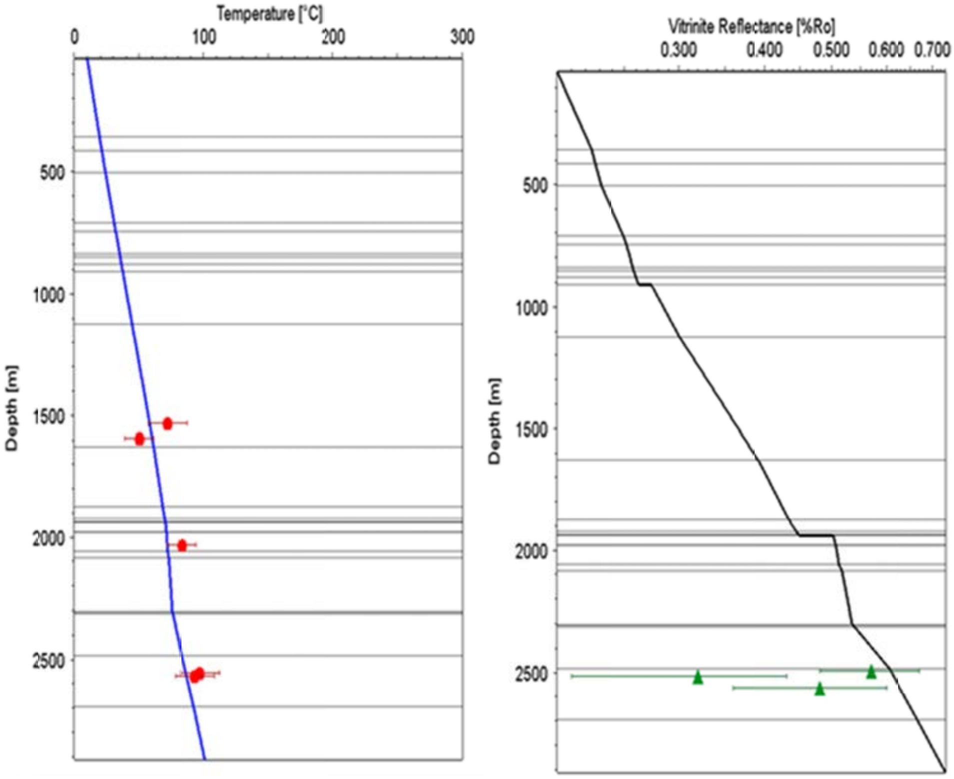


Figure 4.67:Modelled burial history and maturity of the Dinantian Scremerston Fm. at the location of well E02-02.



(A)



(B)

Figure 4.68:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the source rock (A). Results of model calibration to present-day vitrinite reflectance and temperature (B) at well E02-02.

4.6.10 Well 38/03-1

The well is located in the UK offshore (Figure 4.49). The well reached TD in the Kyle Group (Givetian-Frasnian). For maturity modelling purposes, the Frasnian Buchan Formation is assumed to be the source rock in this well.
A thermal peak was included in the heat flow model during the Late Carboniferous and Early Permian based on the analysis of the trends of the maturities data (see appendix 6).

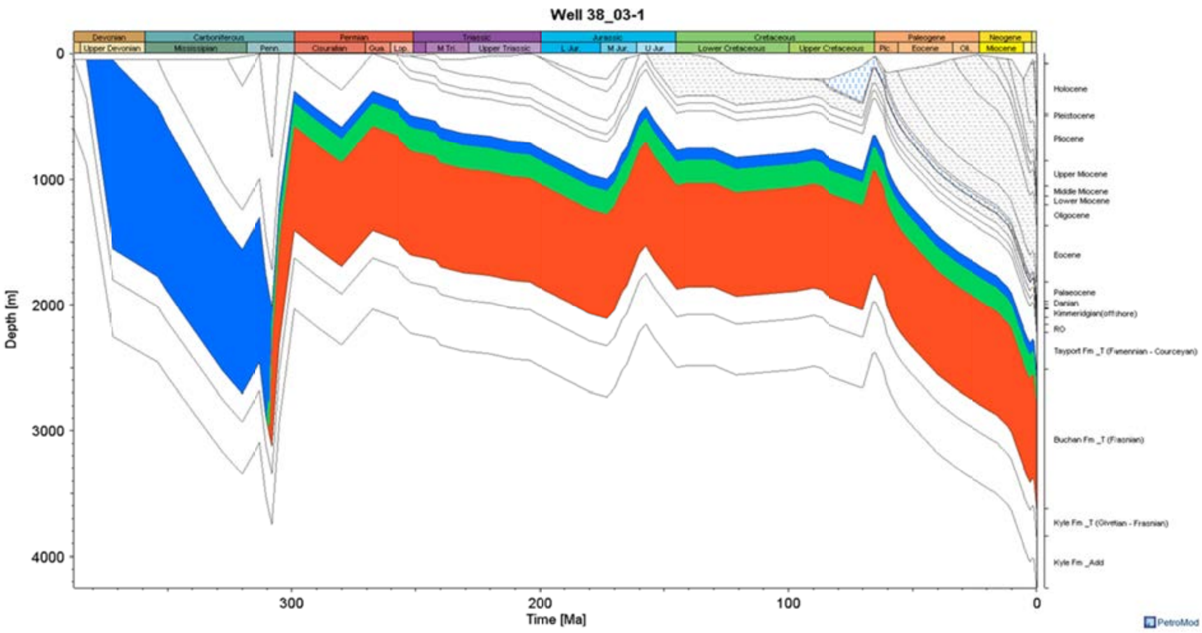


Figure 4.69:Modelled burial history and maturity of the Frasnian Buchan Fm. at the location of well 38_03-1.

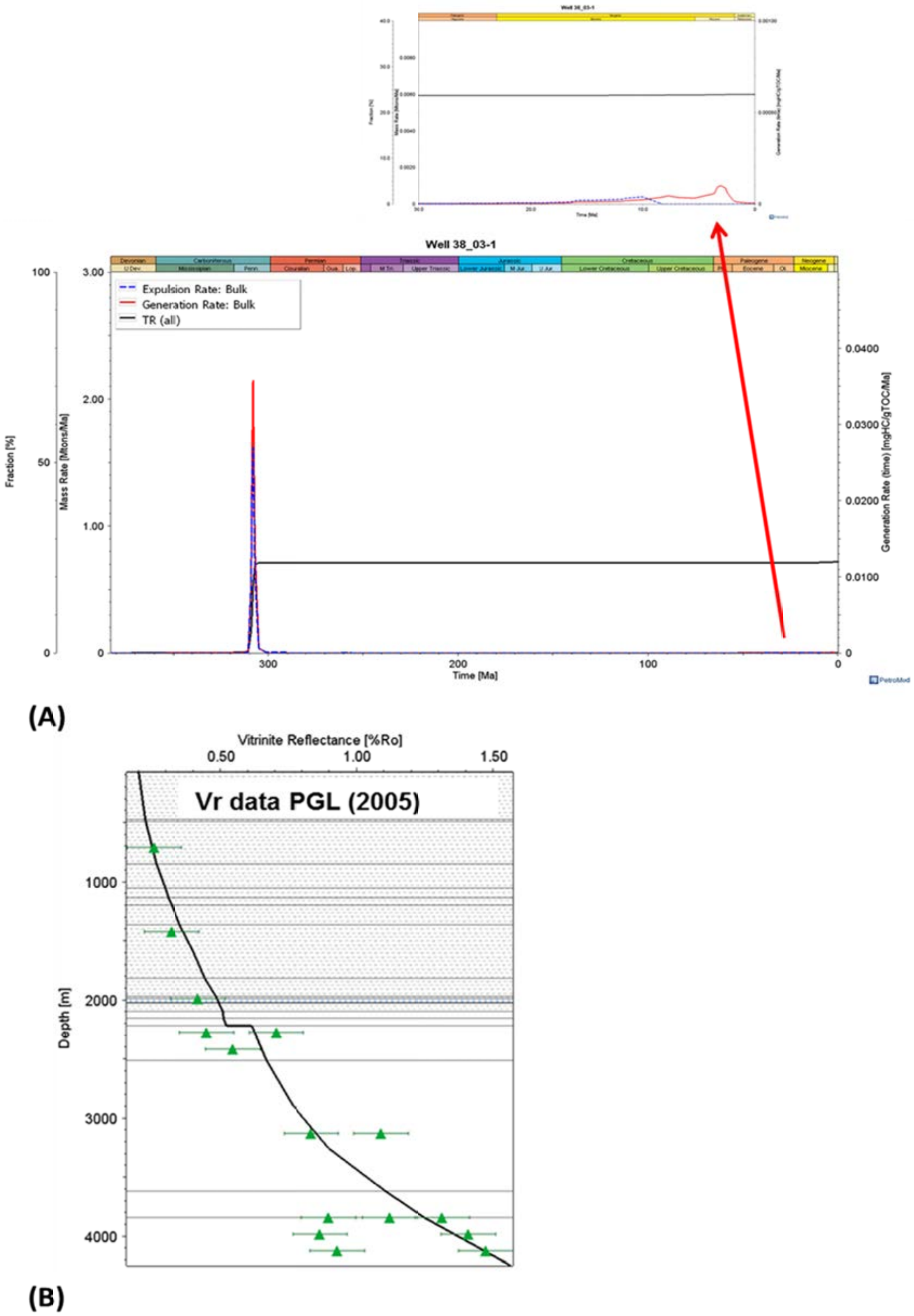


Figure 4.70:Modelled history of hydrocarbon generation, expulsion and transformation ratio of the source rock (A). Results of model calibration to present-day vitrinite reflectance well 38_03-1 (B). Vitrinite reflectance data are based on (PGL, 2005).

The model shows an important phase of uplift and erosion the Late Carboniferous and Early Permian. The main part of the assumed source rock entered the gas generation window in the late Carboniferous (Figure 4.69).

According to our model, there was one major peak of hydrocarbon generation and expulsion in the Late Carboniferous and only limited generation activities took place during the Miocene (Figure 4.70). The Late Carboniferous generation peak is attributed to the implemented thermal model with a heat flow peak in the Late Carboniferous.
If the quality of the vitrinite reflectance data in this well is reliable, then two maturity trends could be observed in the data where Carboniferous maturities show a steeper trend compared to post-Carboniferous data. The implemented thermal model and burial history show maturity trends which provide a good fit with the original different data trends the wells (Figure 4.70).

4.6.11 Top Westphalian maturity map

The modelled maturity map of the top Westphalian is presented in Figure 4.71 and Appendix 7.11. As explained before, a simplified approach was used to calculate the maturities using a constant heat flow and a linear burial. The calculated maturities correlate to present day depth of the formation. Next, the map is calibrated to the modelled present-day maturity (vitrinite reflectance Ro%) at the location of the wells.
The map shows that the deeper parts of the Westphalian show higher thermal maturities that correspond to the vitrinite reflectance values of a source rock in the gas window according to Sweeny & Burnham (1990) thermal maturity kinetics.

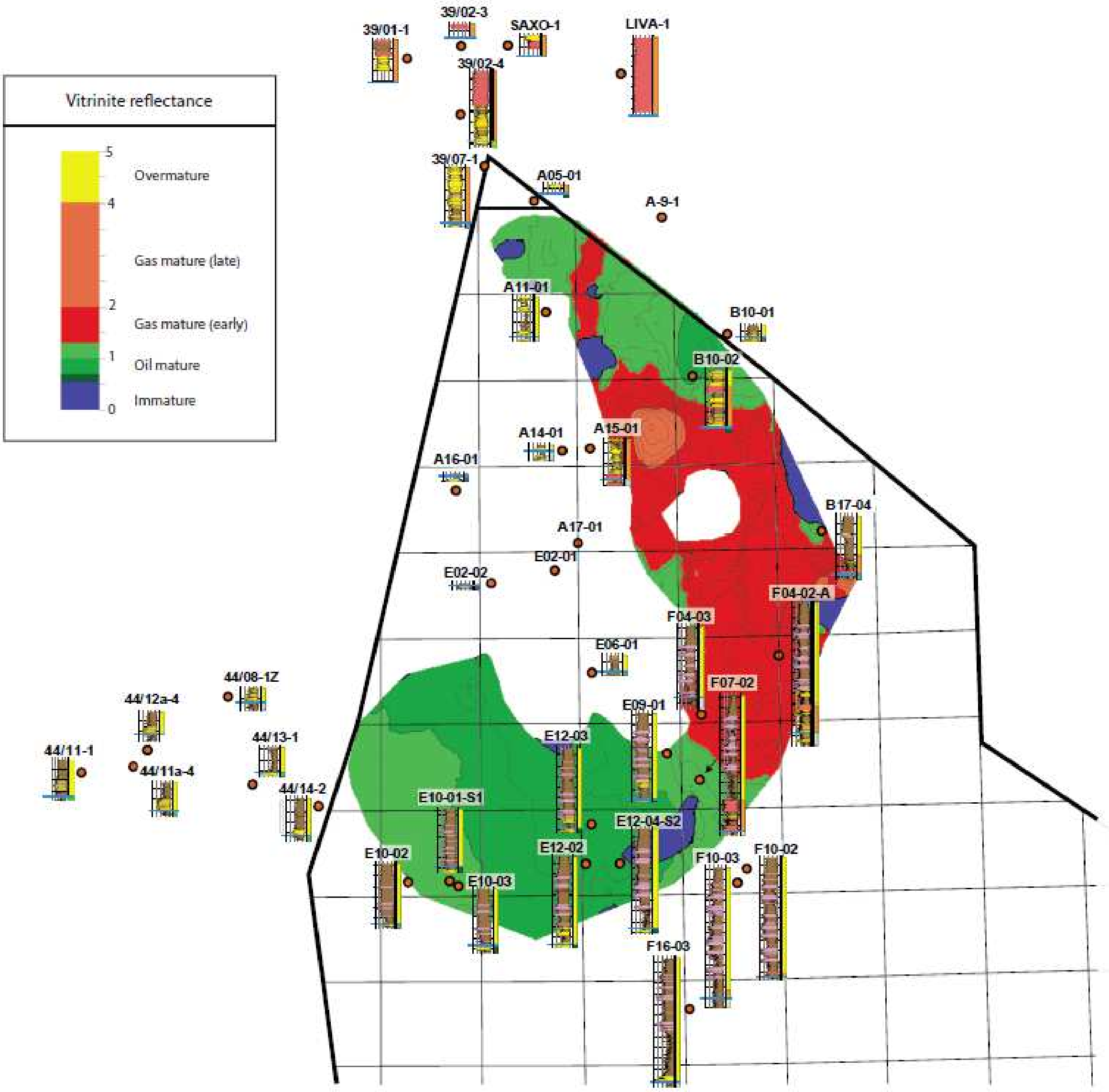


Figure 4.71:Modelled thermal maturity map of the top Westphalian based on a simplified maturity calculation approach and calibrated to modelled present-day maturities at the location of the wells.

5 Synthesis

This chapter discusses the new geological knowledge acquired through the integration of the various analysis carried out in this project. The information that is the basis for this chapter can be found in Chapter 4 or in the Appendices. This synthesis chapter is divided into five section that cover for the Dutch Northern Offshore: 1) the Carboniferous source rocks distribution, 2) the Rotliegend depositional system and reservoir distribution, 3) the source rocks maturity, 4) the Rotliegend reservoir rocks potentials, and 5) the prospective zones where both mature source rocks and reservoir rocks are present.

5.1 Carboniferous source rocks distribution of the Dutch Northern Offshore

The Carboniferous stratigraphy is important since both potential source rocks (Scremerston Formation and Westphalian) are deposited during the Carboniferous. The organic rich intervals found in F10-02 and F10-03, which were initially age dated as Stephanian, turned out to be of Westphalian in age. The Westphalian was encountered in a much larger area than originally anticipated, which could renew interest in exploration efforts in a larger part of the Dutch Northern Offshore. Furthermore, the presence the Dinantian coal-rich Scremerston Formation is a potential source rock in the areas were no Westphalian was encountered.

This study focused on the Permian reservoirs, and therefore no detailed study was done of the paleogeography, tectono-stratigraphy or facies distribution of the Westphalian.

5.1.1 Scremerston Formation

In the UK sector (Block 39), the coal-rich Scremerston Formation has been identified (PGL, 2005). This formation has not been defined in the Dutch Offshore, but is the time equivalent of the younger part of the Visean (Dinantian) Elleboog Formation (Figure 4.14). The Scremerston Formation, and its coals, has been drilled just across the border in well 39/07-1. In the Dutch offshore, it is seismically mappable in a small region in the northernmost part of the study area. It could not be mapped further towards the south-east and it has not been encountered in any well within the A and B blocks. However, we believe this source rock could be present farther south and east of the mapped area since it has been encountered in the German A-9-1 well. Therefore, the Scremeston Formation stratigraphy of well 39/07-1 was used as an analogue for the A blocks wells used in basin modelling (A11-01 and A15-01, see section 4.6).

5.1.2 Westphalian

In this study, wherever the Westphalian was encountered, it was assumed to contain source rock facies. The base of the Westphalian is an unconformity, which can be identified on seismic data. It is characterised by onlap onto the Elbow Spit High (see appendix 4.23 and Figure 4.4). This indicates that the Elbow Spit High was already a (small) topographic high during deposition of the Westphalian sediments. The Westphalian is expected to be deposited over the Elbow Spit High and subsequently eroded. This can be concluded from the fact that the top of the Westphalian saw major erosion and only a few small Westphalian remnants are encountered on the Elbow Spit High (see small remnant of the Step Graben Formation area above the Elbow Spit High in Figure 4.17). This indicates that the younger part of the Westphalian was likely draping all, or a large part, of the Elbow Spit High and was subsequently eroded. Further research into the internal stratigraphy and paleogeography of the Westphalian is advised.

5.2 Rotliegend depositional system and reservoir rocks distribution of the Dutch Northern Offshore

The Rotliegend's stratigraphic and tectono-stratigraphic results gathered in this project reveal a different setting than initially proposed. The idea of a Northern Fringe sands in the Dutch Northern offshore is still a valid model but its distribution, stratigraphic evolution and the syn-depositional tectonics and topographic effects are now better understood and constrained. In this section, the main seismic and well-log analysis results obtained in this project are combined to discuss the complex stratigraphy of the Lower and Upper Rotliegend Groups, as well as the effect of topography and syn-depositional deformation on these depositional systems.

5.2.1 Lower Rotliegend

The depositional environments of the Lower Rotliegend are not clearly established in the Dutch Offshore, due to lack of wells and cores, but predominant alluvial fans and fluvial depositional systems likely compose the non-volcanic strata in the Lower Rotliegend in the study area. This conclusion is based on published results from the UK sector (Martin et al, 2002) that are presented in Appendix 2.2.
The Lower Rotliegend is only present in the north and eastern part of the study area. However, the upper boundary of the Lower Rotliegend is a major unconformity (Saalian Unconformity). Therefore, the areal extent of this interval was likely considerably larger in the Dutch Northern Offshore prior to the Saalian erosional event.

Below is discussed the palaeogeographic evolution of the Lower Rotliegend as well as the topographic effect on deposition of this interval.

5.2.1.1 Lower Rotliegend palaeogeography

The palaeogeography and palaeotopographic evolution of the Lower Rotliegend is difficult to fully understand due to the subsequent major erosion that only preserved strata within topographic lows in the north-eastern part of the study area. However, some lithofacies trends can be observed and shed some light on the palaeogeography during Lower Rotliegend times. The first two stratigraphic units of the Lower Rotliegend analysed (RV1 and RV2, Figure 5.2 and Figure 5.3) show north-eastern sand-rich zones and southern lower net-to gross zones. This setting is interpreted as a deepening of the basin to the south or southwest during this period. The sediment transport directions are interpreted to be from the north during RV1 and the north east during RV2. It is worth noticing that a small remnant area with Lower Rotliegend strata is located to the south (Figure 5.2). We believe that a similar context can be applied to the case of the K02-02 well, where a basal conglomerate has been found that could be attributed to the Lower Rotliegend rather than to a younger interval (H. Mijnlieff personal communication).
The lithofacies distribution of the youngest Lower Rotliegend interval (RV3, Figure 5.4) shows a different palaeogeographic trend than the previous intervals, with coarser strata located to the south and a lower net-to gross area to the north. A SSW to NNE sediment transport direction is inferred for this period.

The relationship between the Grensen Formation in the UK sector and the Lower Rotliegend of the Dutch Northern Offshore is discussed in Appendix 2.2. However, the palaeogeographic map constructed for the oldest section of the Lower Rotliegend (RV1, Figure 5.2) indicates that the Grensen Formation can be found in the northern tip of the Dutch offshore, but was confined to the south by a palaeotopographic high and to the east by predominantly volcanic terrain.
In contrast, the palaeogeographic map for RV2 shows that the depositional system during this period was not topographically confined, but had a NW/SE oriented palaeo-coastline extending across the UK and Dutch sectors. The relationship between the Grensen Formation in the UK sector and the Lower Rotliegend strata in the Dutch offshore get more difficult to establish for the younger Lower Rotliegend interval (RV3) due to the presence of an eroded area (base Zechstein erosion) at the northern tip of the Dutch offshore.

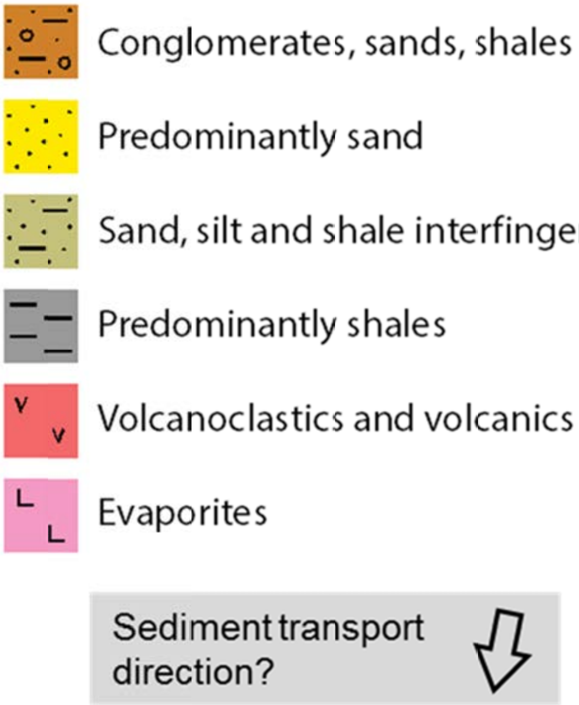


Figure 5.1: Legend for the Rotliegend palaeogeographic maps presented below.

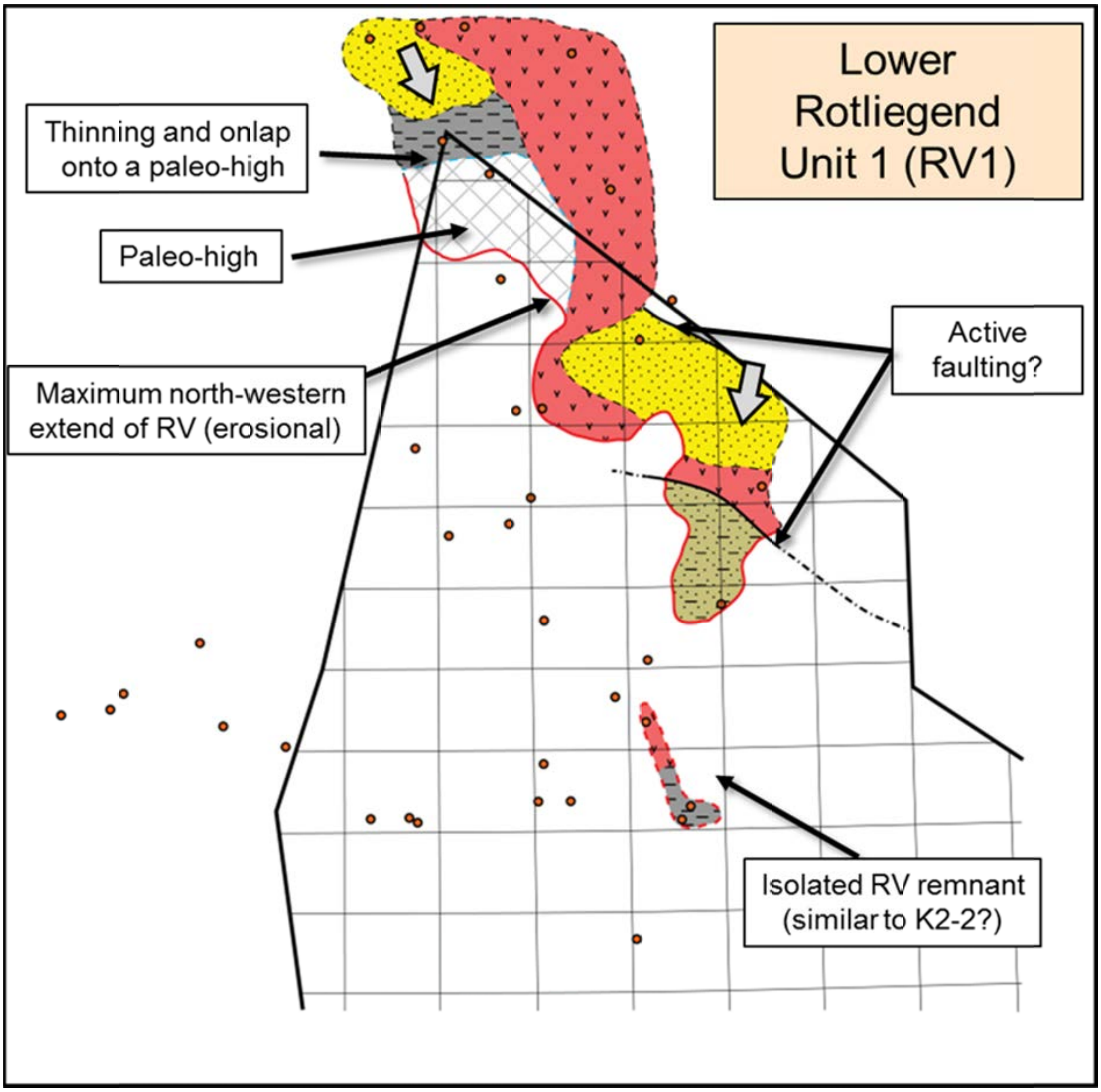


Figure 5.2: Depositional map of the oldest preserved Lower Rotliegend interval in the study area (RV1). See Figure 5.1 for legend and appendix 7.02 for a high detailed version including wells-logs

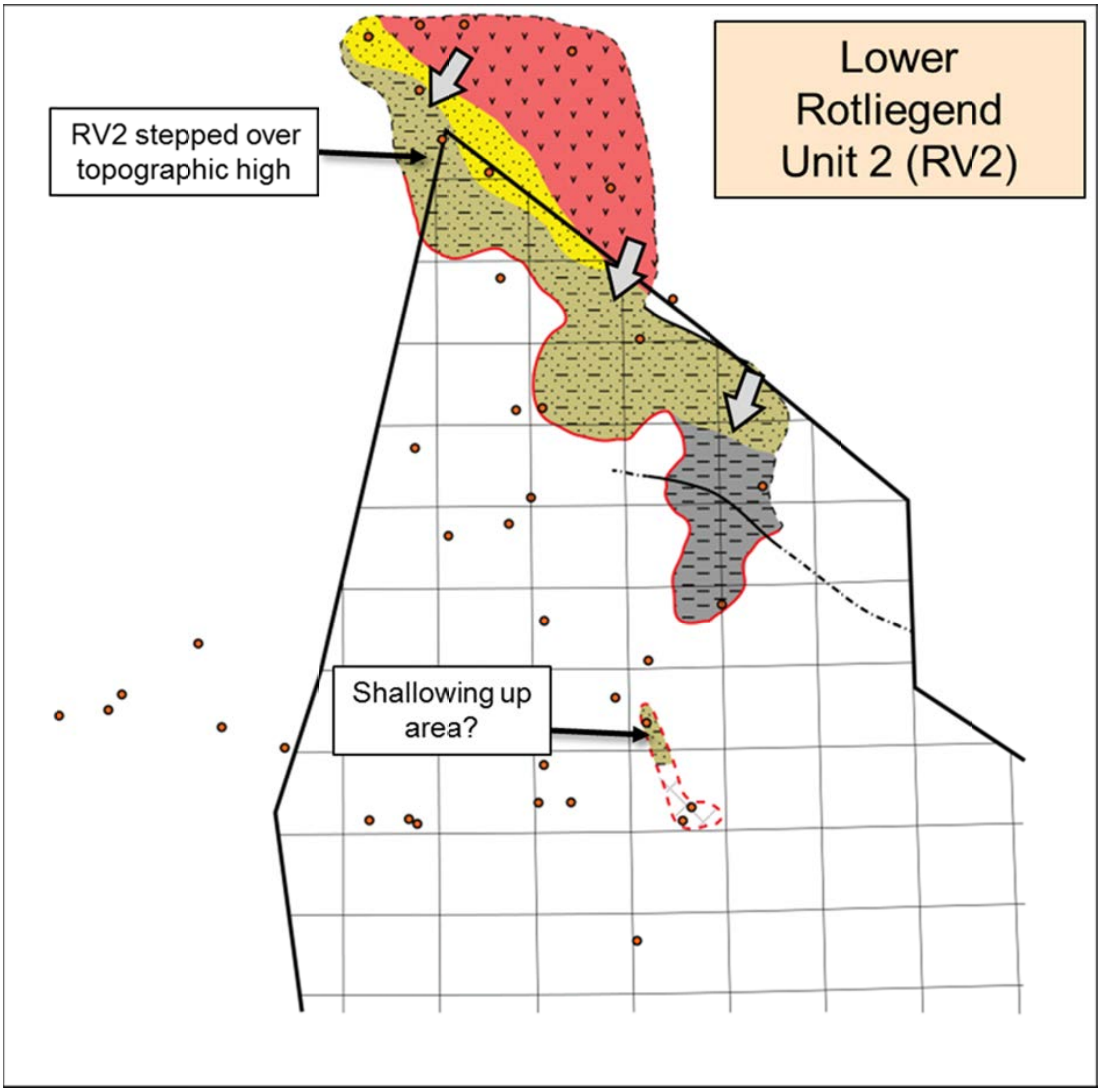


Figure 5.3: Depositional map of the second oldest preserved Lower Rotliegend interval in the study area (RV2). See Figure 5.1 for legend and appendix 7.03 for a high detailed version including wells-logs

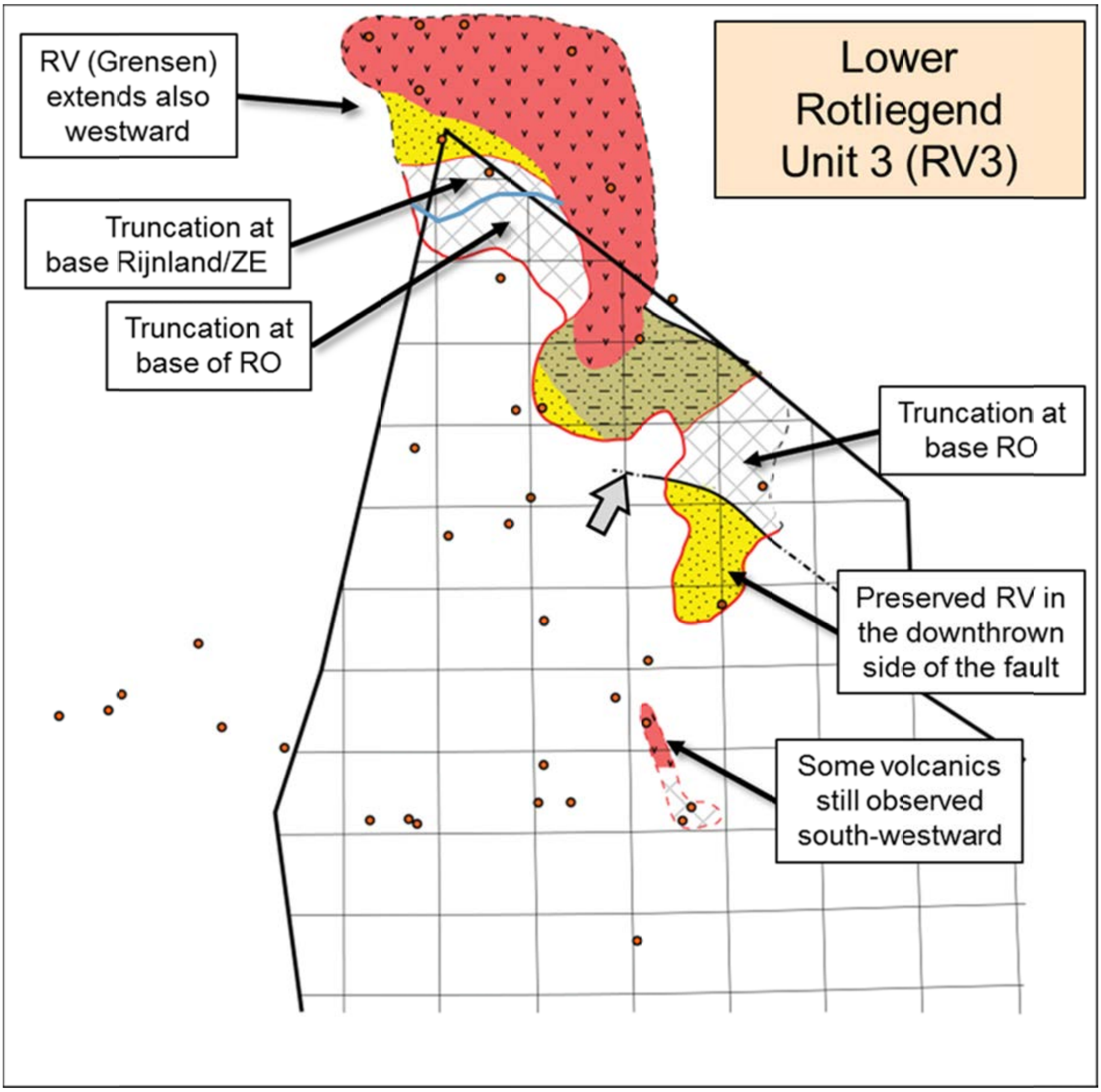


Figure 5.4: Depositional map of the youngest preserved Lower Rotliegend interval in the study area (RV3). See Figure 5.1 for legend and appendix 7.04 for a high detailed version including wells-logs

5.2.1.2 Lower Rotliegend palaeotopography

Palaeo-reliefs affecting the Lower Rotliegend have been observed on seismic and locally explain the discontinuous nature of this interval in the study area. Figure 5.2 shows the location of an E-W oriented palaeotopographic high close to where the, later prominent, Mid North Sea High is located. This topographic high can also be seen on Figure 4.25 (highlighted with black arrows) between wells 39/07-1 and A15-01. No specific isochore mapping has been performed for the specific sub-units within the Lower Rotliegend due to the poor seismic signal for such thin intervals. However the overall Lower Rotliegend isochore maps show how non-homogeneous

the thickness of the Lower Rotliegend is (Figure 4.8), which highlight the complex palaeotopography configuration of the basin at the time.
Several syn-depositional faults may have been active during or prior to the deposition of the Lower Rotliegend. However, due to the limited preservation of these deposits (due to the subsequent Saalian erosional event) it is very difficult to establish if those syn-depositional faults were truly active during this period. A detailed seismic mapping could reduce the uncertainties described above.

5.2.2 Upper Rotliegend

The Upper Rotliegend has a much larger depositional extent within the study area than the Lower Rotliegend. Only a few limited areas show post-depositional erosion (e.g. west of the Elbow Spit High).
Many publications have discussed the depositional systems of the Rotliegend in the Southern Permian Basin and only a few key points will be discussed below to explain the stratigraphy complexities observed within the study area. The simple depositional model presented in Figure 5.5 (A) show the proximal to distal trend within a saline lake. The proximal zone is composed of highlands and fluvial (often ephemeral) depositional systems that are subject to aeolian processes and the formation of large dune fields. Local alluvial fans can be observed around the piedmont as fringes. Fluvial systems drain large areas and are connected to the lake by distributaries (Figure 5.6). The sand flat area is composed of mixed depositional facies with mudstone, siltstones and sandstones and transition distally to the playa zone that is predominantly composed of mudstone and evaporates (depending on climate effects with wet and dry alternating conditions). The formation of small deltas is also possible when the fluvial systems carry large enough sediment charge into the lake (Figure 5.5, B and Figure 5.7). This simple depositional model highlights that the proximal zone area (piedmont to shoreline) is sand-rich and the distal zone (playa margin to lake axis) is sand poor to sand starved. Therefore, the identification of the successive positions of the lake shoreline through time is crucial to establish the location of reservoir quality strata in such a depositional context.

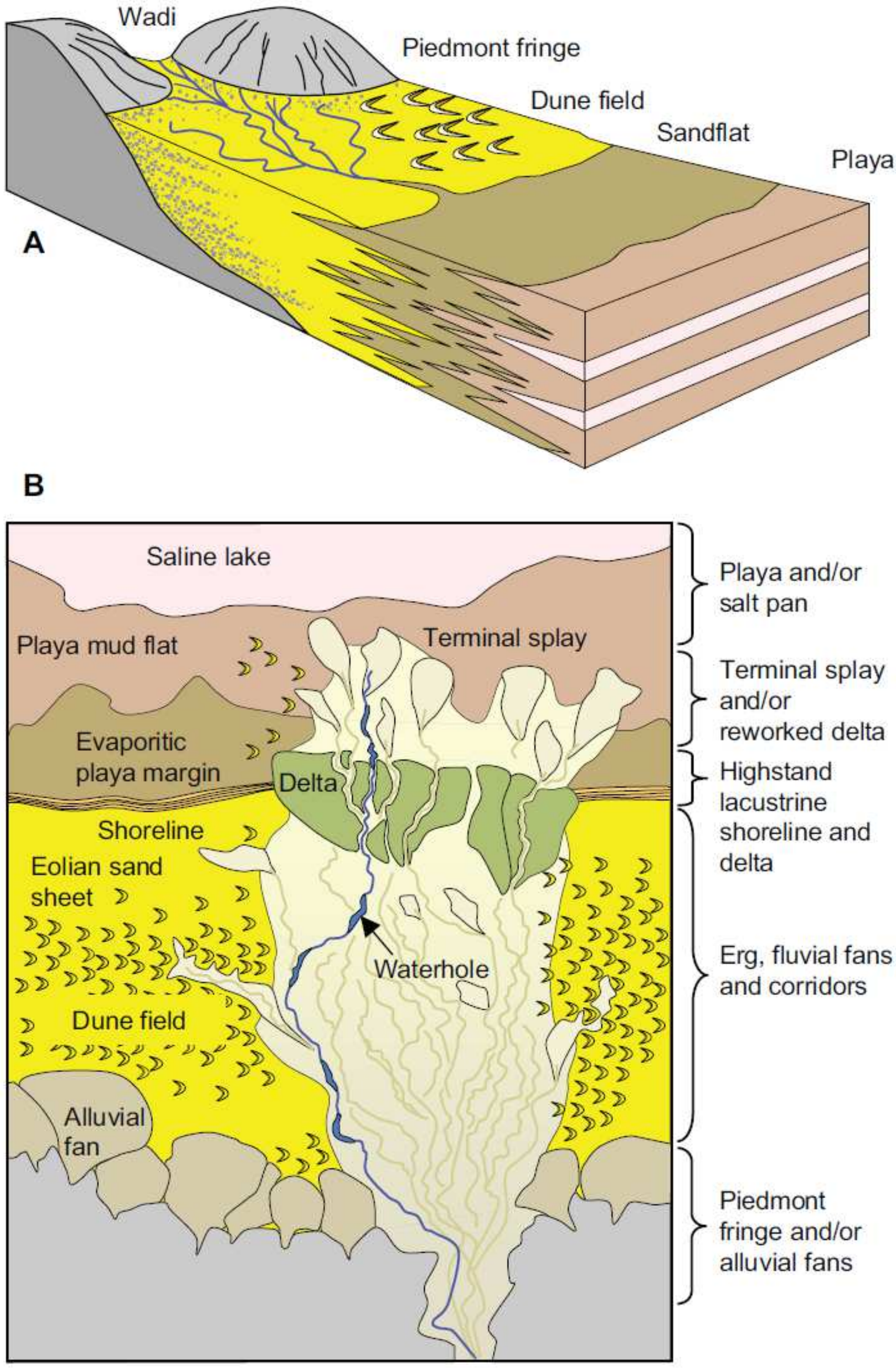


Figure 5.5: Conceptual depositional models for the fluvially dominated Slochteren Formation in the Netherlands. A) Block diagram (based on Geluk, 2007) illustrating the main facies associations and their interpreted lateral relationships. B) More detailed conceptual fluvial model, modified after Moscariello (2005) with the inclusion of stranded highstand lacustrine shoreline and deltaic facies dissected by lowstand fluvial and terminal splay complexes. From McKie (2011)

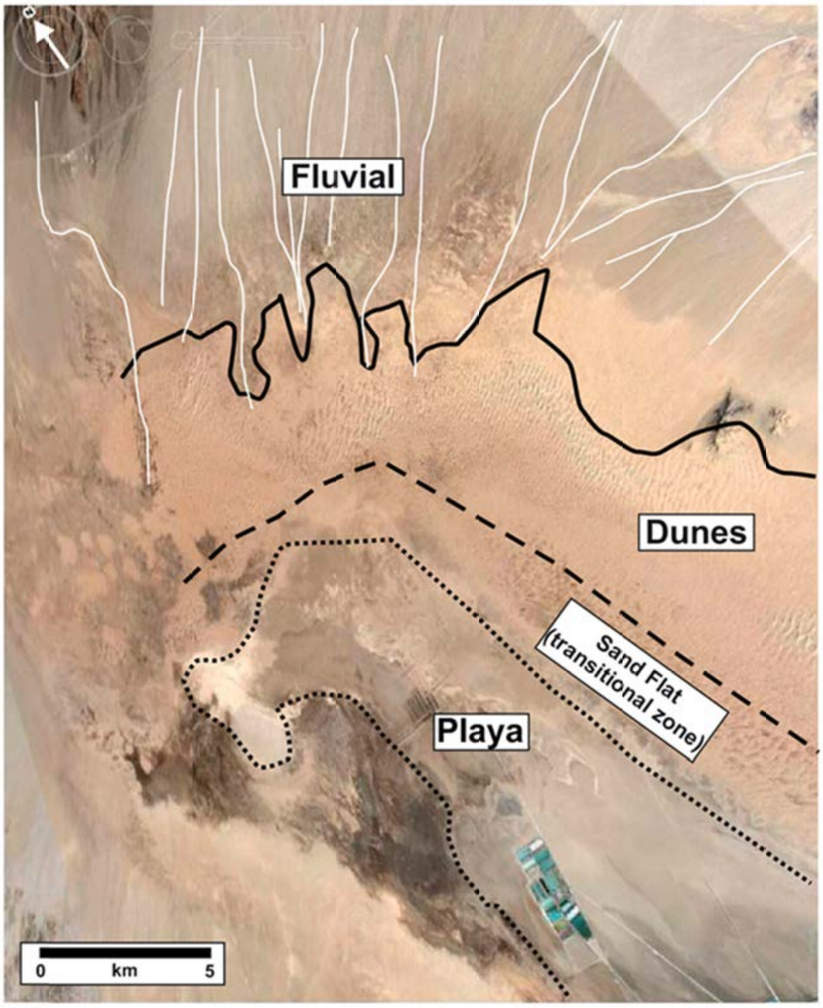


Figure 5.6: Aerial photography of the Cadiz Dry Lake, California, modified from Fryberger et al. (2011)

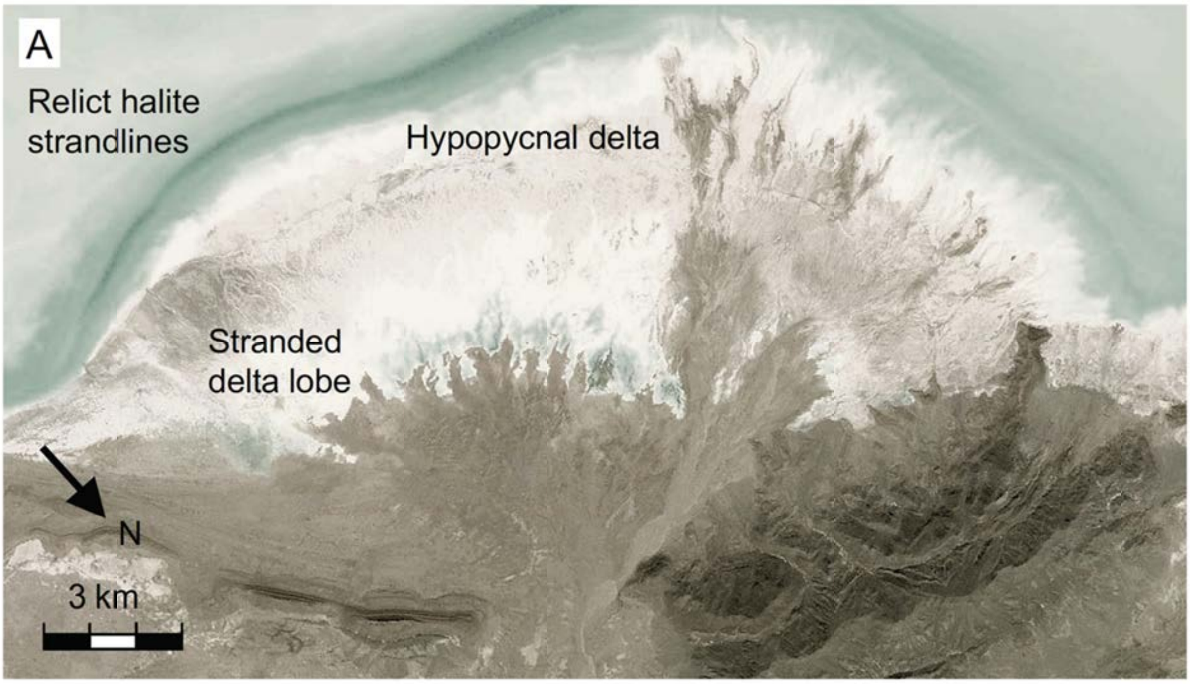


Figure 5.7: Marginal fluvial input into the Salar de Uyuni in Bolivia. From McKie (2011)

5.2.2.1 Upper Rotliegend palaeogeography and palaeotopography

The palaeogeography of the Upper Rotliegend in the study area can be summarized as a large saline lake with a low net-to-gross axis and high net-to-gross margin that transition northward to eolian, fluvial and alluvial fan settings. This lake formed over a complex topography and locally active faulting occurred during deposition.

Maynard & Gibson (2001) show that 1) onlap and pinch-out onto the pre-Upper Rotliegend topographies, and 2) coarser-grained lithofacies were deposited in topographic lows. They concluded that the principal controls on Rotliegend deposition were topography and climate: topography controlling the location of erg and local facies development and climate controlling the first-order effect of aridity and the second-order effect of groundwater and lake-water levels. The results obtain in the present study fully support Maynard & Gibson (2001) conclusions and add significant details in terms of the position and geometry of the palaeotopographic features affecting the distribution and stacking pattern of the Upper Rotliegend in the Dutch Northern Offshore area.

The palaeogeographic evolution of this lake can be summarized in three stages, an initiation (birth), an expansion (growth) and a contraction (death) of the Silver Pit Lake.

5.2.2.1.1 Basin birth: Initiation of the Silver Pit Lake (RO1)

The Silver Pit Lake started as an E/W elongated basin (Figure 5.8), 50 to 60 km wide with sandy coastlines to the north and south (marked respectively by the [2] and [1] in Figure 5.8). The southern sediment source (Figure 5.8) is related to the Lower Slochteren depositional system and will not be discussed in detail in this report due to the amount of detailed work previously done on the subject. The northern sandy margin was narrower than the southern margin likely due to a steeper northern basin margin, similar to what is shown in Figure 5.9. This good analogous conceptual model for the Silver Pit lake palaeogeography was published by Evan (1989), and shows an asymmetric lacustrine basin with a narrow margin to the right and a wide margin to the left. This configuration is likely similar to the Silver Pit Lake in the western side of the Southern Permian Basin during the Upper Rotliegend time. However, some specific results differ from the simple model of Evans (1989). The northern margin of the lake during RO1 period is complex and irregular and is locally fault-bounded. A topographic high was present along the northern margin of the lake in the south-western part of the study area. This high separated two depo-centres, one the UK sector and one in the Dutch sector.

The exact geometry of the northern coastline is difficult to establish in this central part of the study area due to limited well and seismic control. However, the sandy northern margin of the lake should be present in this area but have not been drilled yet.

The northern part of the study area was sub aerially exposed and likely provided sediment southward through the erosion of Lower Rotliegend and Carboniferous strata in the A and B blocks and farther north.

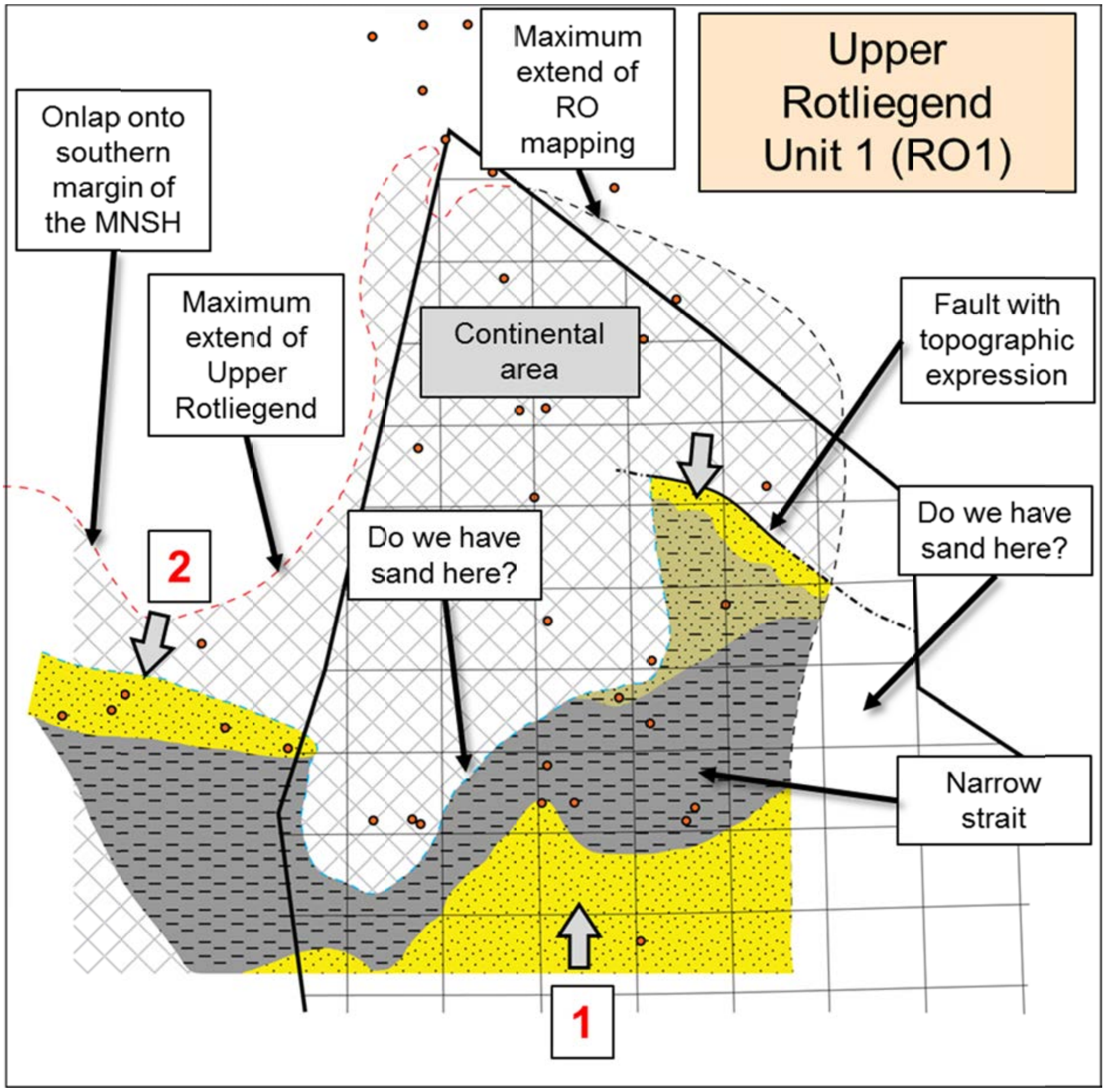


Figure 5.8: Depositional maps of the preserved RO1. The lake started as an E/W elongated, 50 to 60km wide (narrow strait) basin with sandy coastlines to the north [2] and south [1]. See appendix 7.05 for a high detailed version including wells-logs. MNSH = Mid North Sea High.

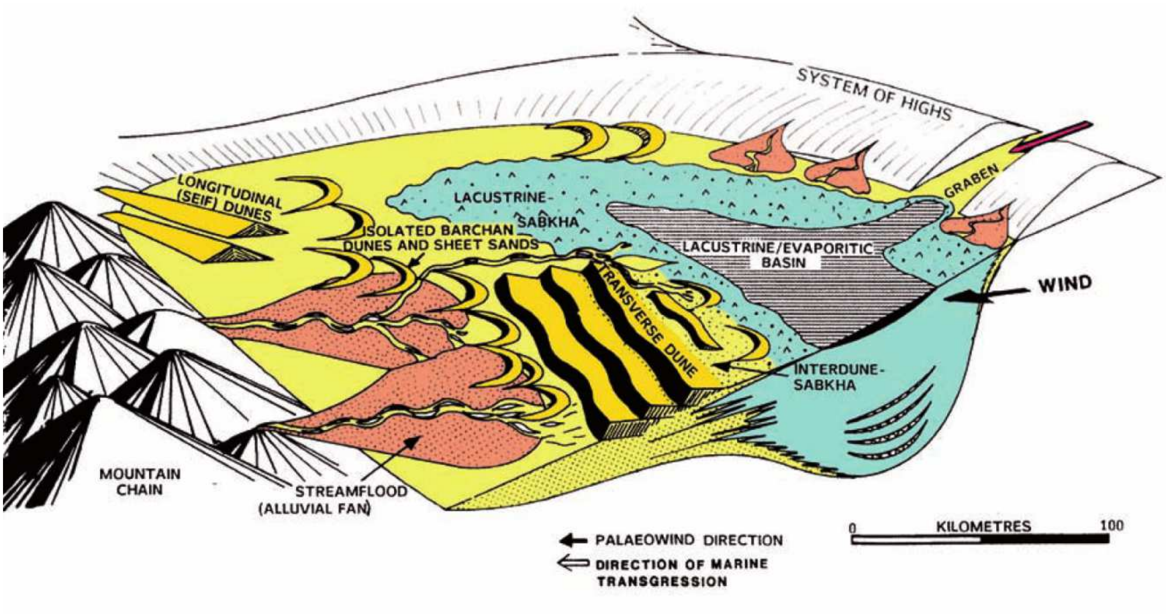


Figure 5.9: Conceptual diagram of a saline basin. From Veeken and van Moerkerken (2013), modified after Evans (1989). Note the asymmetric nature which is caused by a high on the right side, resulting in a narrow margin to the right and a wide margin to the left.

5.2.2.1.2 Basin Growth: The expansion of the Silver Pit Lake (RO2-4)

The three following stratigraphic units of the Upper Rotliegend (RO2-4) show a northward displacement (around 60km) of the northern sandy basin margin. The northern basin margin displacement through time records the growth and widening of Silver Pit Lake and the lacustrine transgression over the northern continental area (Block A and B). The northward migration of the basin margin can be observed also in the stratigraphic correlation panels (e.g. Figure 5.13, where the low angle onlap of successive sandy deposits can be observed. The western part of the northern basin margin migrated faster than the eastern part due to the presence of a major bounding fault oriented NW/SE (Fault 1, Figure 5.13). This fault created had a significant topographic expression that impeded the northward migration of the coastline at this location. This can be observed by the change of map view geometry of the sand-rich basin margin between RO2 (Figure 5.10) and RO3 (Figure 5.12). A thicker sedimentary succession (mainly reservoir facies) has accumulated on the down thrown side of this syn-sedimentary fault (Figure 5.18). The limited map-view extent of the northern basin margin area during RO4 time (Figure 5.15) is likely due to later uplift in the UK, German and Danish sectors (e.g. erosion at the base of Chalk).

The growth of the Silver Pit Lake during RO2-4 period can also be observed by the increased aerial extent of the halite units during this period (Figure 5.10, Figure 5.12 and Figure 5.15). The halite-rich zone extent during RO4 (Figure 5.15) is the maximum extent the halite unit reaches during the existence of the Silver Pit Lake. This illustrates the expansion of the basin axis westward toward the UK sector.

However, the topographic high (southern extent of the Mid-North Sea High) separating the Dutch and UK sector remained a topographic high until the end of RO4 (Figure 4.40, Figure 5.14) and could be related to differential subsidence rather than active syn-depositional activity at this location.

The sediment transport direction for the northern basin margin deposits during this period is believed to be from the north to the south, but a strong aeolian component is also likely contributing to sediment accumulation along the lake margin. An easterly to north-easterly wind direction is frequently proposed for this period (George & Berry, 1997).

The exact relationship between the northern basin margin deposits and the topography along the Elbow Spit High has not been clearly resolved in this study. On most of the palaeogeographic maps in this report, the Elbow Spit High shows as an empty area (e.g. Figure 5.12). It was either always a topographic high with no Rotliegend strata on the crest of the Elbow Spit High, or it was originally draped by Rotliegend strata and later eroded. However, the seismic interpretation around the Elbow Spit High seems to suggest onlap onto the Elbow Spit High and later erosion of Rotliegend strata on the eastern flank of the structure that may suggest a draping followed by erosion. Future work needs to be carried out to clearly conclude on this matter.

Some irregular coastline trend of the Silver Pit Lake can be observed and may have some significance in the detailed geometry of the reservoir rocks in this area. Note the trend of the pink line in Figure 5.10, that represent the farthest extent of a single halite unit for RO2 interval, shows a convoluted geometry. This convoluted geometry can be representing a real embayment at the time of deposition, similar to the geometry of the saline lake Etosha Pan in Namibia (Figure 5.11). If this analogy is true, such information can be used to track the position of fluvial systems and spits along the margin of the Silver Pit Lake.

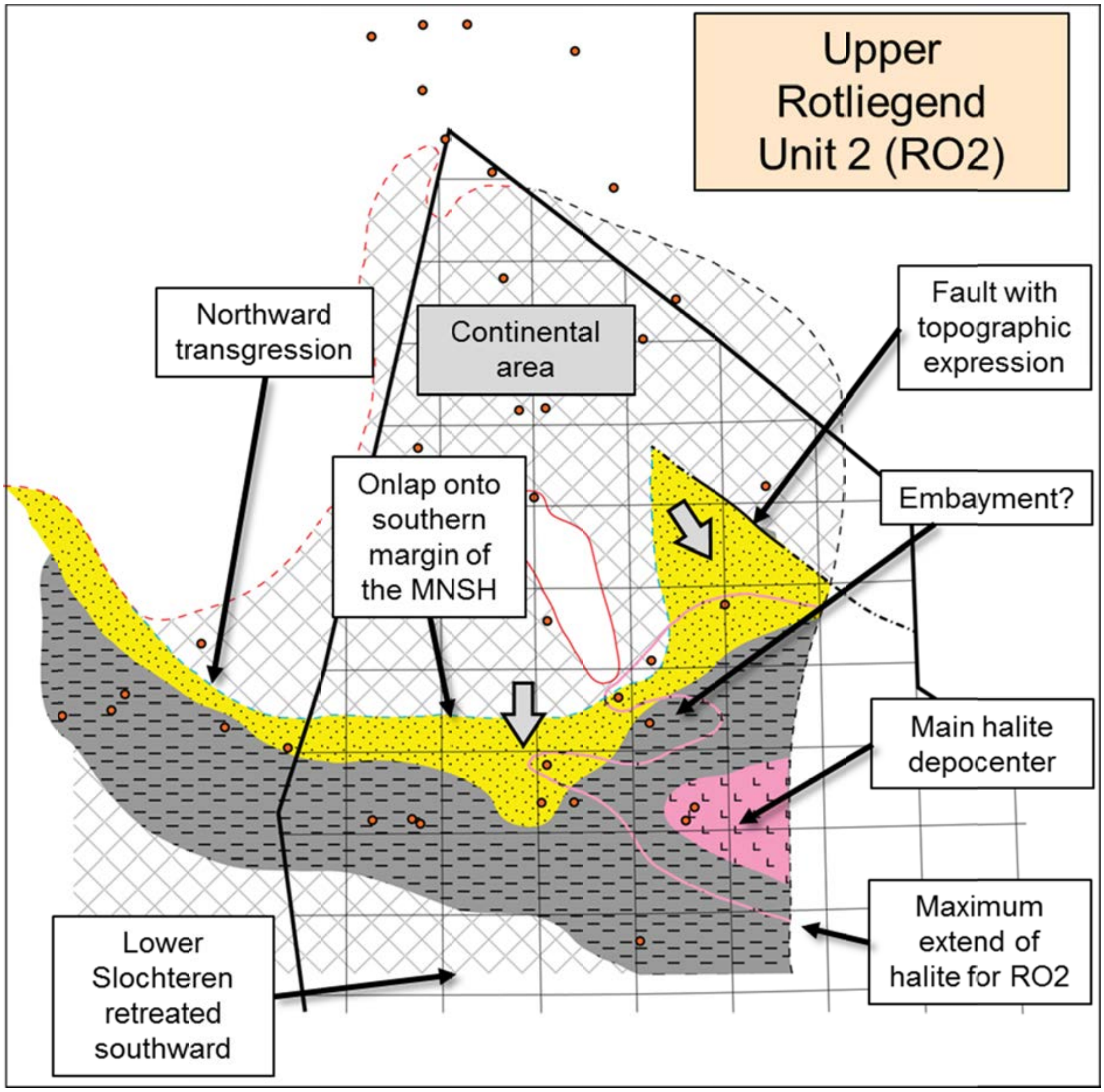


Figure 5.10:Depositional maps of the preserved RO2. See appendix 7.06 for a high detailed version including wells-logs

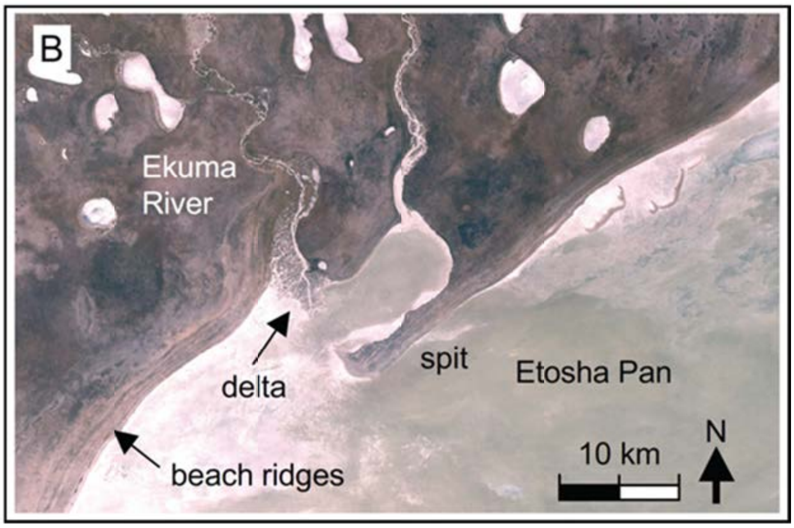


Figure 5.11:Aerial photo of the Oshigambo and Ekuma Rivers, Namibia. From McKie, 2011.

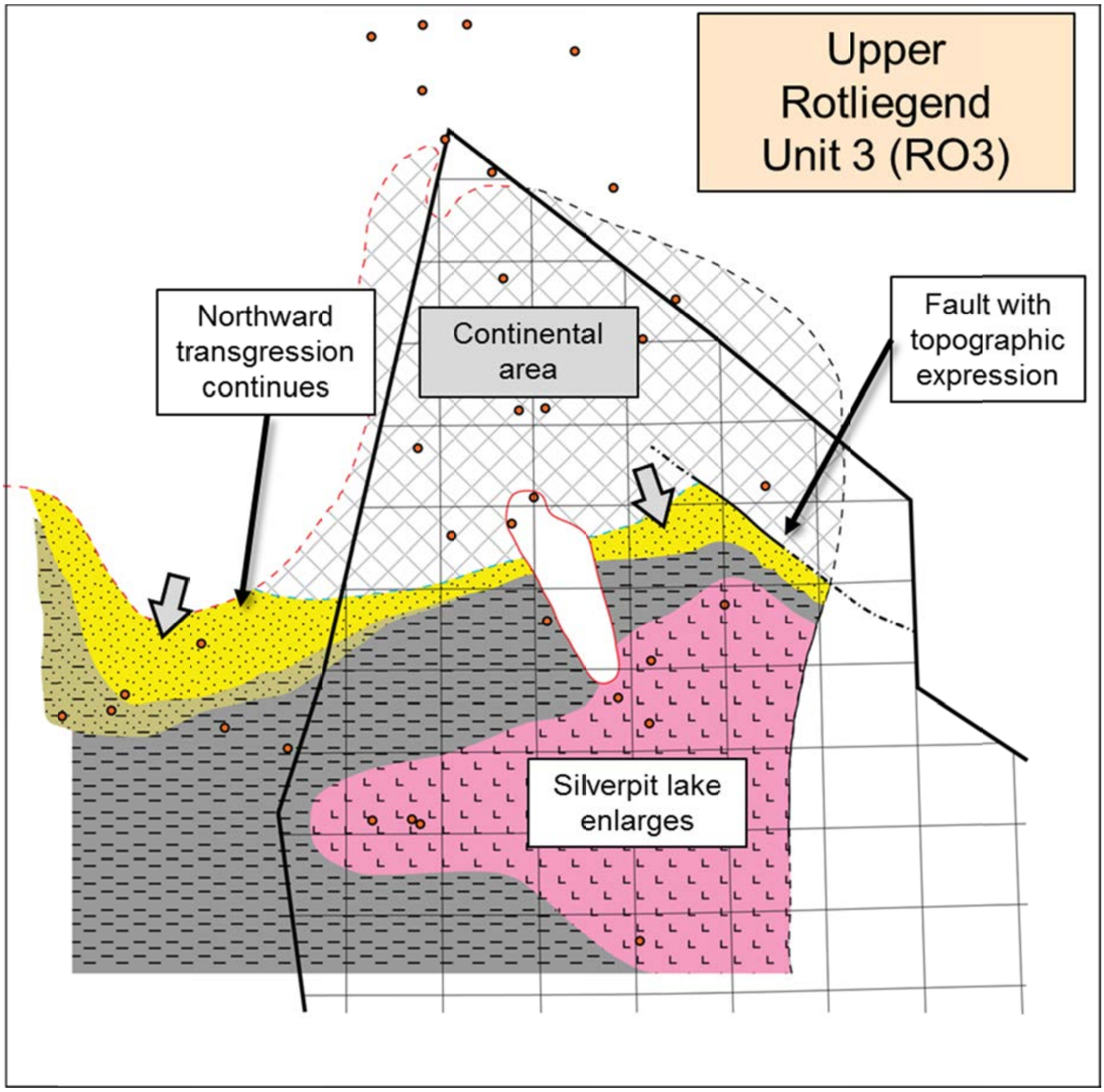


Figure 5.12:Depositional maps of the preserved RO3. See appendix 7.07 for a high detailed version including wells-logs

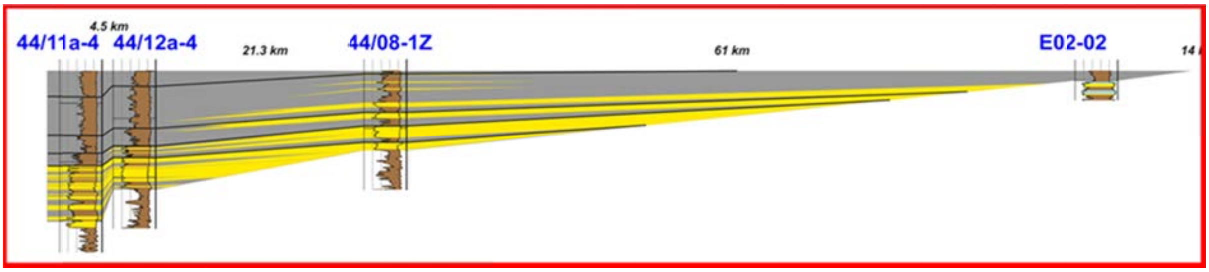


Figure 5.13:WSE-ENE oriented stratigraphic correlation panel illustrating the stratigraphy of the Upper Rotliegend along the northern basin margin.

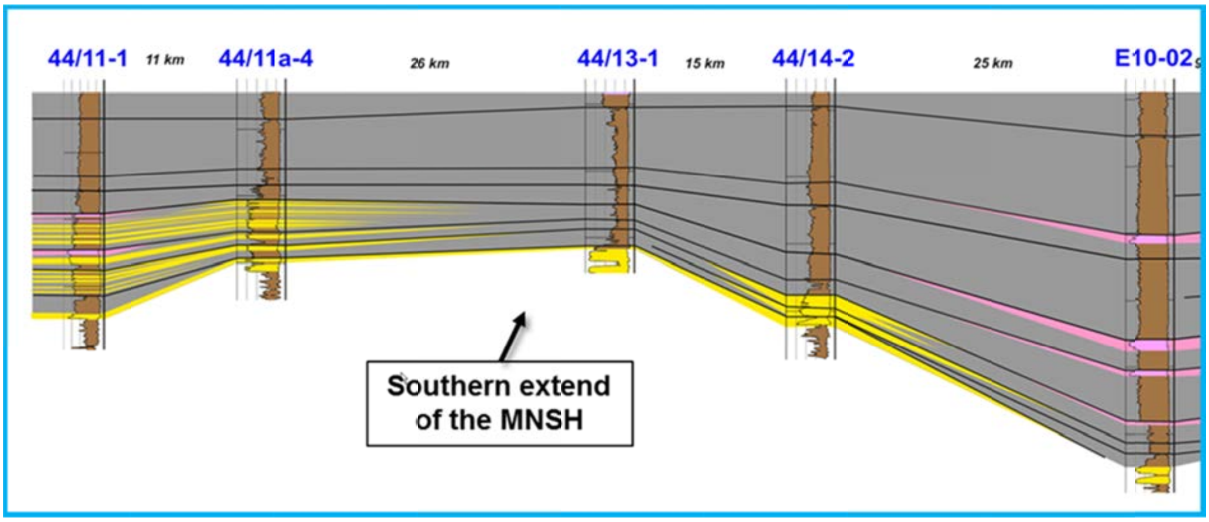


Figure 5.14:E-W oriented stratigraphic correlation panel illustrating the stratigraphy of the Upper Rotliegend around the southern tip of the Mid North Sea High (MNSH) and separating the Dutch and UK sectors.

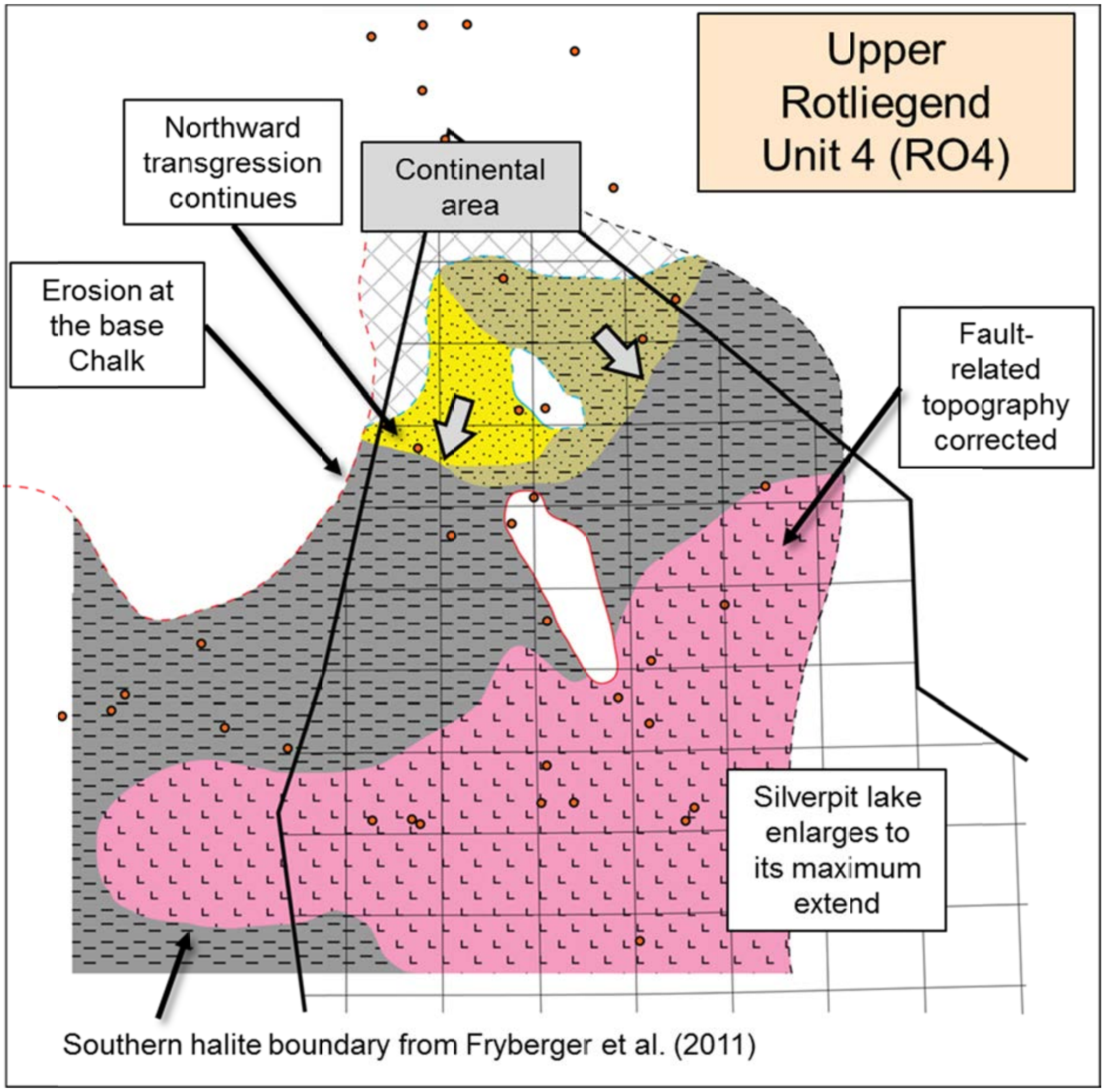


Figure 5.15:Depositional maps of the preserved RO4. See appendix 7.08 for a high detailed version including wells-logs

5.2.2.1.3 Basin death: The contraction of the Silver Pit Lake (RO5)

During this period the Silver Pit Lake shows very different stratigraphic trend than during all the previous period. The map-view extent of the halite-rich basin axis strata is reduced to a small zone in the south eastern part of the study area (Figure 5.16). This reflects the contraction of the saline lake during this period. The northern sandy fringe is interpreted to have a south eastern sediment transport direction during this period. A south eastward migration of the sandy depositional system is also interpreted that represents the first progradational trend observed in the study area during Upper Rotliegend time. The geometry of the northern margin is also very different from previous period (RO1-4) with a high net-to-gross zone topographically (or structurally) confined in a NW SE oriented low (Figure 4.44, Figure 4.46). The north-eastern and south-western limits of this low are likely faulted, but seismic interpretation has not been able to clearly demonstrate this interpretation. Further detailed seismic analysis (of high resolution data) and mapping may be able to shed some light on such a model. The presence of conglomerates in well 39/11-1 in the UK sector has been interpreted as indicative of coarse fluvial deposits in the north-western part of the study area during RO5 time. This fluvial system may have also been structurally confined but its significance in terms of a major sediment input in this part of the basin is still unclear.

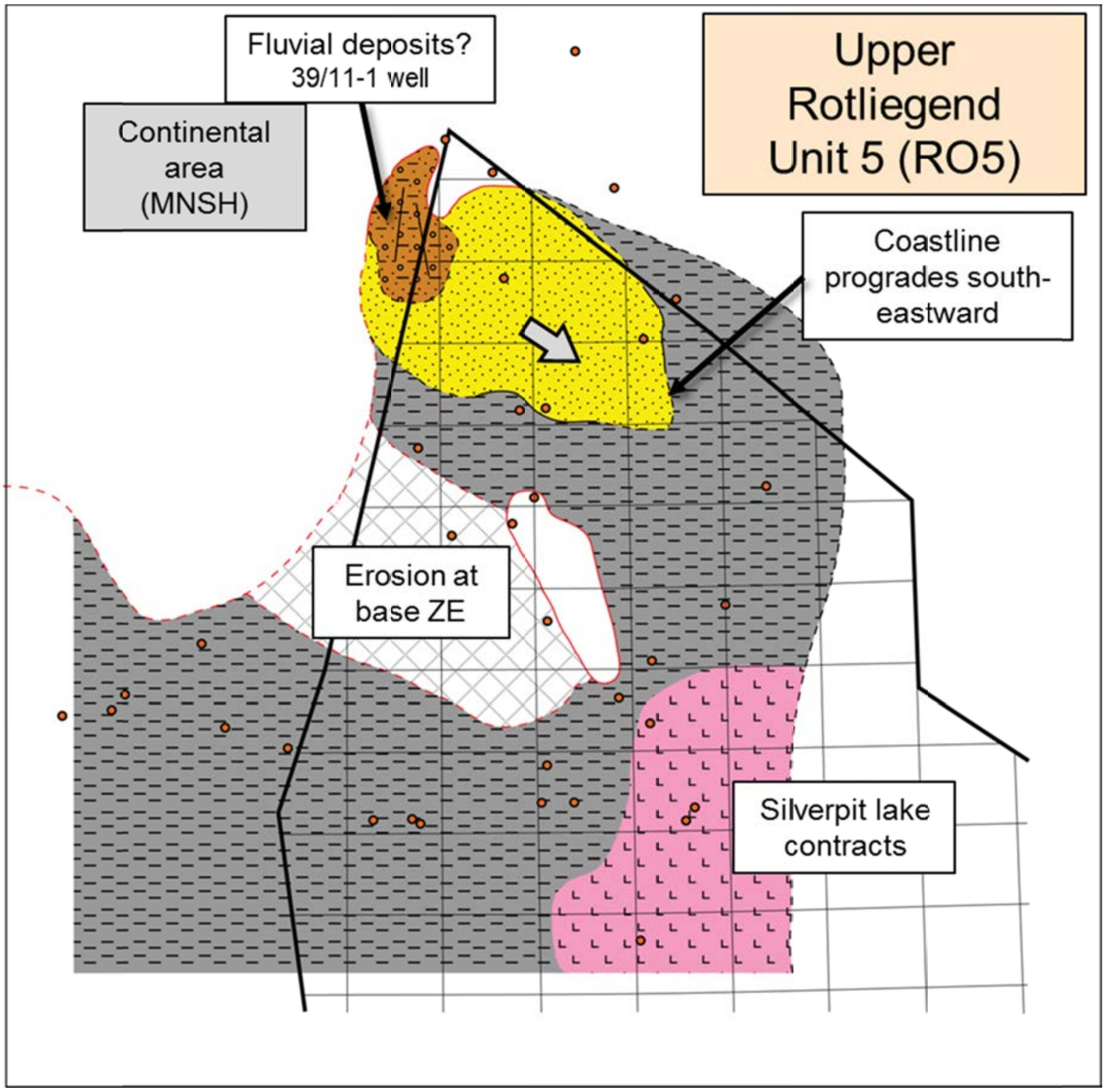


Figure 5.16:Depositional maps of the preserved RO5. See appendix 7.09 for a high detailed version including wells-logs

5.2.2.2 Syn-depositional fault activity during the Upper Rotliegend time.

Several authors have demonstrated that syn-depositional fault activity occurred during deposition of the Rotliegend. Most published results highlight a predominantly NW-SE trend in the orientation of those syn-depositional structures. Below are some of the main publications on this subject:

- George & Berry (1993, 1997): Dowsing Fault Zone and the Texel-IJsselmeer High with alluvial-fan and fan-delta development.
- Chadwick & Evans (1995): NW-SE in southern Britain.
- Glennie (1998): Dextral strike slip, development of a number of sub-basins, Sole Pit, Silver Pit and Broad Fourteens Basins, NW and WNW trending fault systems.
- Jan de Jager (2007): “It is likely that the major faults delineating the Terschelling Basin (Hantum and Rifgronden fault zones) were already in existence in Early Permian times.”

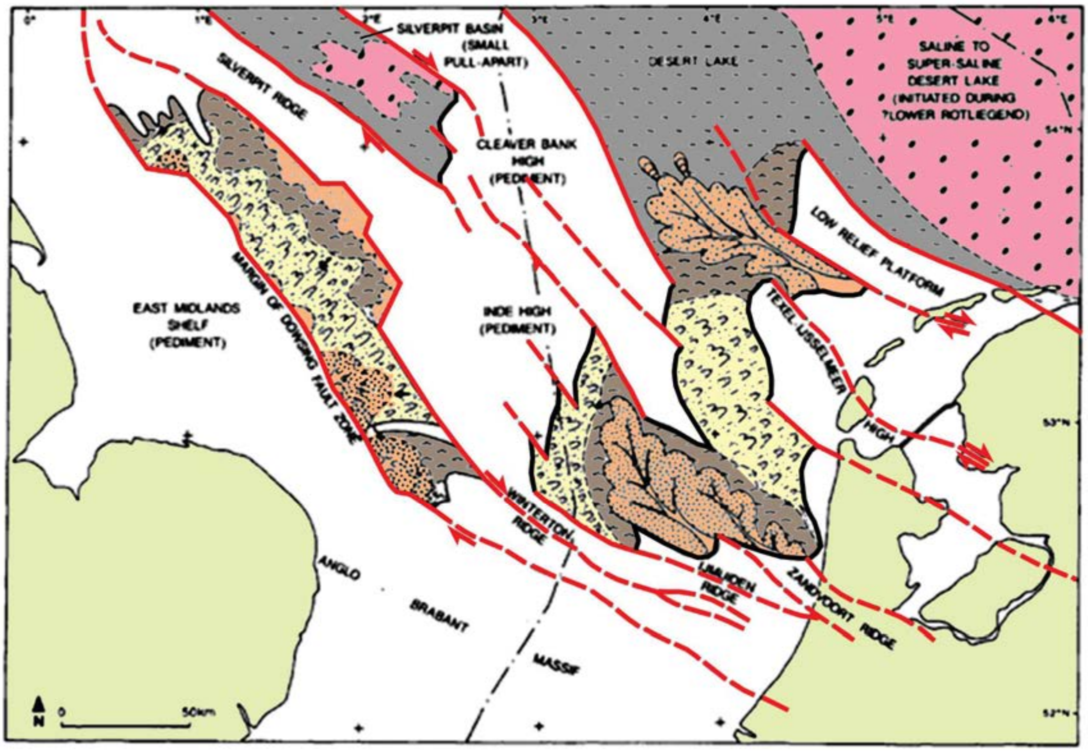


Figure 5.17:Rotliegend tectono-stratigraphic map, Modified after George and Berry (1997)

In the present study new results on syn-depositional activity in the Dutch Northern Offshore are presented. These structures are often challenging to identify on seismic and may often be overlooked during regional seismic interpretations. A few major and minor faults have been analysed with a certain level of detailed in the present study, but many more faults may be of significance but were not included in this project because of the project scope. Additional mapping and fault analysis could however increase our understanding on the detailed relationship between active faulting and reservoir presence, distribution and geometry.

A Base Zechstein / Top Rotliegend time structure map was constructed using all the available 3D data within the study area (Figure 5.19). This map was very useful to identify faults that intercept the Base Zechstein and to locate faults that may have been active during Rotliegend time.

A major fault (Fault 1) was identified in the eastern part of the study area (Fault 1, Figure 5.18). This fault offset the Lower Rotliegend and part of the Upper Rotliegend and is a major topographic boundary affecting the depositional of the Rotliegend in this part of the Dutch Offshore. This fault was the only one that has been studied in greater detail in the present study but other faults in the study area may also be on significance and should require some analysis in future research. Fault 1 likely resulted in the accumulation of coarser strata in the downthrown side of the fault.

Additional seismic analysis demonstrated that this fault is actually a complex fault zone that presents a flower structure geometry symptomatic of strike slip motion (Figure 5.20 and Figure 5.21). Note the over thicken Upper Rotliegend interval in the downthrown side of the fault (Figure 5.20). On the flattened version of the same seismic line (Figure 5.21) the Upper Rotliegend seems to onlap onto a palaeotopographic high, which is interpreted as the degraded footwall block adjacent to the fault plane, and the subsequent resulting slope located above the fault zone. Similar geometry is shown in Figure 5.22 and can be used as an analogue for Upper Rotliegend stratal geometry around these degraded syn-depositional strike slip structures. This result indicates that syn-depositional strike slip structures with topographic expressions were active during Rotliegend deposition. These structures could have locally offsetting particular deposits laterally and may have generated local pop ups structures and/or pull apart minibasins (depending on the geometry of the linked fault segments).

Another aspect to consider while dealing with strike slip faults is that they are often extensive in map view and can be traced for many tens of kilometres. Therefore, structures aligned with such faults may be related or affected by the strike slip motion and be important feature for additional analysis of the Rotliegend in the study area (e.g. NW-SE trending structure in the Dutch Central Graben and Step Graben that are aligned with Fault 1, Figure 5.23). Several faults have been interpreted as potential syn-depositional structure active during Rotliegend time (red faults in Figure 5.24) with some of them displaying echelon type configuration in map view (Figure 5.25) symptomatic of dextral strike slip features. Note that all faults represented in George and Berry (1997) maps are also strike slip structures and have a dextral component (Figure 5.17).

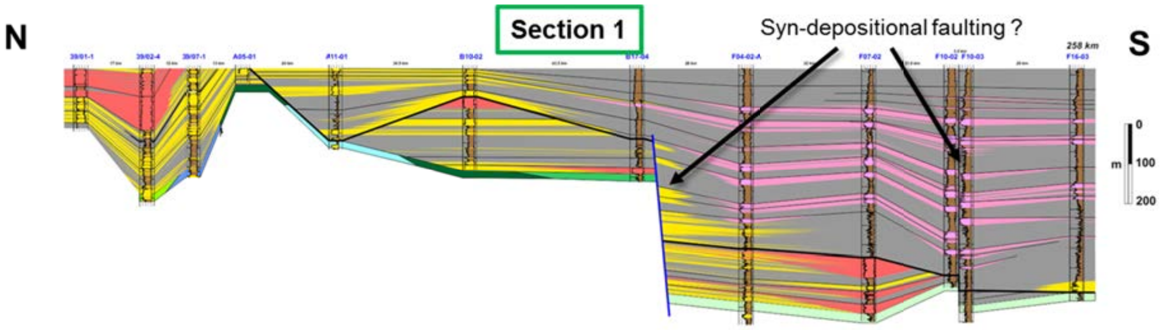


Figure 5.18:N-S stratigraphic correlation panel. Note the two faults highlighted with arrows.

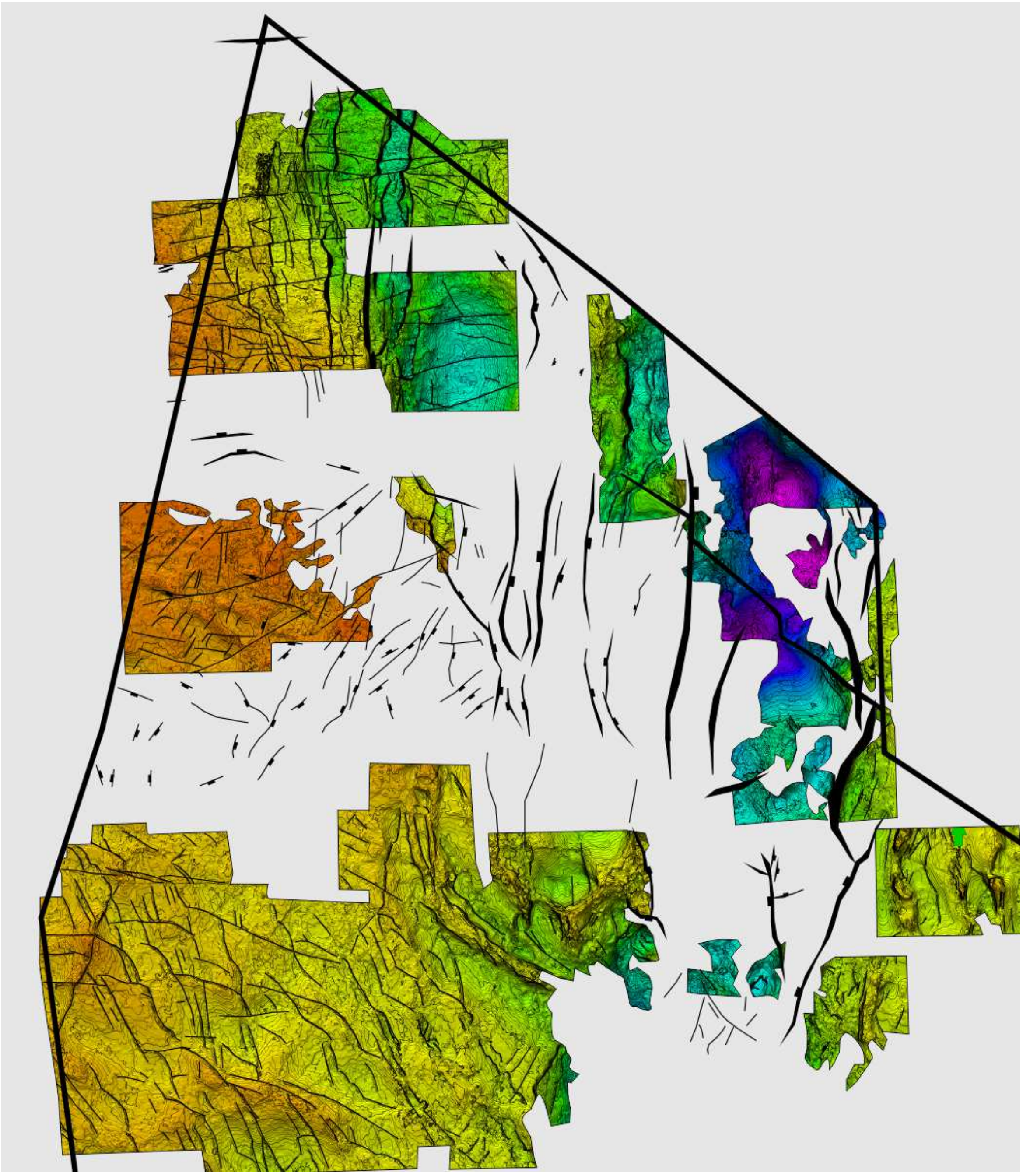


Figure 5.19:Base Zechstein time structure map constructed by auto tracking using all 2D and 3D seismic data from the Northern Offshore Petrel Project.

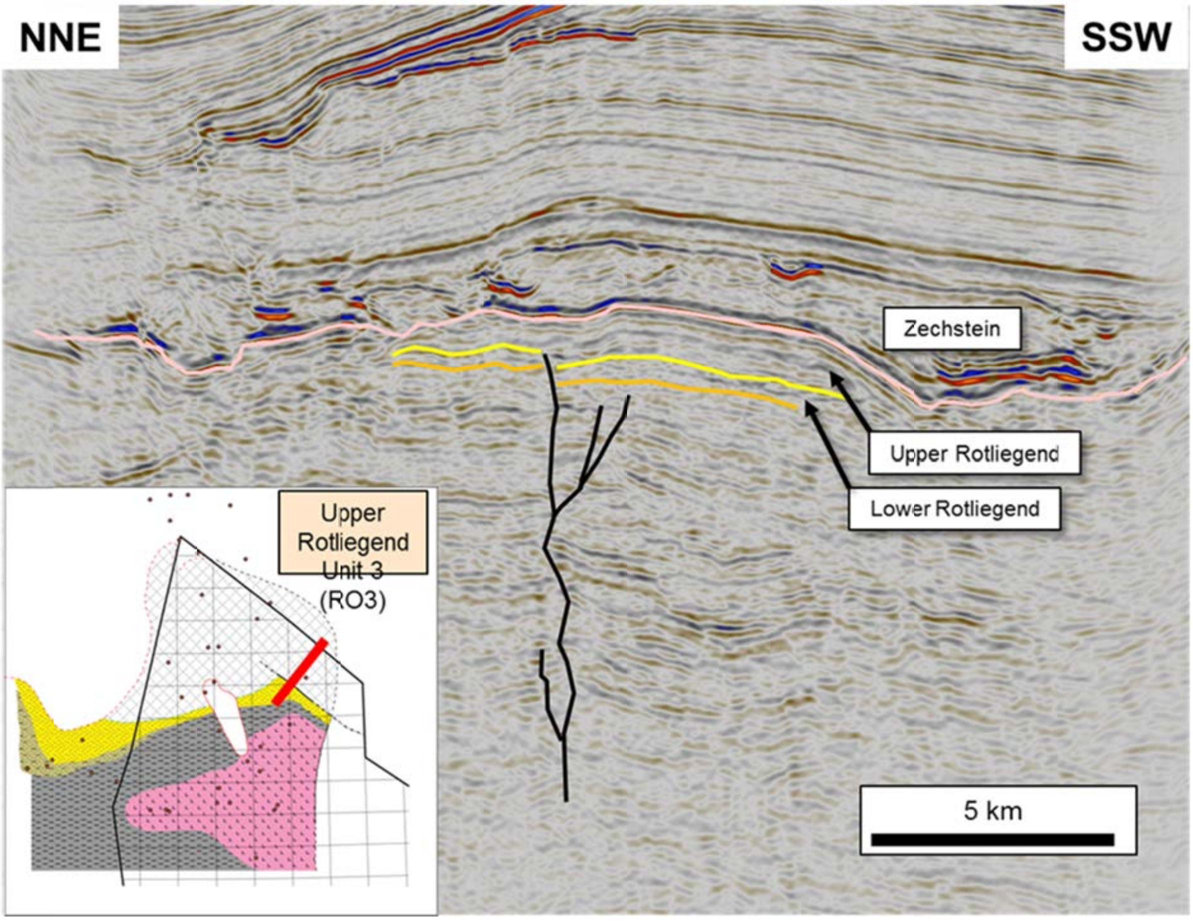


Figure 5.20:NE-SW oriented seismic line illustrating Fault 1 geometry. Random line within the B Block seismic cube. Note the over thicken Upper Rotliegend in the downthrown side of the fault.

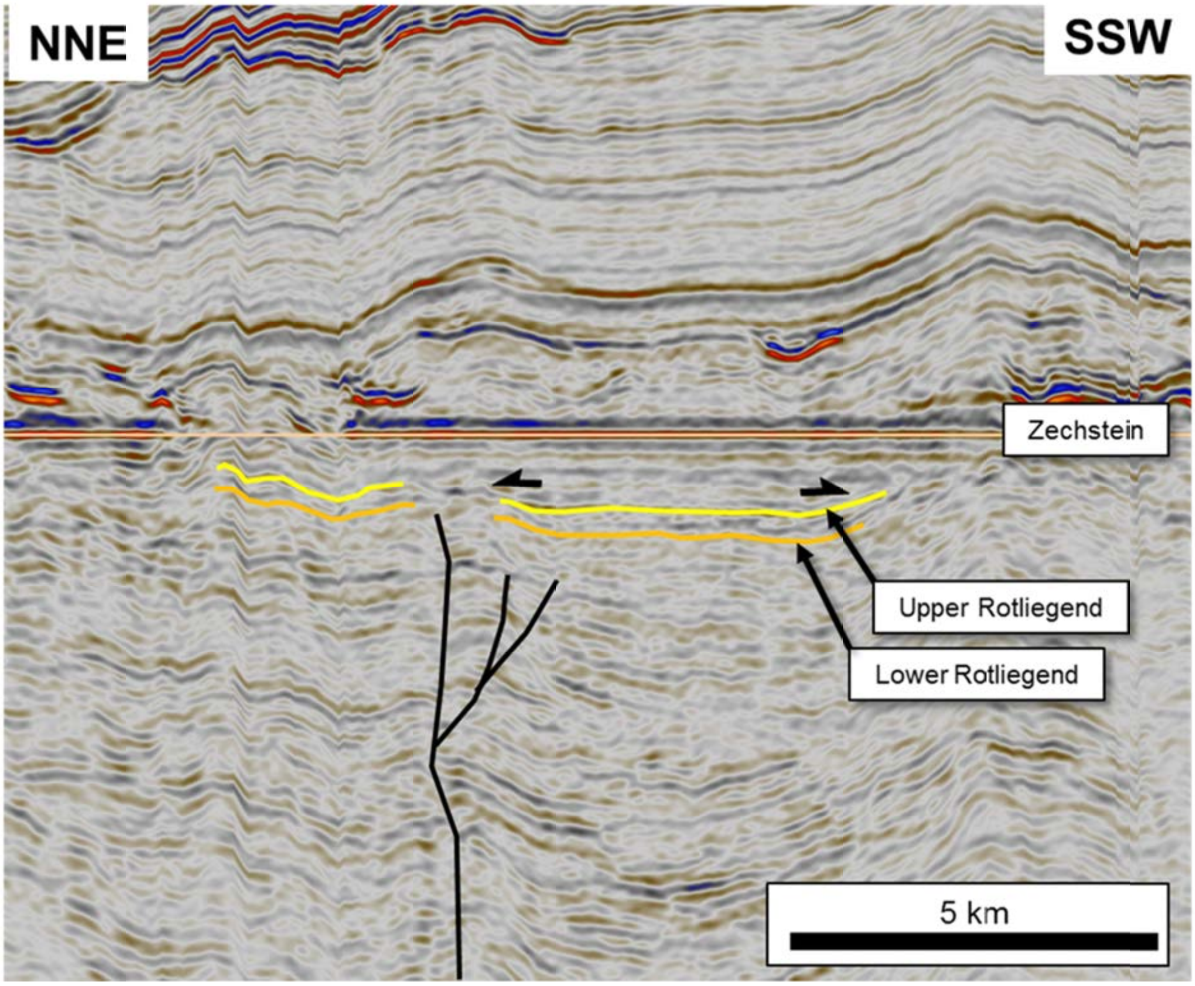
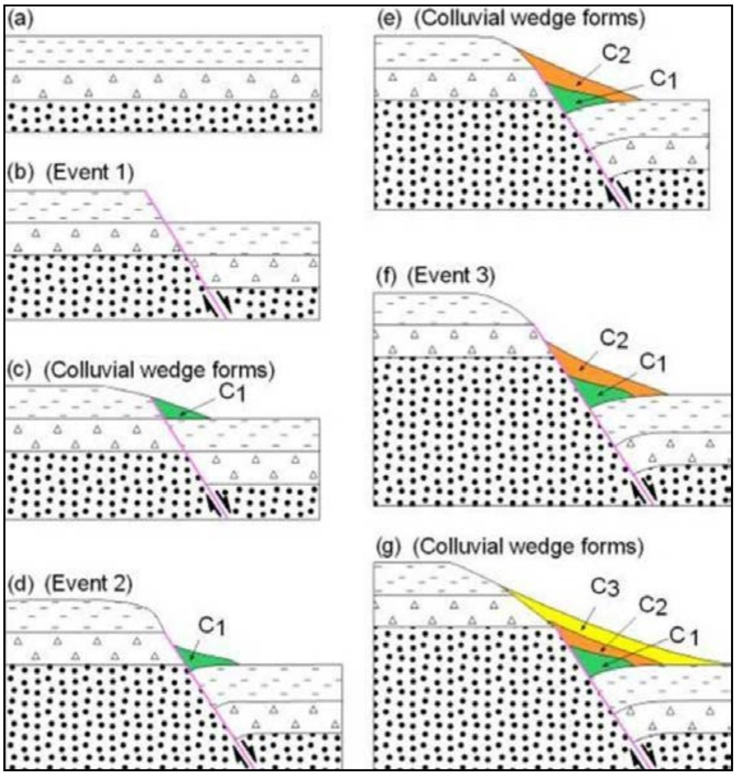


Figure 5.21: Flatten NE-SW oriented seismic line illustrating Fault 1 geometry. This is the same line shown in Figure 5.20 Random line within the B Block seismic cube. The base Lower Rotliegend is shown as an orange horizon while the base Upper Rotliegend is shown as a yellow horizon.



McCalpin, 1987

Figure 5.22:Example of successive footwall degradation of a fault scar at the surface. From McCalpin (1987)

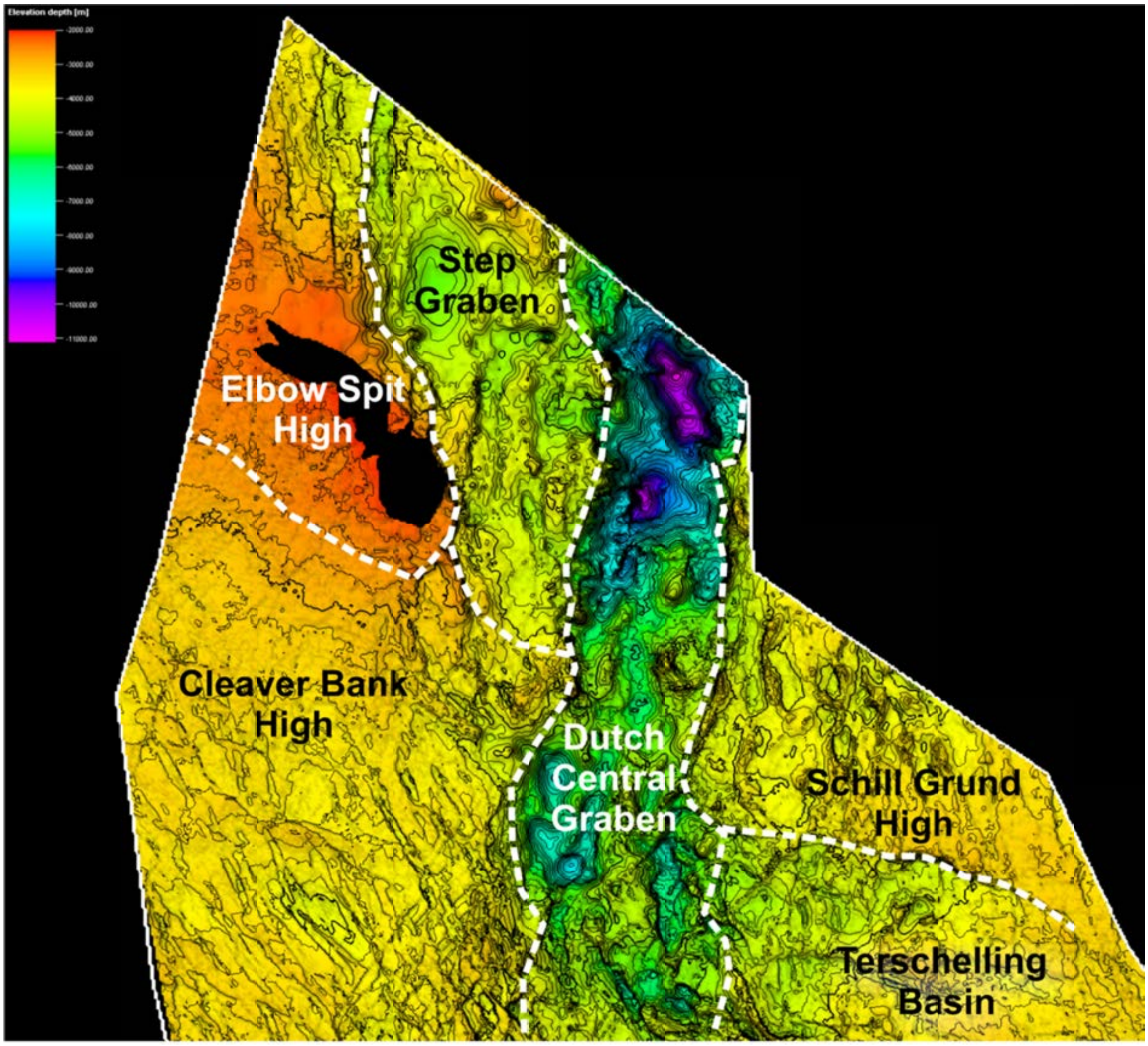


Figure 5.23:Base Zechstein time structure map. Map made by the TNO Geological Survey of the Netherlands.

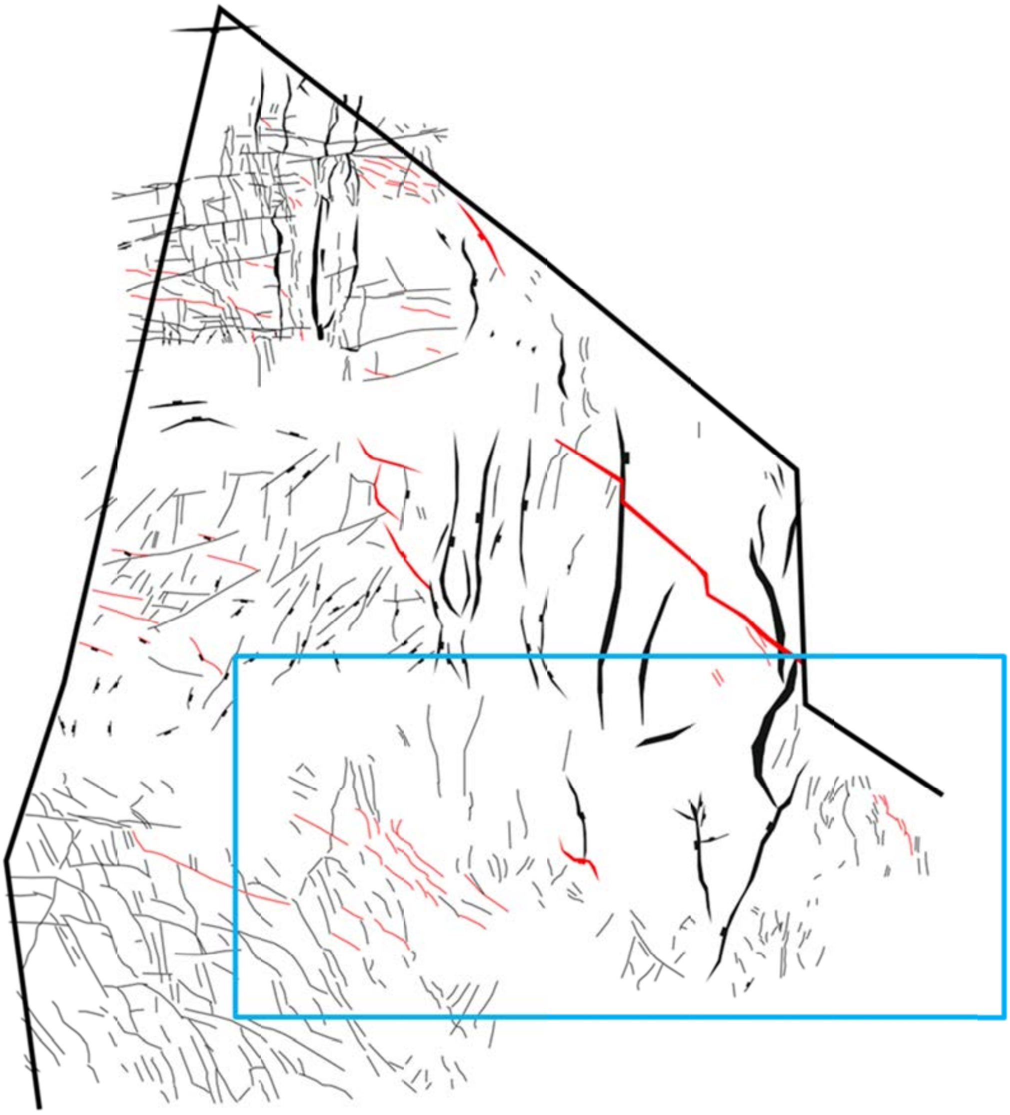


Figure 5.24:Base Zechstein fault map. Red-coloured faults are interpreted as being active during Rotliegend deposition. Blue box: Figure 5.26.

Figure 5.25:Base Zechstein fault map of the central and eastern part of the study area (see Figure 5.24 for location). Red faults are faults interpreted as being active during Rotliegend deposition.

Smaller syn-depositional faults have also been locally observed in the study area such as the faults seen in Figure 5.26. These faults have a SSW vergence, are listric in shape and detach on an intra-Carboniferous level (likely one of the low net-gross succession within the Westphalian A or B). The downward Increased of fault throws (Figure 5.26) from 3 to 45m are indicative of fault growth during deposition and of the syn-depositional nature of these structures.

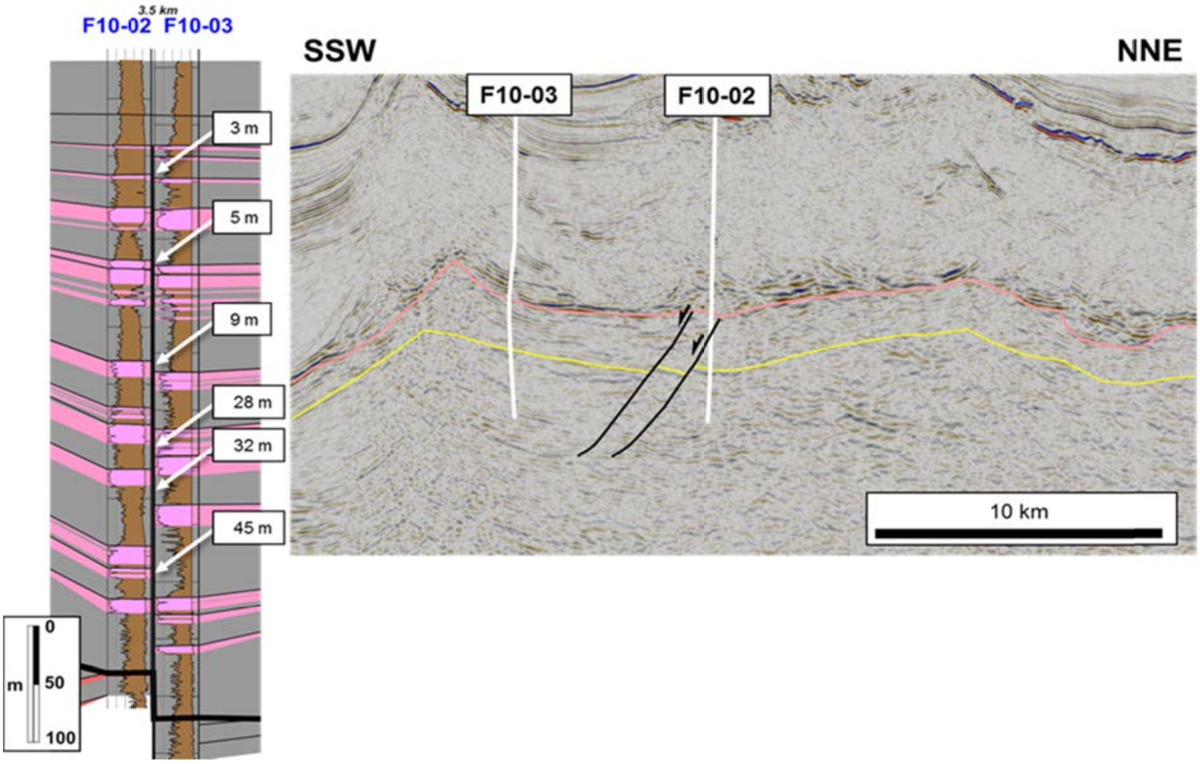


Figure 5.26:The fault system between wells F10-02 and F10-3

5.3 Source Rock Maturity

5.3.1 Scremerston Formation.

The modelled wells are located on the north-eastern flank of the Elbow Spit High. According to the models, potential Dinantian source rocks (such as the Scremerston Formation), are generally in the hydrocarbon generating window (Figure 4.61 to Figure 4.68). In the southern flank of the Elbow Spit High, the Dinantian appears to be immature (well E02-02). To the north of the Elbow Spit High, hydrocarbon generation and expulsion have taken place in the Tertiary (Palaeogene) and continued to present-day. The presence of the Dinantian source rocks is the main uncertainty since it has not been encountered in wells in the Netherlands. The models show that if the formations are thermally in the mature window the area appears to have potential in terms of timing of generation and maturity.

5.3.2 Westphalian

Maturity models show that in the majority of the wells, Westphalian source rocks are in the hydrocarbon generating window (Figure 5.27). There has been active hydrocarbon generation and expulsion from Westphalian rocks in the Step Graben and the Dutch Central Graben. The Palaeogene and Neogene are important phases of hydrocarbon generation and expulsions from the Westphalian source rocks. In many wells, generation and expulsion continues to present-day. This late generation and expulsion could have led to charging of existing structural traps. The models also show that there have been generation of hydrocarbons from the Westphalian already in the Triassic and the Jurassic and in many locations continued in the Tertiary. The modelled transformation ratio at the location of the selected wells indicates that the Westphalian has not been depleted of transformable organic matter and thus it has the potential for generation.

5.3.3 Mature Source rock areas

Although the produced maturity map (Figure 4.71) of the Westphalian is based on a simplified approach and should be taken with caution, it does represent the variations of maturity at the top of the Westphalian. This maturity map, which is calibrated to modelled present-day maturities at the location of the modelled wells, shows that the Westphalian has higher maturity in the deeper parts of the Step Graben and therefore is capable of hydrocarbon generation (See Appendix 7.11).

The generation rates from the available or assumed source rocks in all the modelled wells are presented in (Figure 5.27). The figure demonstrate that two main phase of hydrocarbon generation can be observed in the area; the Early Triassic and the Tertiary. Some generation activities are also observed at some locations in the Middle and Late Jurassic. The amplitude of the generation peaks in all the wells are generally comparable and fall within the same range.

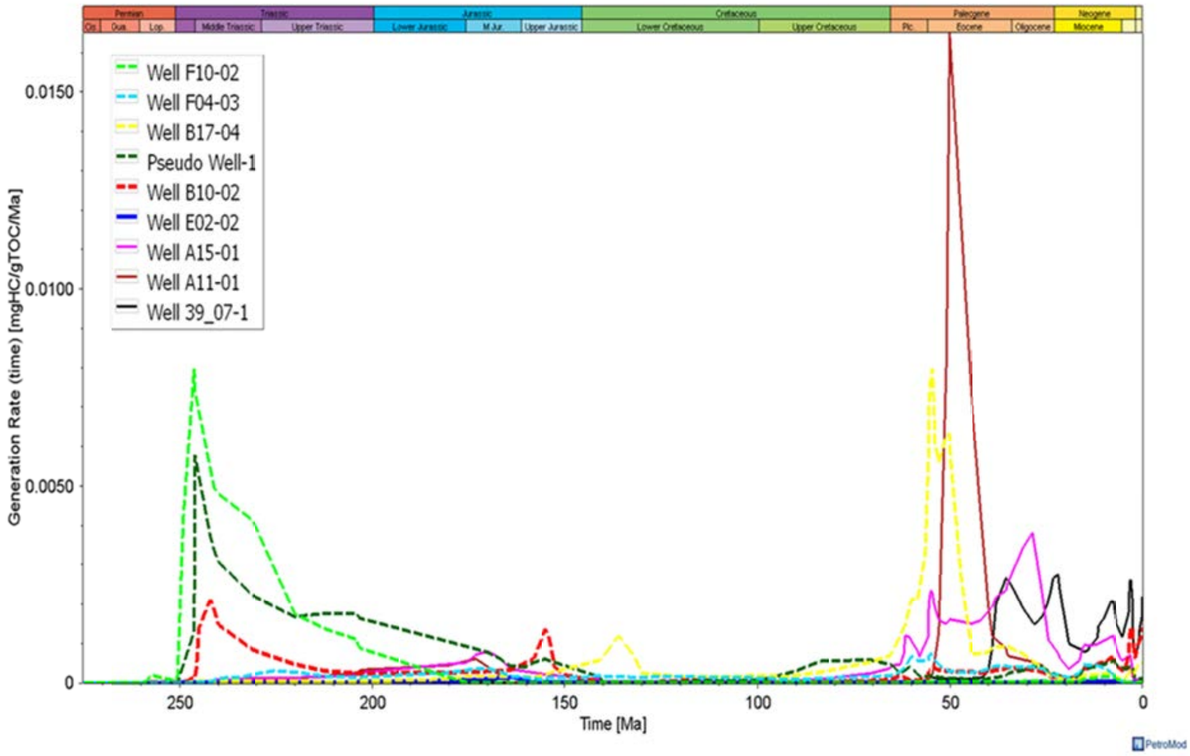


Figure 5.27:Modelled generation rate at the location of the modelled wells.

5.4 Rotliegend Reservoir Potential in the Dutch Northern Offshore

The presence of sandy reservoir strata of Rotliegend age in the Dutch Northern Offshore has been known for many years but the stratigraphic and tectonostratigraphic analysis carried out in the present study allowed to map in detail the distribution of sandy deposits along the northern Silver Pit Lake margin.

Figure 5.28 summarizes the distribution of each of the main sandy deposits identified in the Lower and Upper Rotliegend (RV1-3 and RO1-5) and shows the overlay of those sandy deposits in map-view. It is important to notice that many assumptions were used to build this map that should be taken with care when prospecting or planning exploration activity. This map is a qualitative representation of high net-to gross strata in the study area and is not a net sand map. Therefore the sandy area represented in Figure 5.28 may be aerially extensive and have a high percentage of reservoir facies, but be thin and present complex underestimated heterogeneities.

A net sand map, shown in Figure 5.29, was constructed from a simple interpolation between available well-data. It contains no geological trends and it is not steered by geological models. For example, the large NW-SE trending fault (Figure 5.8) was not incorporated in this map, resulting in an underestimation of sands in area III, Figure 5.28; Block F02). The total sand thickness is highest in the deepest part of the Step Graben (blocks A15 and B13), on the down thrown side of the NW-SE trending fault (Blocks F02, F04 and F05) and in the UK (Grensen Formation around well 39/07-1)

With these comments in mind, it is possible to extract important information from these summary maps. The most promising areas showing sand rich strata are located along NW-SE trends (areas II to IV, Figure 5.28). These area are likely locally structurally confined along topographic highs (e.g. area I along the south-western flank of the Elbow Spit High) and along syn-depositional faults (area III, Figure 5.28). Such regional scale stacking can be used as a guideline for additional research or investigation to analyse in detail the geometry of Upper Rotliegend. The presence of Zechstein salt above the interval of interest will unfortunately always constitute an imaging challenge in tracking such sandy Rotliegend reservoirs on seismic. Nevertheless, additional seismic interpretation and mapping could be performed and add valuable information in mapping such reservoir strata along topographic and structural trends.

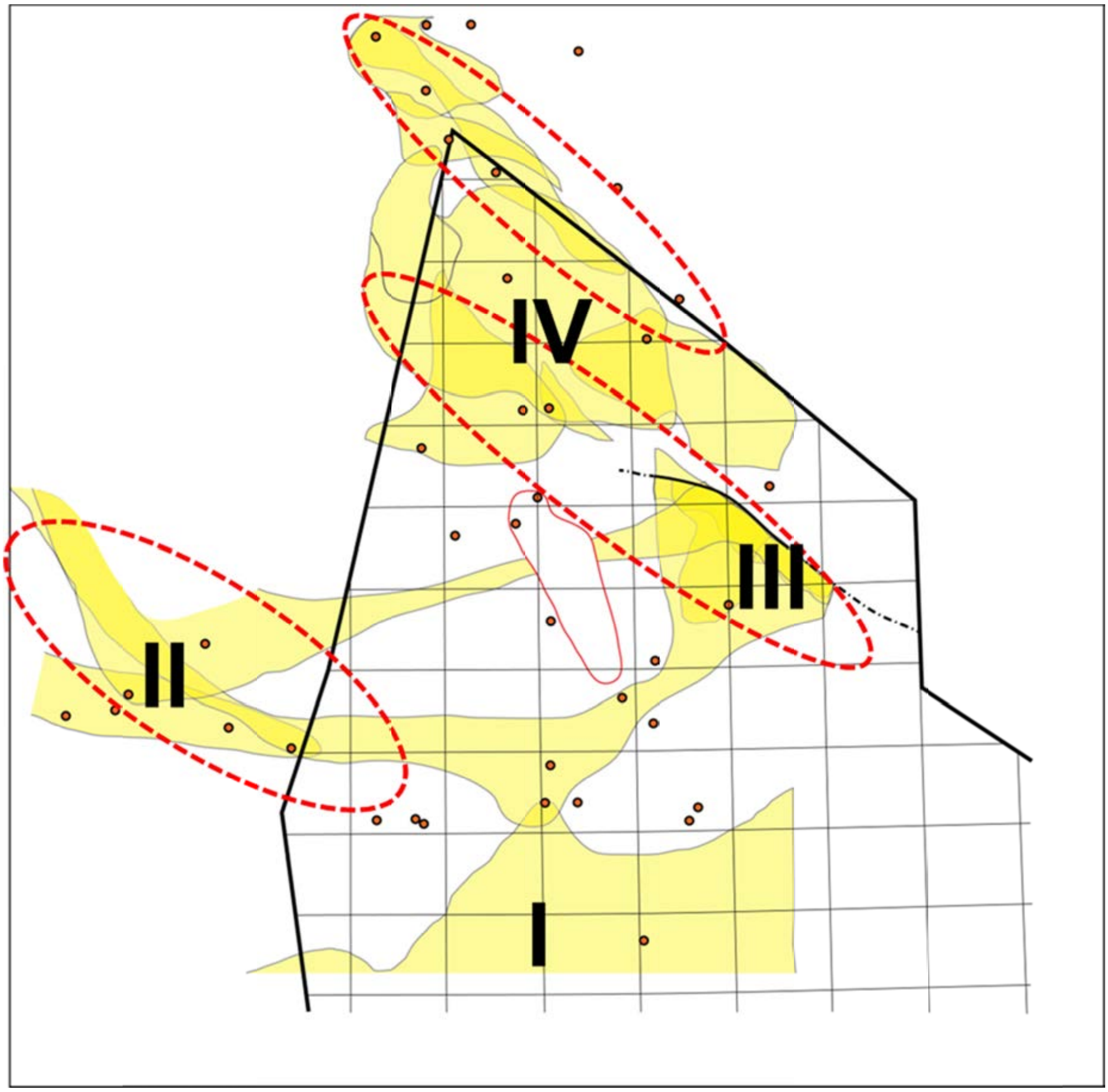


Figure 5.28: Rotliegend sand-rich areas in the Northern Offshore: Stacked sandy areas defined from the individual palaeogeographic maps show: I) Southern “southern fringe” zone. II) Western “Northern Fringe” zone. III) Eastern “Northern Fringe” zone. IV) Northern “Northern Fringe” zone. Important questions: Are the NW-SE oriented trends artefacts or sand-rich zones aligned along active fault zones. Can we find more sand along those trends in the central Graben?

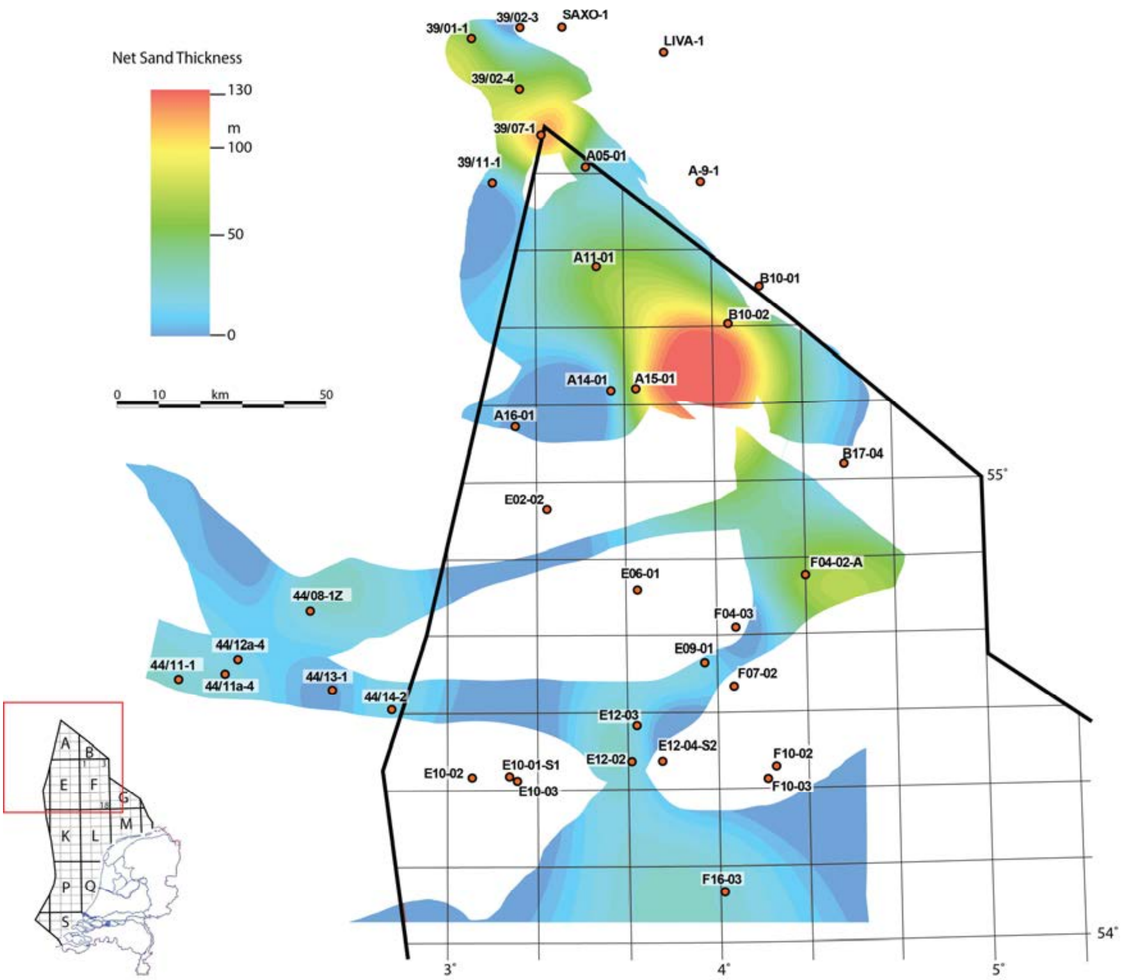


Figure 5.29:Net sand map of the Rotliegend (Upper and Lower). The total sand thickness is the highest in the A15 and B13 blocks.

5.5 Prospective regions

When the maturity map of the Westphalian or Scremerston is combined with the sand maps (see Figure 5.30), prospective regions can be identified. In these regions, potential source rock and reservoir rock are interpreted to be present, although other aspects of the petroleum system, such as trap occurrence and preservation, hydrocarbon migration pathways, and reservoir sealing, are not taken into account in this exercise. With this caveat in mind, the most promising prospective regions are:

1) The A15 and B13 blocks, where the Westphalian has it highest maturity and the Rotliegend contains the most prevalent and proven sands, and
2) the F01, F02, F04, F05 blocks where the Westphalian is also mature, and where significant amounts of reservoir sands are expected to have been deposited along the downthrown side of fault F1 (unfortunately only proven with one well (F04-02A)).

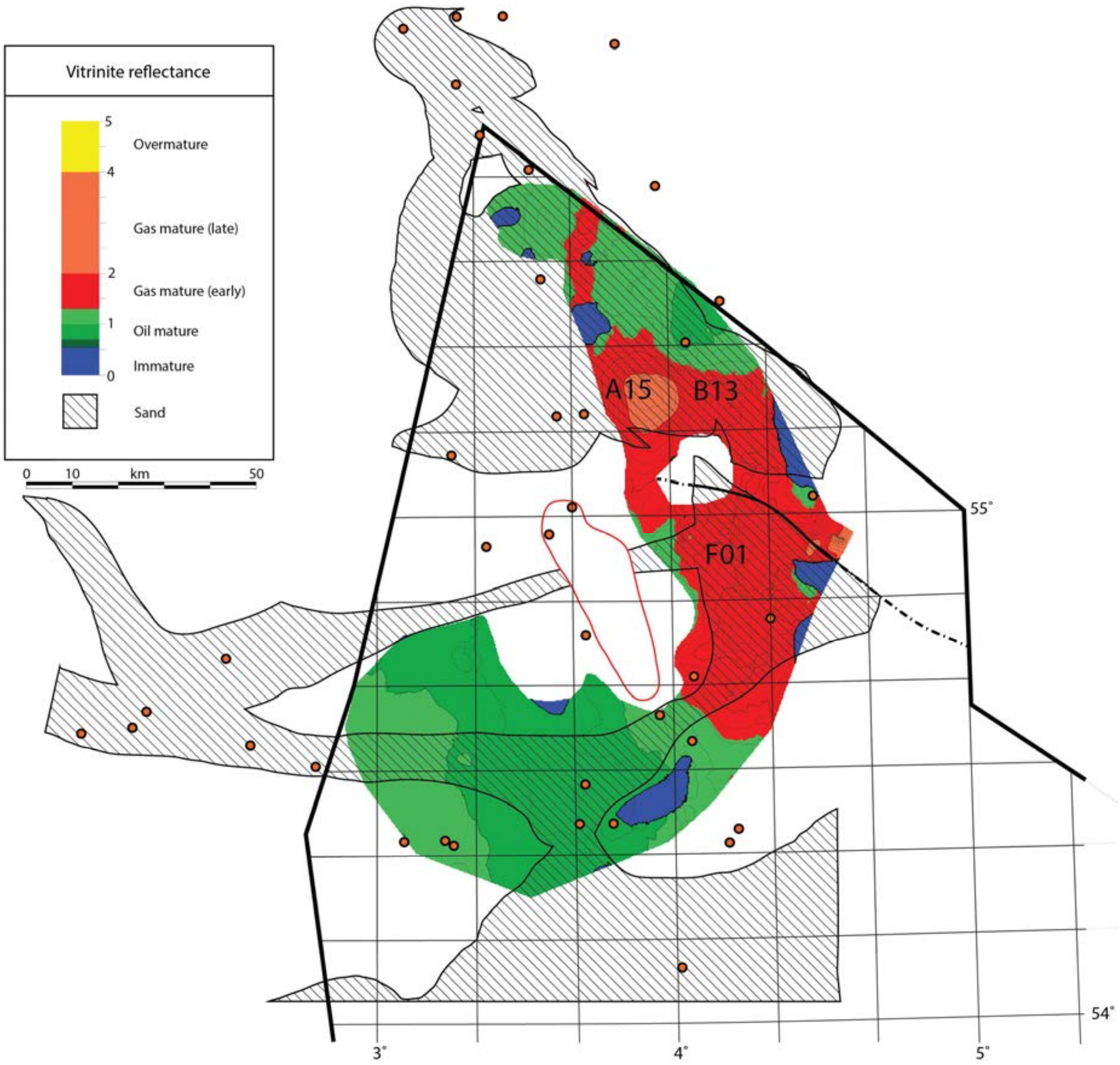


Figure 5.30:By overlaying the Westphalian maturity map with the Rotliegend sand map, prospective regions (that contain both mature source rocks and reservoir rocks) can be identified.

In the western part of block A the Westphalian strata are not preserved, since they were eroded, while Rotliegend reservoir sands are still present there. However, we still expect Namurian and Dinantian source rocks to be present in these regions since the erosion over the ESH didn't reach the deeper part of the Carboniferous. For three modelled wells located in block A (39/07-1, A11-01, A15-01), the Scremerston source rock show maturities in the gas window as well as a late generation (Tertiary; Figure 4.61 to Figure 4.66). The Scremerston Formation could not be mapped within this part of the study area and therefore, no maturity mapping could be performed. However, when combining the 1D modelled maturities of the Scremerston for wells (39/07-1, A11-01 and A15-01) with the Rotliegend sand distribution map (Figure 5.31), the entire block A and part of Block B (B10 and B13) are most likely prospective.

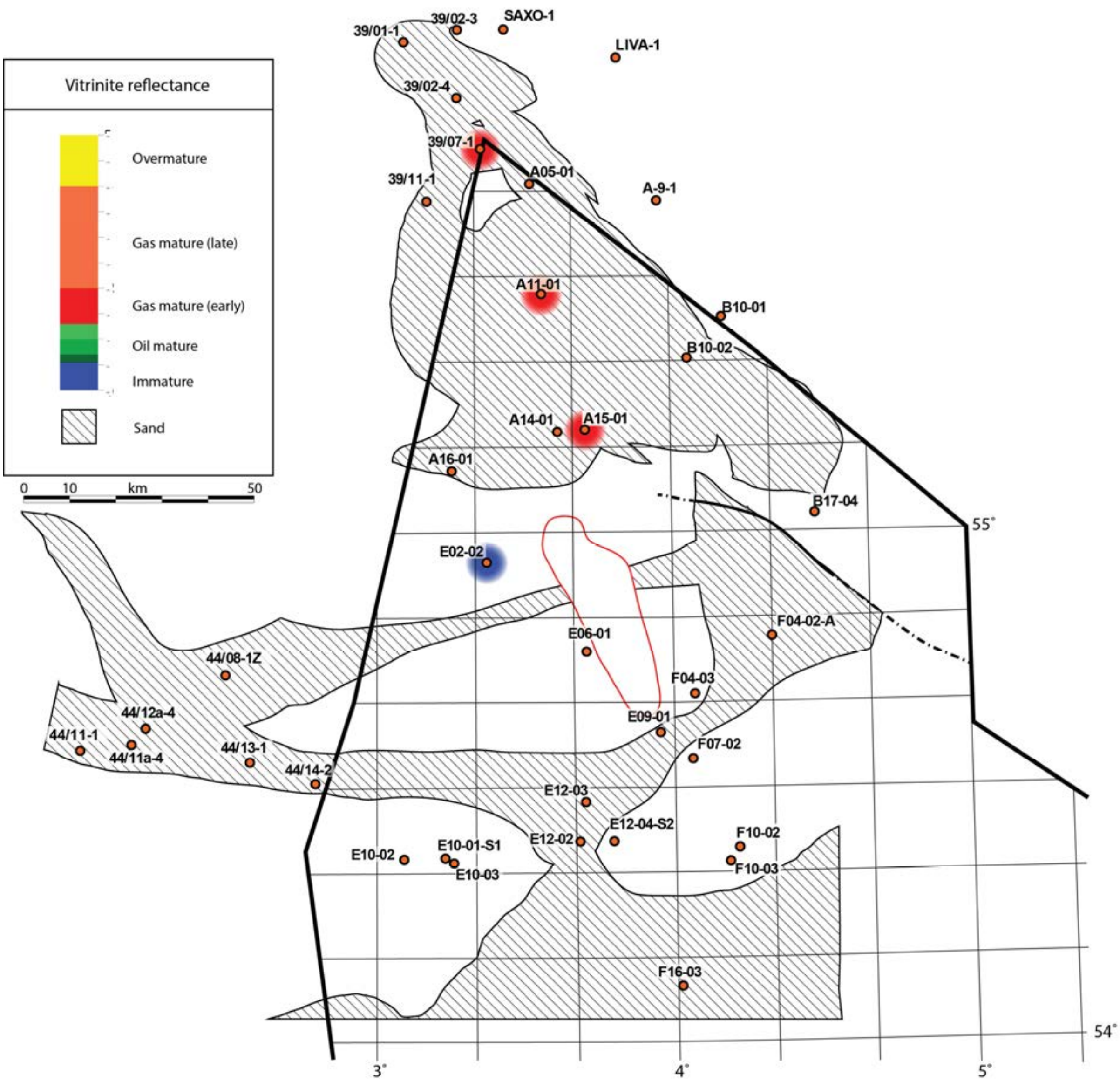


Figure 5.31:The maturity of the Scremerston Fm (in colour) overlain by the combined sand map of the Rotliegend (dashed), shows that the western A blocks are prospective.

5.6 Petroleum systems

This part of the study focussed on source rocks (Westphalian and Scremerston Fm.) and the distribution of Rotliegend reservoir sands. Other elements of a petroleum system, such as seal, trap formation, timing and preservation were not studied. Two wells (A15-01 and B10-02), that lie within the prospective region, have gas shows. This indicates that hydrocarbon migration pathways and/or trapping did not favour accumulation and preservation of hydrocarbons. A petroleum event chart was made for the study area (Figure 5.32) and shows all elements of the petroleum system. Note that the trap formation and preservation is one of the major unknowns in this chart and should be investigated. Finally, it is important to consider shallower reservoir layers, which could be charged and have preserved traps (structural and/or combined traps). Evidence for this was found in the block F, were Triassic strata show a flat-spot, indicating the presence of a gas accumulation. Gas chimneys are observed underneath this Triassic accumulation and originate from the Westphalian.

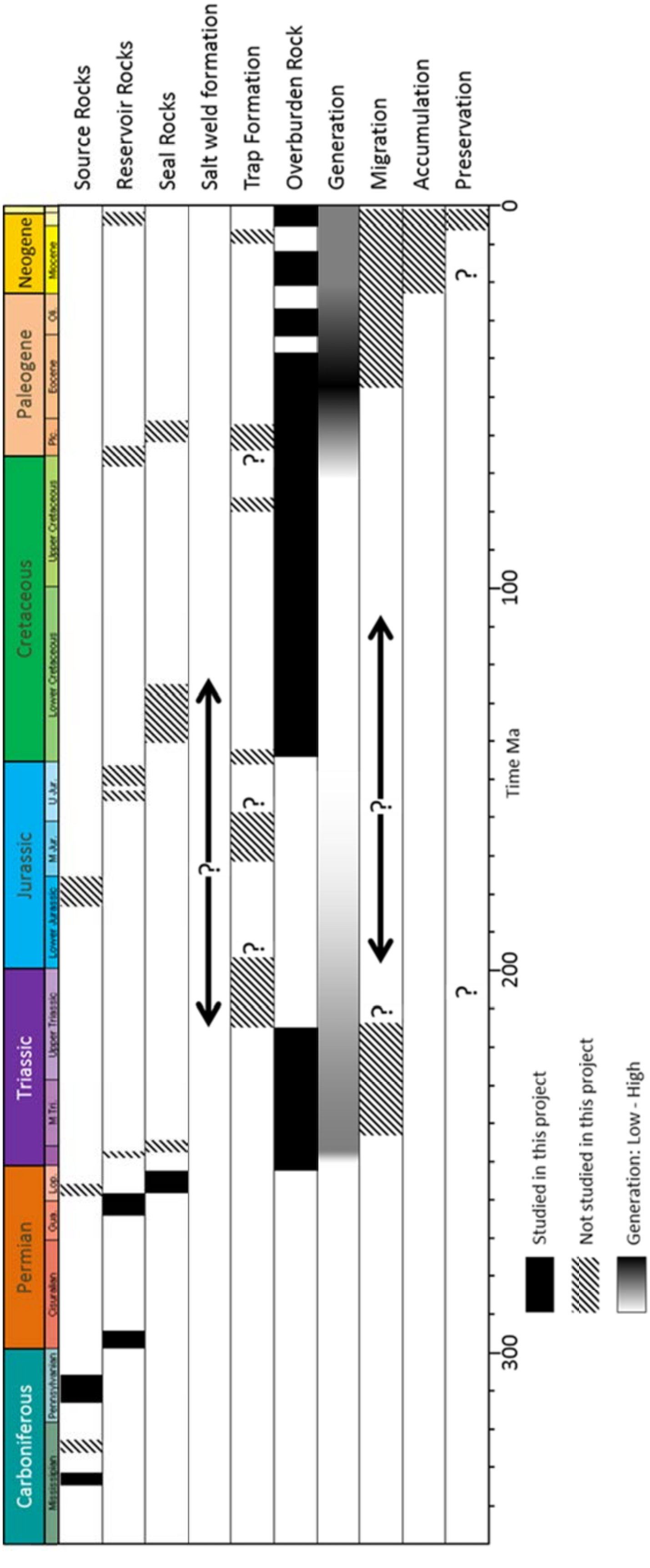


Figure 5.32:Petroleum Chart of the study area.

6 Conclusions

This multidisciplinary project has drastically improved our understanding of the Permo-Carboniferous in the Dutch Northern Offshore and has shown real exploration potential for the Rotliegend. The Westphalian is considered to be the best potential source rock in this part of the basin and is aerially extensive in the Step Graben. Basin modelling results show that two different Carboniferous source rocks (Dinantian and Westphalian) are mature in the study area. Initially a series of twelve specific questions were asked. Now, at the end of the project, all can be answered.

6.1 Rotliegend stratigraphy

The presence of a “Northern Fringe Sand”, as initially proposed, is still a valid model but is now better constrained in terms of distribution and stratigraphic evolution. The Rotliegend in this part of the Southern Permian Basin is divided into two groups, the Lower Rotliegend (clastics, volcano-clastics and volcanics) and the Upper Rotliegend (clastics). The Lower Rotliegend, equivalent to the Grensen Formation in UK, is only present in the NE part of the Dutch Northern Offshore since it was eroded (Saalian event) in the rest of the study area. The stratigraphic evolution of the Upper Rotliegend can be summarized as a growing and widening saline lake associated, in the proximal setting to the north, with alluvial fans as well as aeolian, fluvial and coastal depositional systems that form the bulk of the so called “Northern Fringe Sands”. This sandy area migrated northward during the Upper Rotliegend time (retrogradation) and its distribution and geometry was highly affected by syn-depositional deformation and the presence of topographic features along the basin margin.

6.2 Source rocks

The supposed absence of an adequate source rock was one of the main reasons the Northern Offshore remained under explored. After the well reinterpretation and regional seismic mapping, the Westphalian, known as an effective source in other part of the Basin, is believed to be present in a large part of the Dutch Northern Offshore, including in the Step Graben. In the deepest part of the Step Graben (e.g. block A15) the basin modelling predicts the highest maturity for the Westphalian-age Maurits Formation source rocks. The Westphalian source rocks are in the gas window within a 100km long, 30km wide area from the F07 block in the South, to the A15 block in the North (see appendix 7.12)

6.3 Reservoir rocks

The occurrence, distribution and geometry of sandy strata within the Rotliegend is now better understood. The Lower Rotliegend contains good amounts of sand (overall 20-30%) but its complex depositional setting and the presence of interbedded and locally thick volcano-clastics and volcanics makes it a challenging target. However, more detail seismic mapping should be performed and this interval should be closely evaluated in terms of reservoir potential in the Dutch Northern Offshore. The Upper Rotliegend is a good reservoir target in this part of the Dutch Offshore. It has an overall lower proportion of sand (5%) than the Lower Rotliegend, but the occurrence, distribution and geometry of these reservoir sands are more predictable than the Lower Rotliegend reservoir sand. The sandy deposits of the Upper Rotliegend are locally thick and are distributed across large areas along the northern margin of the Silver Pit Lake, which make them prime targets for future exploration within the DEFAB area.

6.4 Prospective regions

The most promising prospective regions in the Dutch Northern Offshore are:
1) the A15 and B13 blocks, where the Westphalian has it highest maturity and the Rotliegend contains the most prevalent and proven sands, and
2) the F01, F02, F04, F05 blocks where the Westphalian is also mature, and where significant amounts of reservoir sands are expected to have been deposited along the downthrown side of fault F1 (unfortunately only proven with one well (F04-02A)).

Other areas can also be of interest for future exploration, especially if other source than the Westphalian rocks are clearly identified (e.g. Scremerston Formation) or if additional Rotliegend reservoir sand accumulations are identified (e.g. along other syn-depositional faults or paleo-reliefs)

6.5 Research Questions

Q1: Are Stephanian sediments present in the Grabens? Does the conglomerates of K2-2, E12-4 correlate to the Step Graben section in F10-2?

A1: Based on the seismic interpretation, new biostratigraphic results and the literature review, it was concluded that there are no Stephanian deposits in our study area. Therefore, the conglomerates found in K02-02 are most likely Lower Rotliegend in age. The sediments with high TOC found in F10-02 are of Westphalian age.

Q2: Are the organic-rich strata in F10-2 part of a more extensive organic-rich (lacustrine?) depo-centre in the Dutch Central Graben?

A2: As mentioned above, the organic rich intervals are of Westphalian age and they are present in a large parts of the study area.

Q3: Can they be effective source-rocks in the study area?
A3: Yes, the Westphalian is known to be an effective source. In the deepest part of the Step Graben the basin modelling predicts the highest maturity.

Q4: When are these source rocks in the right maturity window?
A4: The Westphalian source rocks have two phases of gas production, during the Triassic and Cenozoic.

Q5: What is the reservoir potential of the conglomerates, and are there laterally interfingering with sands?
A5: As mentioned above, the conglomerates are believed to be of Lower Rotliegend age. Unfortunately, we have too little core data to clearly answer this question. Nevertheless, significant amounts of sand are present in the Lower Rotliegend (30% of the overall sediments are sands).

Q6: What is the lithological infill between wells A15-02 and B10-02?
A6: This question predates the well re-interpretation when both wells were considered to have Upper Rotliegend strata overlaying the Millstone Grit Formation. However, after the well-reinterpretation was performed, the Lower Rotliegend strata where identified in both well, which drastically changed the initial correlation model. The Upper Rotliegend is onlapping on the Lower Rotliegend, which consists of interbedded sands and shales.

Q7: What is the E-W lateral extent of the Rotliegend sands within the Step Graben?
A7: The distribution of the sands are deposited along a, broadly, E-W basin margin and are linked to paleotopography, syn-depositional faults and follow a retrogradational trends trough out the Upper Rotliegend time. However, some unexplained bright amplitudes are seen on seismic, that could not be explained by a sand-shale alternation. These bright amplitudes could be caused by intrusive rocks or halite, but this remains unclear.

Q8: Is there a sand filled corridor (N-S) through the Ringkøbing Fyn High?
A8: There is no sand filled corridor towards the north. The lower Rotliegend sands are not continuous towards the north and interfinger with volcanics in the North (Denmark, Germany and UK). The Upper Rotliegend is not present towards the north.

Q9: What is the sand development on the west flank of the Elbow Spit High?
A9: A series of onlapping sands that extend into the Cygnus field are found on the western and also the southern flanks of the Elbow Spit High.

Q10: What is the source of gas shows in well B10-02?
A10: At the start of the project there was no prolific source rock identified at this well's location. After the seismic interpretation and well re-interpretation was completed, a Westphalian source rock is proposed as the most likely source of the gas shows observed in the B10-02 well.

Q11: What happens between wells B10-1 and B10-2?
A11: There is a fault between those wells

Q12: Is there a stratigraphic connection between the Northern and the Southern Fringe sands in the deepest part of the basin?
A12: No, the Northern Fringe sands are not connected to the Southern Fringe sands in the study area. Only at well E12-02 are both sands present but are separated by low net-to-gross strata. The relationship between the two fringes are however less constrained in the Dutch Central Graben and stacked sands from different sedimentary sources can possibly occur.

7 Further research

Even if significant progress has been made during this project, regarding the tectono-stratigraphy and petroleum system of the Dutch Northern Offshore, numerous questions still remain and new ones have arisen. It is our opinion that several research topics could, and preferably should, be further investigated. Preferably as an integrated research project, possibly as part of a larger "programme". Below some brief examples of possible follow up work is presented.

7.1 Detailed structural analysis, especially around the Elbow Spit High

The Dutch Northern Offshore is a structurally complex area, especially when considering the poorly imaged Permo-Carboniferous section. For example the presence of the Old Red Group to the North of the Elbow Spit High (ESH) and just across the UK border, needs to be taken into account when Investigating the lateral distribution of potential source rocks such as the Scremerston coals. One of the goals of such study could be to further refine the Base Permian subcrop map by integrating a robust structural framework based on detailed fault mapping of the Carboniferous and Permian. Such a detailed structural analysis around the ESH will also improve the understanding of the distribution of Devonian and Lower Carboniferous source and reservoir rocks. This study would also contribute to the identification of the structures that might have been active during the deposition of the Rotliegend and so may have affected the local distribution of reservoir sands (e.g. along NW-SE trending faults).

7.2 Extend the study area

The Lower Rotliegend (including the Grensen Formation) proved to be stratigraphically heterogeneous and complex, yet it holds some reservoir potentials. The study area could be extended towards the North (Denmark, Southern Norway, UK) and to the East and Southeast (SW Dutch Offshore, Germany) where Lower Rotliegend stratigraphy is preserved and has been locally targeted (e.g. by Hanza Hydrocarbons in G18, H16, M3 and N1 blocks, Cram et al., 2014).

7.3 2-D structural restorations in combination with basin modelling

2-D structural restoration of across the study area, for example from the western flank of the elbow Spit High to the Dutch Central Graben or in the axis of the Step Graben, would clearly add tremendous value in understanding the tectonic history of the Dutch Northern Offshore. Such study would increase our understanding of the compressional and extensional events that affected the area since the Carboniferous, as well as giving more precise insights on the main erosional events and the complex salt tectonic history in the area. Such 2-D structural restorations could be combined with 2-D petroleum system modelling, give insights into the relationship between burial, local deformation, timing and location of source rock maturation, hydrocarbon migration and trap timing and preservation.

7.4 3-D basin modelling and fluid migration study (chimneys)

Seismically imaged chimneys are observed in the study area that originate from the Westphalian source rocks and end in shallow gas fields, the Trias and in other overlying intervals. For example, five shallow gas fields are found in a halo around the high Westphalian maturity zone defined in the present project. The timing of expulsion and modelled migration pathways could be compared to seismic chimney configuration, in order to better understand migration dynamics and charging.

7.5 Extended isotope analyses for the Rotliegend Group

Good chronostratigraphic control is essential to enable high-resolution regional stratigraphic correlation in an area with lateral facies variability. In absence of robust biostratigraphic information, such as in the Rotliegend, carbon isotope stratigraphy represents an alternative method for obtaining additional chronostratigraphical controls. In continental red-bed settings, it is important to develop a regional standard curve, which can be correlated to the global curve, and that could be used as a new local correlation tool in an accurate way. For this project we propose to study approximately 50 wells (cutting samples) across the basin.

7.6 3-D seismic attribute analysis

A few tests have been carried out in this project using 3D seismic attributes to identify sands in the Rotliegend. Spectral decomposition showed some promising results, even if the obtained signals were difficult to interpret. An in-depth study is needed to establish whether Rotliegend sands could be delineated in seismic data available in the study area. First, seismic modelling is needed to establish the hypothetical visibility of sands. If it is indeed possible, seismic attributes analysis should be carried out on higher quality 3D seismic data. Several techniques will be tested, including spectral decomposition, sweetness, waveform segmentation (seismic facies), and seismic inversion (property predictions, such as porosity). Additionally, fluid substitution modelling can be proposed to study whether or not the presence of gas is detectable in the Rotliegend using seismic data.

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9 Signature

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10 Appendices

Appendix 1: Proposal

Appendix 2: Literature Review

Appendix 3: Well re-interpretation

Appendix 4: Seismic Mapping

Appendix 5: Isotopes

Appendix 6: Basin Modelling

Appendix 7: Geological Maps

Appendix 8: Stratigraphic Correlations

Appendix 9: Chronostratigraphical Chart

TNO report
New Petroleum plays in the Dutch Northern Offshore
Appendices

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1 Proposal

New petroleum systems in the Dutch Northern Offshore

Innovation Program
Upstream Gas
Appendix 1 Project Plan

Project Title	New petroleum systems in the Dutch Northern Offshore
Program Line	New Fields
Project Manager	Vincent P. Vandeweijer
Partners	Centrica, Chevron, EBN, Fugro, NAM, TOTAL, Wintershall.
Start- and end dates	01/01/13 - 30/06/15
Author	Johan H. ten Veen, Vincent P. Vandeweijer
Version	V07

Innovation Program Upstream Gas

Appendix 1 Project Plan

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Contents

Summary

This project aims to test a new hypothesis for the Permo-Carboniferous structural-sedimentological development of the Central and Step Graben and the implications for the potential of play types consisting of Westpahlian (and older?) – Stephanian or Rotliegend reservoir- and source rocks. In order to reach this aim an integrated multidisciplinary approach is proposed, which is underbuilt by tectono-sedimentary reasoning, and focuses on integrating sedimentology, biostratigraphy, sequence stratigraphy, well log analysis, seismic interpretation and petroleum-system modelling. Based on the integrated results, the research will provide a description of potential areas in the Northern Netherlands offshore that might become subject of future exploration activities.

1 Introduction

In the light that gas can take a roll as a flexible, low CO_2 emitting fuel towards a durable energy supply realizing possible new resources is very welcome. For years the only developments of oil and gas in the Dutch Northern offshore were in the Upper Jurassic F3-FB and the Chalk F2-Hanze fields. Recently, this trend changed and a series of stranded fields came on production, shallow (Tertiary) gas fields become exploited and the development of the Upper Jurassic F2-FA field have started. Despite these encouraging developments the Dutch northern offshore remains a relatively underexplored area. This especially holds for the Pre-Zechstein reservoir- and source rocks of the Rotliegend Group and underlying Carboniferous strata. Underexploration is mainly based on a number of assumptions:

- These two stratigraphic units are devoid of adequate source rocks and reservoir sequences;
- If reservoir- and source rocks are present they have been buried too deep and are tight and over mature.
- Salt withdrawal associated with activity of major deep seated basin-bounding faults compromised the sealing capacity of the Zechstein seal.

Notwithstanding, three encouraging new discoveries underline the need for additional research as proposed herein:

1) Recent research on the Cleaverbank Platform (Petroplay, Carboniferous study) and Elbow Spit High (van den Hemel, 2010) continuously improved the facies distribution models in tilted sub-BPU rocks (Devonian, Carboniferous). This calls for a higher-detailed view on the presence of source- and reservoirs rock, trapping geometries and possible HC migration pathways.

2) The find of the Cygnus field in the UK sector proved the presence of a Rotliegend reservoir section on the Northern fringe of the Southern Permian Basin (SPB). The presence of gas proves the presence of a source rock which timely generated gas with respect to the formation of the trap. In the Dutch sector thin Rotliegend sandstones have been encountered on the SPB's northern fringe in for example well A16-1. A Cygnus equivalent may well be present in the Dutch northern offshore.

3) The increased understanding of the Westphalian A to C/D series combined with the new insights in the palaeo-depositional environment (based on palynology) of the youngest Carboniferous sediments and the recently published Rotliegend depositional models (results from TNO project "Explore") may be beneficial to the understanding of the youngest Carboniferous strata (Westphalian D to Stephanian). A large part of the Central Graben and Step Graben have the Step Graben Formation (of presumed Stephanian age) as subcrop of the

Permian. Several lines of stratigraphic, geobiological, tectonic and sedimentological evidence suggest that:

a) Source rocks and reservoirs exist on stratigraphically higher levels in the Carboniferous (Westphalian D to Stephanian)
b) Hitherto unknown basin structures may have formed traps in these rocks
c) Petroleum system development on underexplored local highs in these basins may deviate from the regional trend of over-maturing.

Inspired by these discoveries, interest in the exploration of the Pre Zechstein sequences renewed after years of neglect. Following this renewed interest new 2D and 3D seismic surveys have been shot to fill the gaps in the seismic coverage and improve the efficiency of exploration activities. The recent seismic acquisitions have been designed to image the deep pre-Zechstein (Permo-Carboniferous) series appropriately. In order to help exploration, the next logical step is to develop a theory that supports the likely presence of (additional) reservoir and source rocks. In this study we propose to investigate the Permo-Carboniferous reservoir and source rock potential of the Central Graben and Step Graben area in the Northern offshore and focusing on the three aforementioned themes. We aim at finding and delineating those "hot" spots where the right source-reservoir-seal conditions are met, both spatially and in terms of (timing of) HC generation, -migration and trapping.

1.1 Proposed research strategy

The set-up of this project is to test a new hypotheses (see next section for details) for the Permo-Carboniferous structural-sedimentological development of the Central and Step Graben and the implications for play types consisting of Westpahlian (and older?) – Stephanian or Rotliegend reservoir- and source rocks.

The project aims to focus on the geology around the Elbow Split high and Dutch Central Graben (A, B, D, E and F blocks) in order to identify and evaluate the reservoir and source rock potential in rock sequences from the latest Carboniferous to earliest Rotliegend. In order to reach this aim an integrated multidisciplinary approach is obligatory. The hypothesis is built on a tectono-sedimentary reasoning with a strong link to biostratigraphy. Intricate integration of sedimentology of cores, biostratigraphic analysis of rock samples, (sequence)stratigraphic evaluation of logs, interpretation of key seismic lines and analysis of petroleum system scenarios is proposed.

2 Current state of knowledge and intended innovation

2.1 Current level

The Northwest European Carboniferous Basin (NWECB) or Anglo-Dutch Basin developed in the Devonian and Carboniferous in response to lithospheric stretching and Late Carboniferous flexural subsidence (Kombrink et al, 2008) along the southern margin of the Old Red Continent (more or less the southern margin of the Rhenohercynian Zone; Ziegler, 1990, Oncken et al., 1999; Burgess & Gayer, 2000; Narkiewicz, 2007) The basin consisted of a series of WNW-trending half-grabens in the southern North Sea, similar to E-W basins described in the British offshore (e.g. Fraser & Gawthorpe, 1990) in which a thick pile of Devonian and Lower Carboniferous sediments was deposited, sourced from the Mid German Crystalline High in the south and the Old Red Continent in the north.

During the Westphalian, the Variscan deformation front continued to migrate northward and the Namurian sediment package of the Rhenohercynian zone was deformed into major thrust and nappe complexes (Ziegler et al., 2004). The main depocenter of the NWECB progressively moved northward from a position near the Ruhr Valley Graben in Namurian to the Ems Deep in the Stephanian, during various compression-extension cycles. The end of orogenic activity in the Variscan Fold Belt during the latest Westphalian was followed by the establishment of a dextral and sinistral wrench-fault system (Ziegler, 1990a; Ziegler et al., 2006) that led to the development of transtensional and pull-apart basins. The most important example of this type of basin system in the NWECB is the Ems Basin (a north–south-trending belt of Stephanian deposits in north-west Germany). This Stephanian basin probably developed due to the underlying Teisseyre-Tornquist Zone and is considered to be the result of a secondary shear system linking the major systems, such as the Teisseyre-Tornquist Zone (Ziegler et al., 2006).

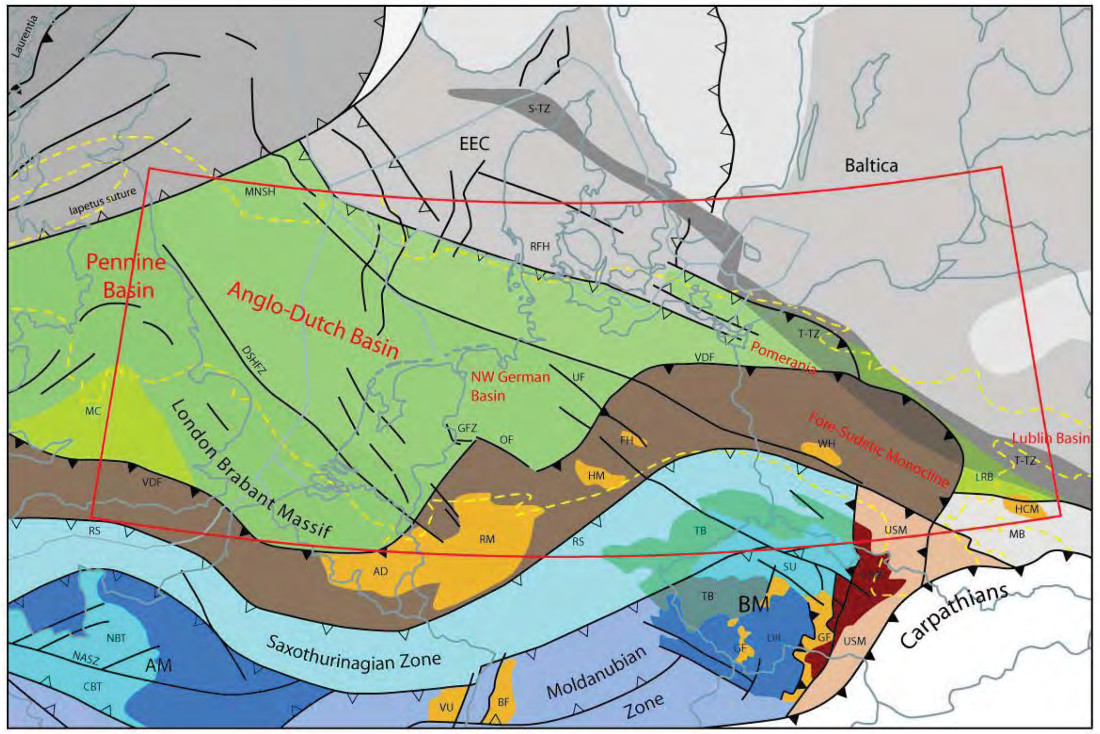


Figure 1: Structural elements of the Carboniferous NWECB.

Several studies in the Dutch offshore also suggest a changing Late Carboniferous (Stephanian) tectonic configuration. For instance a Late Stephanian – late Autunian initiation of a precursor of the Central Graben (proto CG) is assumed by Adrichem Boogaert & Kouwe (1993) based on the preservation of Lower Rotliegend and Stephanian volcaniscs on the flanks of the graben and isopach patterns of the Permian succession (see also Appendix 1).
Also, the Horn Graben (HG; in the German part of the North Sea), shows a similar N-S pattern of preserved ?Lower Rotliegend deposits that may hint at a comparable and contemporaneous formation mechanism. MONA-LISA deep seismic lines across the HG reveal substantial occurrences of lower and upper Paleozoic strata below the graben. This is seen as an indication that the Horn Graben developed as a Paleozoic graben structure during the late Paleozoic in the former Caledonian foredeep (Abramovitz & Thybo,1999).

2.2 Intended innovation

The main innovation of this project is the postulation of a new and alternative, hypothesis for the Late Carboniferous-Permian structural- and sedimentological development of the Dutch Northern Offshore. This hypothesis, which differs importantly from current accepted views, is outlined below:

During the latest Carboniferous on-going N-S compression, as a consequence of the northerly prograding Variscan front, results in folding of older Carboniferous strata, inversion of specific structural elements and, most importantly for the hypothesis, E-W extension. The E-W extension is concentrated in for example the Central- & Step Graben area and the Horn Graben (Figure 2). These areas form (mild) depressions or alternatively accommodation space for firstly latest Carboniferous sediments and later Rotliegend sediments. Sediments from both eras are thought to have been deposited in a terrestrial environment. This means that fluvial drainage system would direct itself into the depression resulting in a sand-prone sequence. Additionally, being in a depression the depositional surface will be closer to the water table which on the one hand increases possibility to form vegetated area’s and on the other hand increases the preservation potential of organic matter resulting in the formation of source rocks.

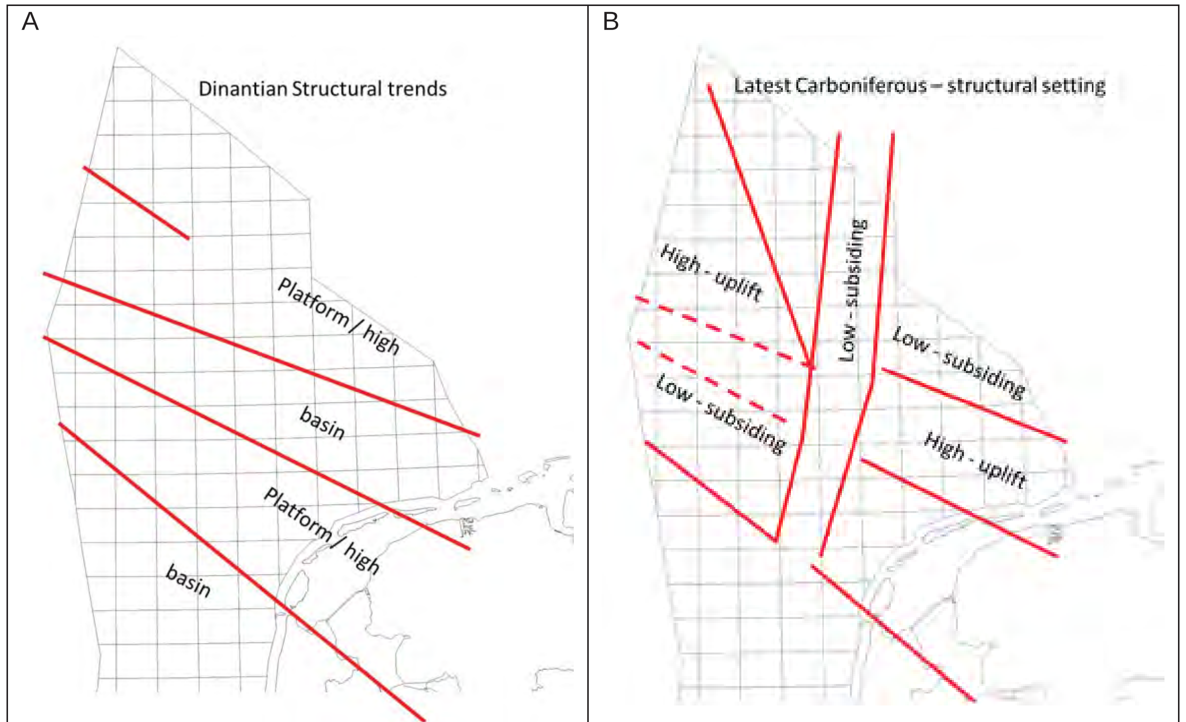


Figure 2: Sketch maps of the presumed tectonic evolution of the larger study area.

A) During the Early Carboniferous the structural grain was NW-SE in a predominately extensional setting creating block and basins. On the high block the reefal build ups were situated.
B) The end stage of the Variscan orogeny resulted in a rearrangement of structural elements. A N-S oriented graben system developed as a result of N-S compression. Diantian structural elements were split and. The various new blocks started to invert with respect to Dinantian movements.

Figure 3 depicts a schematic E-W cross-section over the southern part of the Step & Central Graben. During the latest Carboniferous the Step and Central Graben started to subside with respect to its neighbouring blocks as for example the Cleaver Bank High. Within the depression the Step Graben sequence was deposited and preserved. On the flanking highs condensed sequences may have been deposited and sparsely preserved. This configuration persisted in the Rotliegend where the depression may have entrenched sand prone sediments sourced by the SPB fluvial systems from the south and north (Elbow Spit, Mid North Sea and Ringkøbing-Fyn Highs and possibly the Northern Permian Basin). The incipient Step- and Central Grabens may have acted as a passage for sand from north to south. As base level rose, the N-S basins were flooded and filled with clay prone sediments.

Observations and arguments supporting the hypothesis:

1. The preservation of Stephanian red-bed deposits in- and across incipient N-S structures, such as the Step Graben, the Dutch Central Graben and presumably the Horn Graben. These suggest a configuration of N-S depressions in which latest Carboniferous sediments were deposited either / or preserved from “Saalian” erosion. (Appendix A)
2. The occurrence of non- to poorly dated reddish conglomerates underlain by a mature soil horizon on the Cleaverbank High (Mijnlieff et al., 2011), indicating the presence of a (?Upper Carboniferous) conglomeratic drape between an intra-Carboniferous unconformity and the base Permian unconformity.
3. A thicker (sandprone?) equivalent in the high accommodation space incipient Step Graben and Central Graben.
4. New TNO analysis shows the occurrence of small organic rich intercalations in red-bed facies contained palynoflora’s characteristic for coal-forest vegetation on the edge of the Step Graben.
5. Palynological data revealed that on the edge of the Step Graben small organic rich intercalations in red-bed facies contained palynoflora’s characteristic for coal-forest vegetation in combination with dry upland-elements of late Stephanian – Early Permian age. For these elements to have survived red-bed conditions, wet refugia should have been present nearby. If the grabens were structural lows already during the Latest Carboniferous (a view supported here), they could have acted as refugia for these hydrophytic communities and possibly contain coal-measure facies of Westphalian D – Stephanian age. Westphalian D – Stephanian coal-bearing facies is not uncommon in UK onshore basins (e.g. Forest of Dean), onshore Germany (e.g. Saar-Nahe basin) and Spain (Cantabria). In most Appalachian coal-basins, coal deposition continued into the Stephanian. Recent studies revealed that chemical composition of these young Carboniferous coals differs from those of the classic coal measures (REF). Throughout the latest Carboniferous a shift in coal-forming vegetation occurred which has a postulated effect on the chemical composition of the coal. This might had have an effect on gas-composition which should be traceable in the gas-compositions measured

2.3 Research questions

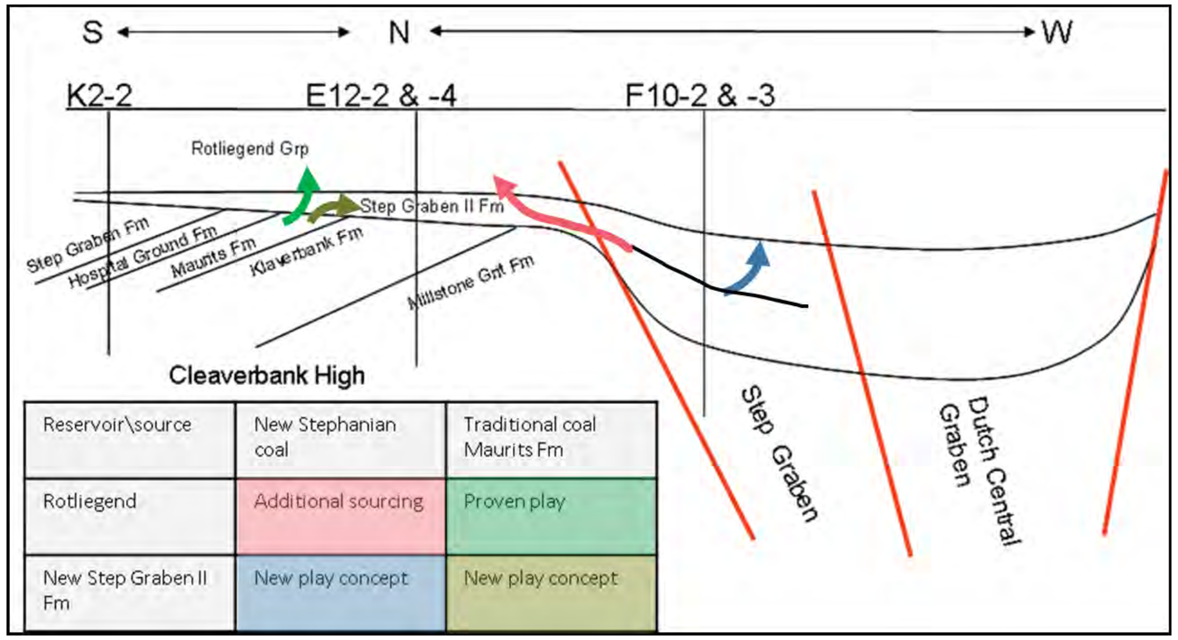
To test the hypothesis and to see if and where additional Carboniferous–Permian plays exist the following knowledge needs to be developed:

- What is the tectonic evolution of the Step and Central Graben in conjunction with its neighbouring blocks during the late Carboniferous to Rotliegend times?
- What is the facies distribution and basin configuration during the latest Carboniferous
- Is there additional evidence for coal deposition in the Grabens during the Westphalian D – Stephanian?
- Would they have generated hydrocarbons and when?
- Is the chemical composition of Westphalian D – Stephanian coal traceable in the measured chemical composition of gas (from www.nlog.nl), i.e. is this coal an additional source to proven fields?

- What is the structural development (incl. erosion, timing unconformities) of the potential reservoir sands in relation the source and migration of HCs
- What is the likelihood of the four play scenarios as listed in Figure 3.

- What is the distribution of the marginal ”northern fringe” Rotliegend (Silverpit equivalents) deposits in the area of interest?
- What is their potential source?

- Is their potential for additional sourcing from stratigraphically older Carboniferous levels in the Elbow Spit area, which can be seen as the tilted footwall to the SG and DCG?



Reservoir\source	New Stephanian coal	Traditional coal Maurits Fm
Rotliegend	Additional sourcing	Proven play
New Step Graben II Fm	New play concept	New play concept

Figure 3: E-W schematic cross-section over southern end of the Step- & Central Graben supporting the hypothesis. Based on seismic section shown in Appendix B. Table shows play scenarios to be tested.

3 Project plan

3.1 Work plan and work packages

Testing the innovative hypothesis for the Carboniferous-Permian tectonosedimentary development of the area will mainly occur through traditional techniques and methods such as seismic interpretation and analyses of well-, core- and gas data. The results will be integrated with both traditional and newly established stratigraphic techniques, enabling to make significant improvements in the stratigraphic- and palaeo-environmental interpretation of the considered stratigraphic interval.

3.1.1 Definitions of the work packages

WP1 – Acquiring, reviewing and loading data (total 100 man hours)

Within this work package data essential for the project is acquired, QC’ed and loaded in the to-be-used software and models.

When all data deemed necessary is reviewed and loaded onto workstations and the software to be used Milestone M01 (Table 3) is reached.

WP2 - Regional geology and Structural Geology (total 400 man hours)

Within this work package the public literature will be screened on relevant information on the Permo-Carboniferous evolution of the study area. This will result in a comprehensive summary of the tectono-stratigraphic evolution of the study area in the light of the regional geologic picture. This will be delivered as (intermediate) Petrel model (deliverable D01) with structural model, well log correlations of sedimentological, bio-, chemo- and isotope stratigraphy and supported by report. Secondly, this review will help in detailing and supporting a hypothesis/concept on the regional evolution of the Carboniferous-Permian period. This concept will constitute sketch maps and cross-sections and will be supported by multi 1D Petroprob models to assess the tectonics history and heat-flow evolution.

This will be reported in deliverable D02.

At the end of WP2 (Milestone M02, See also Table 3) a workshop will be held discussing the progress made and in which the results so far are presented

WP3 to 5 – Play types 1 to 3
Within these work packages we investigate the various plays scenarios. In WP3 the generation and migration in and through Late Carboniferous cross-grabens and Stephanian source and reservoirs. In WP4 package we investigate the play concept of the SPB Northern fringe reservoirs (e.g. Cygnus field). And in WP5 the possible play concept of Visean/Namurian onlap against Devonian Elbow Spit High granite and related facies distribution.

This will be achieved by integrating structural, sedimentological and stratigraphical information in petroleum system analysis. For more detail see section 0 on the integrated workflow.

The results will be reported in Deliverables D03 to D05.

Each work package will be concluded (Milestone M03 tot M05) with a workshop, where progress, conclusions and the road ahead will be discussed

WP6 - Reporting

- Final Petrel model with integrated products and data summary, this is Deliverable D06.
- A written report containing the evaluations of the Play types, structural framework, general conclusions and recommendations. This is Deliverable D07, the end report

WP7 – Project management
Project management is split up in content and procedural management. The senior scientist is responsible for the content management and the project coordinator for the procedural management.

Table 1: Work package overview

WP	*Work Packages name*	*Short description*	*Contractor*	*Result*	*Delivarable or Milestone*	*Start and End date*
1	Acquiring, reviewing and loading data	-	TNO	-	M01	1/1/13 – 9/13/13
2	Regional geology and Structural Geology	Regional evolution of the study area	TNO	Tectono-stratigraphic model & detail descriptions of plays	M02 & D02	10/21/13-1/31/14
3	Play type I		TNO	Report	M03 & D03	2/4/14 – 7/15/14
4	Play type II		TNO	Report	M04 & D04	7/17/14 – 12/25/14
5	Play type III		TNO	Report	M05 & D05	12/29/14-6/8/15
6	Reporting		TNO	Final report & Petrel project	M06 & D06, D07	6/10/15 – 7/13/15
7	Project Management	Progress, meetings etc.	TNO			1/1/13 – 7/14/15

3.1.2 Integrated workflow

An integrated workflow, to test the play types 1 to 3 is described in more detail below. This workflow will be applied in WP3 to WP5, as much as possible and where applicable.

Structural geology
In order to create a structural framework a selection of seismic lines will be interpreted with the focus on the Permo-Carboniferous. For the purpose of basin modeling a few main (Paleo-, Meso, and Cenozoic) lithostratigraphic Group boundaries will also be picked to quantify the overburden. The seismic interpretation will focus on:

1. Verify and detail the proposed Permo-Carboniferous tectonic and tectonic evolution model
2. Extract thickness trends and facies trends of the Permo-Carboniferous strata.

To cope with seismic coverage of deep targets across the DCG, some lines of the Long offset North Sea Reconnaissance data (Fugro/TGS) can be used (Appendix B) alongside publicly available data.

Sedimentology
Available sedimentological and petrographical core descriptions will be re-evaluated and if deemed necessary described again in the light of the present knowledge. These interpretations will serve as an anchor point for more regional depositional environment interpretation of the Rotliegend and latest Carboniferous. Only cores from the Rotliegend and presumed latest Carboniferous will be checked. We will compile well panels of key transects with biostratigraphical and sedimentological data. The structural framework will be integrated into a (sequence) stratigraphical correlation. Appendix C gives a quick inventory of wells which may be included in the study.

Source rock evaluation, kerogen typing & palynology (partially optional)

The organic matter in the latest Carboniferous will be geochemically analysed for kerogen typing and maturity value.

The link between geo-chemical composition of coals and vegetation development during the Westphalian D –Stephanian can (is optional) be evaluated by using combined palynology and geo-chemistry data of analogue basins. In order to study a possible sourcing from Stephanian source rocks, available data on gas-composition and fluid inclusions can be evaluated.

Chemo-, Bio- and isotope Stratigraphy

To unravel the stratigraphy of the Late Carboniferous strata we will apply a multidisciplinary approach on a number of key wells. Available chemostratigraphy and sparse biostratigraphy will be lined up with time lines provided by stable isotope stratigraphy. During the Westphalian D / Stephanian the usability of biostratigraphy as a high resolution chronostratigraphical tool becomes hampered by the overprint of facies related occurrences of species (van Hoof et al., in press), but major shifts in ^{13}C records have been proven to be good chronostratigraphical anchor points in terrestrial setting. Available chemostratigraphical and biostratigraphical correlations will be verified by developing high resolution carbon 13 records from selected key wells.
For all play types the results will include:

- Where applicable, a standard isotope geochemical framework for the late Carboniferous-Permian interval considered based on a compilation of key wells.
- A stratigraphical framework based on isotope geochemistry and palynology focusing on the stratigraphic interval of interest and based on a selected number of key-wells

Petroleum system analysis and –scenario testing

We will model (in 1 and/or 2 D) the burial, temperature, maturity and HC generation history of the source rocks identified in the Central Graben and Step Graben. The preservation of generated gas will be evaluated by comparing the timing of gas generation with timing of seal and trap formation, timing of periods of fault (re)activation during tectonic phases. Simple migration and charging modeling may be part of the evaluation and will serve to test the likelihood of the proposed play scenarios.
For the evaluation of all play types the Petroleum systems description will include:

- Reservoir distribution sketch maps
- Qualitative description of play with proof of concepts from well and outcrop/analogue data
- Petroleum systems scenarios (generation and migration) of the hydrocarbons, including source rock maturity and HC generation history in relation to seal-trap formation history.
- Description of potential areas in the Northern Netherlands offshore area based on interdisciplinary integrated results

3.2 Results, Deliverables and Milestones

Table 2: List of deliverables

Deliverable	Title	Due date
D01	Intermediate Petrel model	**2/3/14**
D02	Review of Tectono-stratigraphic evolution including Palealeogeographic sketch maps and cross-sections, i.e. detailed formulation of and support for the main research hypothesis	**2/3/14**
D03	Evaluation Play type 1	**7/16/14**
D04	Evaluation Play type 2	**11/28/14**
D05	Evaluation Play type 3	**5/12/15**
D06	Final Petrel model with integrated products and data summary	**6/30/15**
D07	Final Report	**6/30/15**

Table 3: List of milestones

Milestone	Title	Due date
M01	Conclude acquisition, review and loading of data	**10/21/13**
M02	Conclusion of regional work, start of detailed analysis of plays	**2/3/14**
M03	Conclusion of evaluation of Play type 1	**7/16/14**
M04	Conclusion of evaluation of Play type 2	**11/28/14**
M05	Conclusion of evaluation of Play type 3	**5/12/15**
M06	Conclusion of evaluation of final deliverables	**6/30/15**

3.3 Risks and alternatives

Success of the project is to great extend dependent on the possibility to visualize the sub Zechstein salt stratigraphy in seismic data and to tie this to the available well and core material. The quality of the publically available seismic data that can be used is (for the targeted stratigraphy) of moderate quality, but in deep basin areas the data might be of too low a quality to provide the required detail. So it seems that the success of this project for a large part is dependent on the seismic data Fugro is contributing.

3.4 Follow up of the project

Based on the outcome of this project scope may lie in further detailing areas, either through additional 2D lines, 3D data sets and/or well data. Or possibly analyzing more new play types in the Northern Offshore and possibly elsewhere.

4 Project organization

4.1 Collaboration between contractor and partners

Parties involved:

1. "TNO, Netherlands Organisation for applied scientific research" (contractor), registered office at Schoenmakerstraat 97, 2628 VK Delft, The Netherlands.
2. "Wintershall Nederland B.V.", registered office at Bogaardplein 47, 2284 DP Rijswijk (ZH), The Netherlands.
3. "EBN B.V.", registered office at Moreelsepark 48, 3511 EP, Utrecht, The Netherlands.
4. ''Chevron Exploration and Production Netherlands B.V.'', registered office at Appelgaarde 4, 2272 TK Voorburg, The Netherlands
5. ''Centrica Production Nederland B.V.'', registered office at Polarisavenue 39-Transpolis, 2132JH, Hoofddorp, The Netherlands.
6. "TOTAL E&P Nederland B.V.", registered office at Bordewijklaan 18, 2591 XR, Den Haag, The Netherlands.
7. ''Fugro GeoServices B.V.'', registered office at Veurse Achterweg 10, 2264 SG, Leidschendam, The Netherlands.
8. "NAM, Nederlandse Aardolie Maatschappij B.V.", registered office at Schepersmaat 2, 9405 TA, Assen, The Netherlands.

A steering comity (SC), consisting of JIP Participant representatives, needs be formed within the JIP. The SC shall be chaired by a JIP Participant. The SC shall be responsible for the management of the overall progress and quality within the JIP.

The SC shall gather as often as it deems necessary, but at least annually, in order to discuss the progress of the research and results.

The SC shall decide on the following matters:

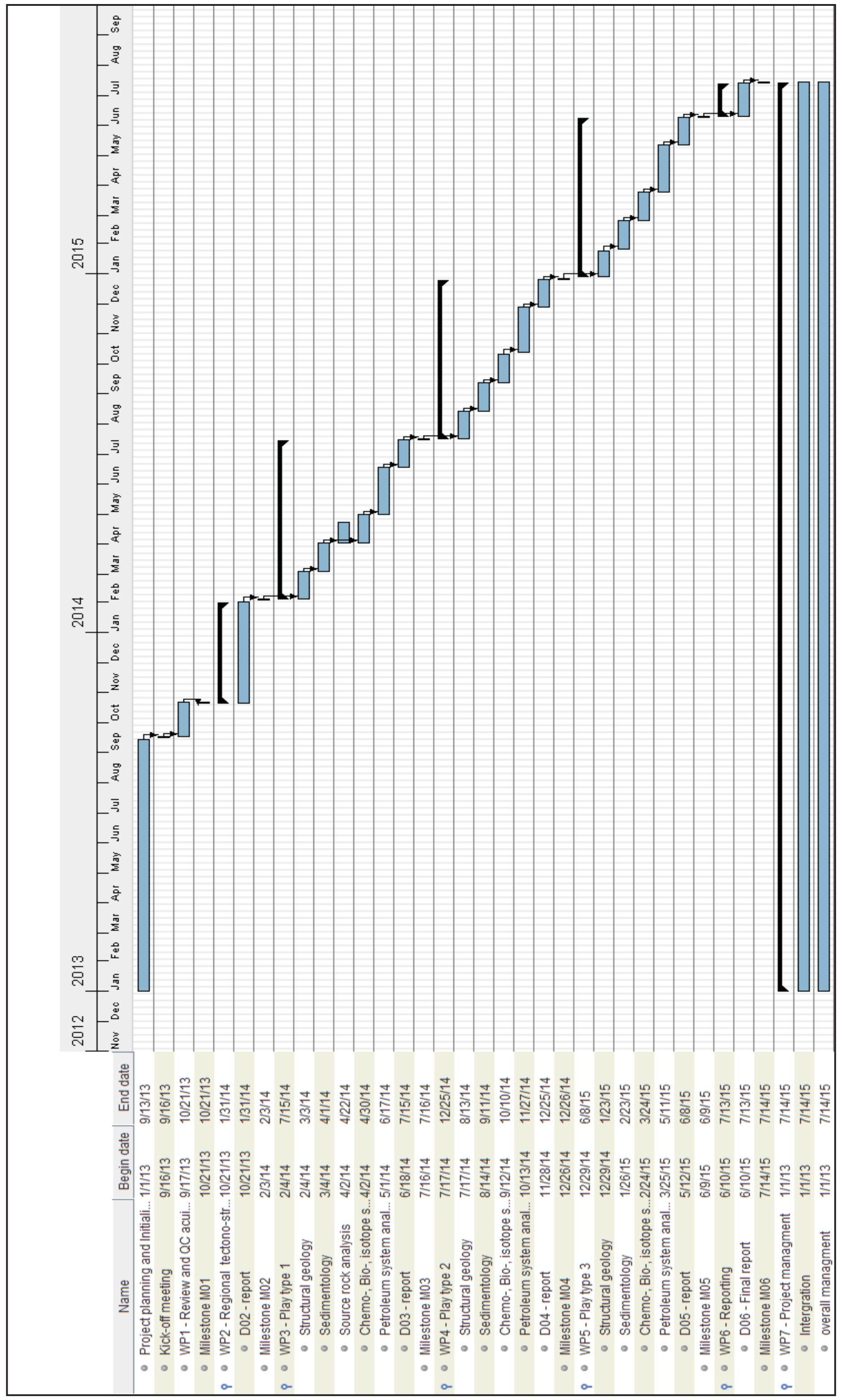
1. Proposals regarding the scope of the research;
2. Evaluation of the progress of the research;
3. Evaluation of results;
4. Entry of late participants and the conditions thereof;
5. The height of a late participant fee to be paid by a late participant in excess of the participation fee;
6. Any other key executive decision that the SC deems necessary to decide on during the course of the JIP;
7. The review of publications.

TNO has provided a project coordinator for the JIP (Vincent Vandeweijer). The SC chairman shall be the single point of contact for the project coordinator within the SC. The project coordinator shall be the single point of contact for the SC chairman within the project management team.

Project coördinator: TNO
Project Manager: Vincent Vandeweijer
Principal Scientist: Johan ten Veen
Business Developer: Yvonne Schavemakers

New petroleum systems in the Dutch Northern Offshore

4.2 Planning



4.3 Meetings

Date	Meeting	Short description of the meeting
2013.09.09	*Kick off meeting*	*SC installation & discuss project plan*
2014.02.03	*Milestone M02 meeting*	*SC meeting & Discuss results WP2 and decide on execution of the analysis of play types*
2014.07.14	*Milestone M03 meeting*	*Discuss results WP3, evaluate progress and apply in work ahead*
2014.12.26	*Milestone M04 meeting*	*Discuss results WP4, evaluate progress and apply in work ahead*
2015.05.12	*Milestone M05 meeting*	*Discuss results WP5, evaluate progress*
2015.06.30	*Final closing meeting*	*SC meeting & Discuss end results & recommendations*

Note: Additional meetings can be scheduled if deemed necessary by the SC or project manager.

4.4 Financing

CONTRACTORS **Execution of the project**	Budget per contractor **2012 (€)**	**Clarification**
TNO	*€ 720.000*	
TOTAL BUDGET	***€ 720.000***	

FINANCERS **Financial contributions**	Contribution per partner **2012 (€)**	**Clarification**
CASH contribution		
TOTAL E&P Centrica Wintershall EBN Chevron NAM **Total**	*€ 65.000* *€ 65.000* *€ 65.000* *€ 65.000* *€ 65.000* *€ 65.000* ***€ 390.000***	Equally divided (€ 65.000) by six companies:
INKIND contribution		
FUGRO TNO **Total**	*€ 65.000* *€ 65.000* ***€ 130.000***	Seismic Data Results KIP Explore (T. Donders)
Subsidy EL&I	***€ 330.000***	Innovation contract subsidy Upstream EL&I budget
TOTAL BUDGET	***€ 850.000***	Total project amount.

New petroleum systems in the Dutch Northern Offshore

4.5 Breakdown of the project costs

WP		**Total (k€)**	**Labour TNO (k€)**	**Labour external (k€)**
Project startup & initialisation		**20**	**20**	
1	*Acquiring, reviewing and loading data*	25	25	
2	*Regional geology and Structural Geology*	100	80	20
3	*Play types 1*	160	140	20
4	*Play types 2*	145	140	5
5	*Play types 3*	145	140	5
6	*Reporting*	40	40	
7	*Project management*	85	85	
	Total	**720**		

Note: amounts are estimations

5 Dissemination and communication

Possible dissemination to the outside world could go through conferences like:
1. EAGE
2. Petex
3. Prospects

No final decision is taken yet, as this dissemination is highly dependent on the progress and outcome of the project.

6 References

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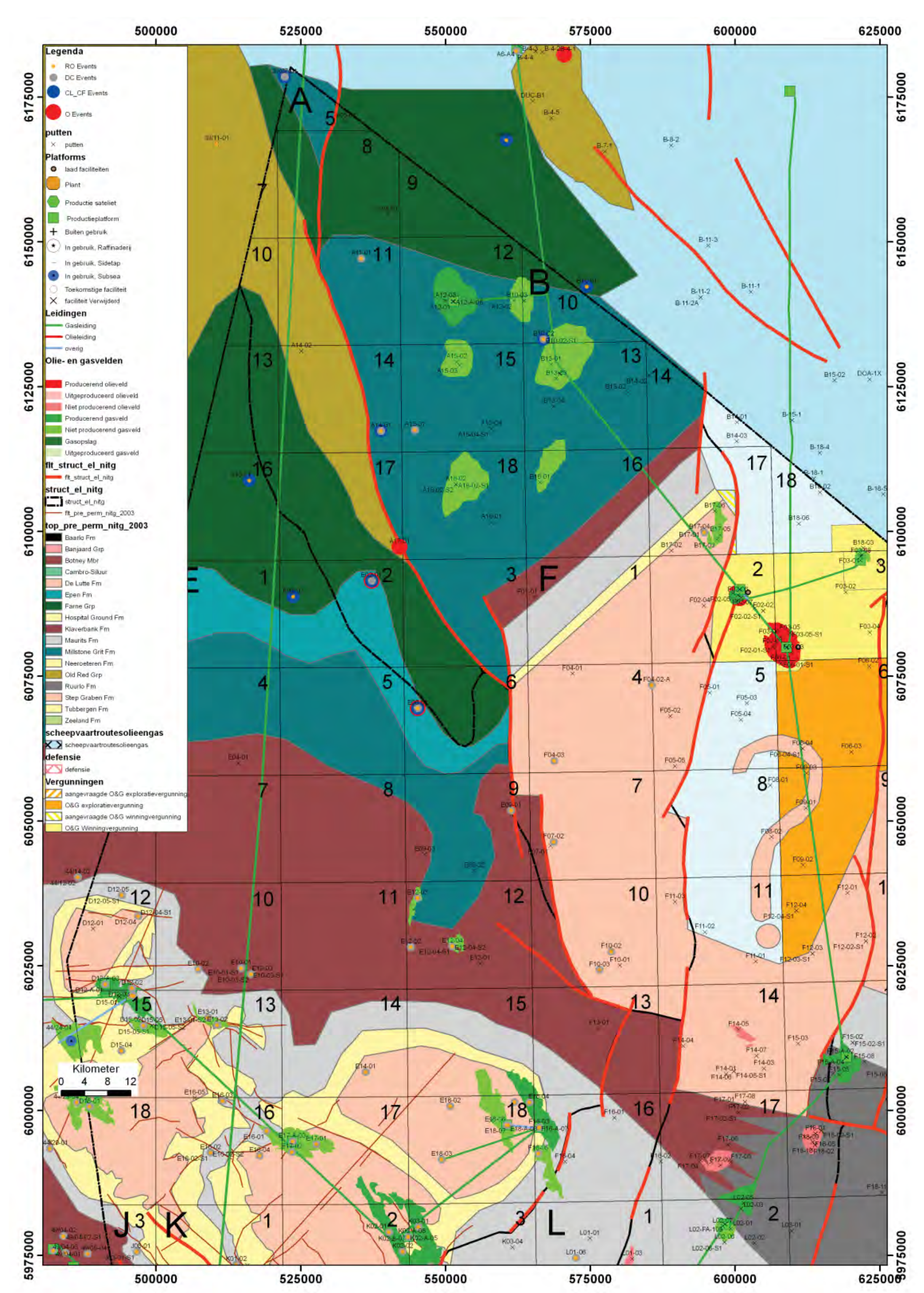
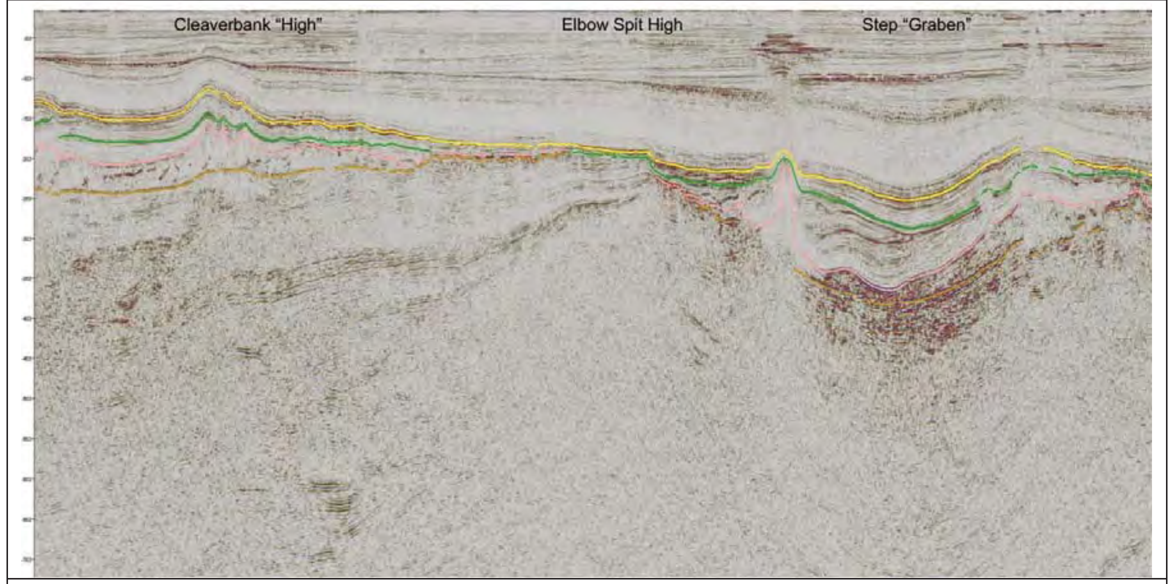
Appendix A

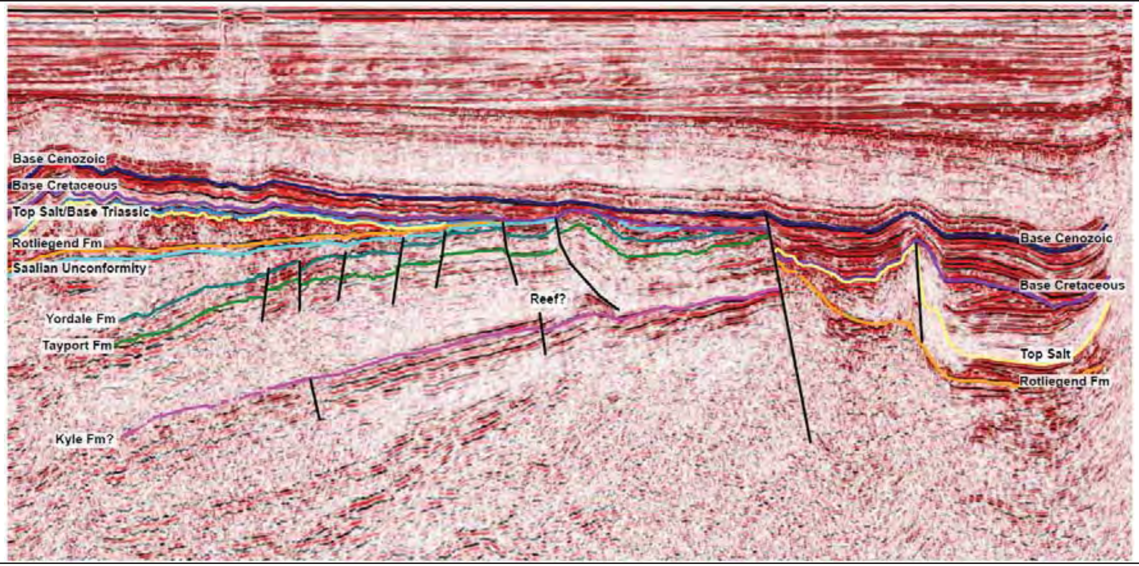


Top Pre-Permian distribution map

Appendix B



Long offset NSR data, courtesy of Fugro and TGS. Ref: Poster 8, Shallow gas prospectivity. (EBN et al 2010)



Seismic line from the Cleaverbank High towards the Elbow Spit High From the new 3D long cable Spec survey (EBN et al 2011)

New petroleum systems in the Dutch Northern Offshore

Appendix C

Preliminary selection of wells in the northern Dutch offshore that penetrate Lower Carboniferous rocks. (from: van den Hemel 2010)

Well	X-Coord (UTM-3)	Y-Coord (UTM-3)	Total depth (m)	Strat at TD	Client name	Result	Year
A11-01	535448	6147143	3900	Millstone Grit Fm	Placid	Dry	10/31/1981
A14-01	538868	6117385	3014	Elleboog Fm	NAM	Dry	6/4/1982
A15-01	544753	6117561	3912	Millstone Grit Fm	Placid	Gas shows	4/13/1987
A16-01	516154	6108805	2708	Farne Group	Elf Petroland	Dry	6/10/1974
A17-01	542083	6097329	3044	Plutonic rock	Mobil	Dry	4/27/1972
B10-01	574439	6142306	3188	Visean-Namur	Amoco	Dry	8/25/1977
B10-02-s1	566941	6133197	3972	Yoredale Fm	Amoco	Dry	9/21/1982
B17-04	594727	6099868	4657	Maurits Fm	ARCO	Dry	2/21/1990
E02-01	537297	6091503	2595	Tayport Fm	NAM	Dry	4/1/1972
E02-02	523748	6088759	2647	Elleboog Fm	Mobil	Dry	11/13/1990
E06-01	545213	6069482	3200	Tayport Fm	NAM	Dry	10/25/1983
E09-01	561371	6051807	3401	Millstone Grit Fm	NAM	Gas	10/31/1980
E10-01-s1	514735	6024611	3859	Klaverbank Fm	Placid	Dry	10/16/1984
E10-02	507283	6024417	4385.5		Wintershall	Gas shows	3/6/1990
E12-02	544026	6028262	4428	Millstone Grit Fm	Conoco	Dry	3/29/1990
E12-03	545198	6036716	3865	Igneous rock	Elf Petroland	Gas	9/4/1991
E12-04-s2	551201	6028394	4046	Klaverbank Fm	Elf petroland	Gas shows	2/7/1996

Appendix D

Rotliegend Lithostratigraphy in wells of the Dutch northern offshore .

SHORT_NM	END_DATE	END_AH_DEPTH	END_TV_DEPTH	X_CRD	Y_CRD	STRAT_UNIT_CD	STRAT_UNIT_NM	TOP_AH	BOTTOM_AH	THICKNESS_AH	TOP_AH_NAP
A11-01	31-okt-81	3900	3899.402	535448	6147143	ROCL	Silverpit Formation	3682	3705	23	3648.49
A14-01	04-jun-82	3014	3012.219	538868	6117385	ROCL	Silverpit Formation	2569	2598	29	2538.8
A15-01	13-apr-78	3912	3911.259	544753	6117561	ROCL	Silverpit Formation	3588.5	3635	46.5	3557.3
A16-01	10-jun-74	2708		516154	6108805	ROSL	Slochteren Formation	2219	2226	7	2188.7
B10-01	30-aug-77	3188.2	3187.66	574439	6142306	ROCL	Silverpit Formation	3028	3073	45	2996.2
B10-01	30-aug-77	3188.2	3187.66	574439	6142306	ROSL	Slochteren Formation	3073	3081	8	3041.2
B10-02-S1	21-sep-82	3972	3967.649	566941	6133197	ROSL	Slochteren Formation	3708	3722	14	3671.1
B17-04	21-feb-90	4657.65	4654.034	594727	6099868	ROCL	Silverpit Formation	4116.5	4300	183.5	4075.25
E02-02	30-nov-90	2647		523748	6088759	ROCL	Silverpit Formation	2342	2351	9	2306.27
E06-01	25-okt-83	3200	3199.384	545213	6069482	ROCL	Silverpit Formation	2123	2196	73	2083.7
E09-01	31-okt-80	3401	3397.068	561371	6051807	ROCLU	Upper Silverpit Claystone Member	2790.5	2876.5	86	2762.5
E09-01	31-okt-80	3401	3397.068	561371	6051807	ROCLE	Silverpit Evaporite Member	2876.5	3109	232.5	2848.5
E09-01	31-okt-80	3401	3397.068	561371	6051807	ROCLL	Lower Silverpit Claystone Member	3109	3192	83	3081
E10-01-S1	16-okt-84	3859		514735	6024611	ROCL	Silverpit Formation	3422.5	3691	268.5	3389.2
E10-02	06-mrt-90	4385.5	4046.955	507283	6024417	ROCLU	Upper Silverpit Claystone Member	3595	3703	108	3560.6
E10-02	06-mrt-90	4385.5	4046.955	507283	6024417	ROCLE	Silverpit Evaporite Member	3703	3874	171	3668.6
E10-03-S1	03-sep-02	3623	3620.447	516422	6023573	ROCL	Silverpit Formation	3367	3623	256	3328.55
E10-03-S2	07-okt-02	3800	3790.611	516422	6023573	ROCL	Silverpit Formation	3367	3634	267	3328.55
E12-02	29-mrt-90	4428	4426.438	544026	6028262	ROCLU	Upper Silverpit Claystone Member	3272.5	3369	96.5	3237
E12-02	29-mrt-90	4428	4426.438	544026	6028262	ROCLE	Silverpit Evaporite Member	3369	3594.5	225.5	3333.5
E12-02	29-mrt-90	4428	4426.438	544026	6028262	ROCLL	Lower Silverpit Claystone Member	3594.5	3672	77.5	3559
E12-02	29-mrt-90	4428	4426.438	544026	6028262	ROSLL	Lower Slochteren Member	3672	3679	7	3636.5
E12-03	04-sep-91	3865	3862.547	545198	6036716	ROCLU	Upper Silverpit Claystone Member	3119	3223	104	3083.9
E12-03	04-sep-91	3865	3862.547	545198	6036716	ROCLE	Silverpit Evaporite Member	3223	3442	219	3187.9
E12-03	04-sep-91	3865	3862.547	545198	6036716	ROCLL	Lower Silverpit Claystone Member	3442	3491	49	3406.9
E12-04-S2	07-feb-96	4046	4040.1	551201	6028394	ROCLU	Upper Silverpit Claystone Member	3365	3470	105	3326.5
E12-04-S2	07-feb-96	4046	4040.1	551201	6028394	ROCLE	Silverpit Evaporite Member	3470	3740	270	3431.5
E12-04-S2	07-feb-96	4046	4040.1	551201	6028394	ROCLL	Lower Silverpit Claystone Member	3740	3830	90	3701.5
E13-01-S2	21-mei-84	4277	4266.805	509007	6016047	ROCL	Silverpit Formation	3287	3575	288	3251.9
E13-02	22-jun-85	4109	4106.98	510637	6014777	ROCLU	Upper Silverpit Claystone Member	3319	3433	114	3285.6
E13-02	22-jun-85	4109	4106.98	510637	6014777	ROCLE	Silverpit Evaporite Member	3433	3578	145	3399.6
E13-02	22-jun-85	4109	4106.98	510637	6014777	ROCLL	Lower Silverpit Claystone Member	3578	3628.5	50.5	3544.6
E14-01	30-jul-86	4208	4205.455	536240	6006679	ROCLU	Upper Silverpit Claystone Member	3573.5	3687	113.5	3541.8
E14-01	30-jul-86	4208	4205.455	536240	6006679	ROCLE	Silverpit Evaporite Member	3687	3835	148	3655.3
E14-01	30-jul-86	4208	4205.455	536240	6006679	ROCLL	Lower Silverpit Claystone Member	3835	3989	154	3803.3
E14-01	30-jul-86	4208	4205.455	536240	6006679	ROSLL	Lower Slochteren Member	3989	3999	10	3957.3
F04-02-A	16-okt-80	4656		585602	6073477	ROCLU	Upper Silverpit Claystone Member	3932	4031.5	99.5	3901.42
F04-02-A	16-okt-80	4656		585602	6073477	ROCLE	Silverpit Evaporite Member	4031.5	4333.5	302	4000.92
F04-02-A	16-okt-80	4656		585602	6073477	ROCLL	Lower Silverpit Claystone Member	4333.5	4400	66.5	4302.92
F04-02-A	16-okt-80	4656		585602	6073477	ROCLL	Lower Silverpit Claystone Member	4425	4444.5	19.5	4394.42
F04-03	04-mei-92	4547.6	4545.715	568781	6060433	ROCLU	Upper Silverpit Claystone Member	3842.5	3935	92.5	3802.5
F04-03	04-mei-92	4547.6	4545.715	568781	6060433	ROCLE	Silverpit Evaporite Member	3935	4170	235	3895
F04-03	04-mei-92	4547.6	4545.715	568781	6060433	ROCLL	Lower Silverpit Claystone Member	4170	4288.5	118.5	4130
F07-02	05-nov-92	4200	4188.364	568695	6046405	ROCLU	Upper Silverpit Claystone Member	3294.5	3374	79.5	3256.98
F07-02	05-nov-92	4200	4188.364	568695	6046405	ROCLE	Silverpit Evaporite Member	3374	3660	286	3336.48
F07-02	05-nov-92	4200	4188.364	568695	6046405	ROCLL	Lower Silverpit Claystone Member	3660	3783	123	3622.48
F10-02	17-sep-85	4442	4439.595	578616	6027473	ROCLU	Upper Silverpit Claystone Member	3514.5	3585	70.5	3481.64
F10-02	17-sep-85	4442	4439.595	578616	6027473	ROCLE	Silverpit Evaporite Member	3585	3999	414	3552.14
F10-02	17-sep-85	4442	4439.595	578616	6027473	ROCLL	Lower Silverpit Claystone Member	3999	4061	62	3966.14
F10-03	03-jan-99	4498	4481.917	576619	6024319	ROCL	Silverpit Formation	3391	4006	615	3351.4

2 Literature Review

Appendix 2.1: Overview of the tectono-sedimentary evolution of the Dutch northern offshore within the Northwest-European palaeogeographical context

Appendix 2.2: The Grensen Formation

Overview of the tectono-sedimentary evolution of the Dutch northern offshore within the Northwest-European palaeogeographical context

(with emphasis on the proto-Central Graben area during the Late Palaeozoic)

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Reviewed by: Renaud Bouroullec and Johan H. ten Veen

1 Introduction

This report summarizes the results of a literature review and data-integration exercise on the Late-Palaeozoic evolution of the West European basin (Palaeozoic) system and succeeding Southern Permian Basin. The main focus is on the development of the area that now comprises the Dutch northern offshore. This is a relatively underexplored part of the Dutch offshore sector that may contribute to future reserves.

The area encompasses the N-S aligned Dutch Central Graben (Fig. 1), a mainly Mesozoic extensional basin, which may have been active as a gently subsiding feature during the latter part of the Palaeozoic Era. A number of basement highs and platforms are located on both side, and are discussed in detail in the next section.

This analysis consists of three parts:

1. a comprehensive literature overview of the tectono-sedimentary evolution of the study area with the NW European larger-scale framework, and
2. an integration of available data from part 1 to produce regional maps with the aim of developing new insights with respect to:
    a. tectonic history
    b. source area evolution
    c. sediment dispersal patterns
3. general conclusions about the tectono-sedimentary evolution of the Northern offshore.

2 Summary of structural elements

In the northern offshore area, the following main structural elements are distinguished (Fig. 1):

Grabens - Dutch Central Graben, North Sea Central Graben and Step Graben.

Platforms and Highs – Mid North Sea High (with sub-element Elbow Spit High), Ringkøbing-Fyn High, Cleaver Bank Platform and Schill Grund Platform.

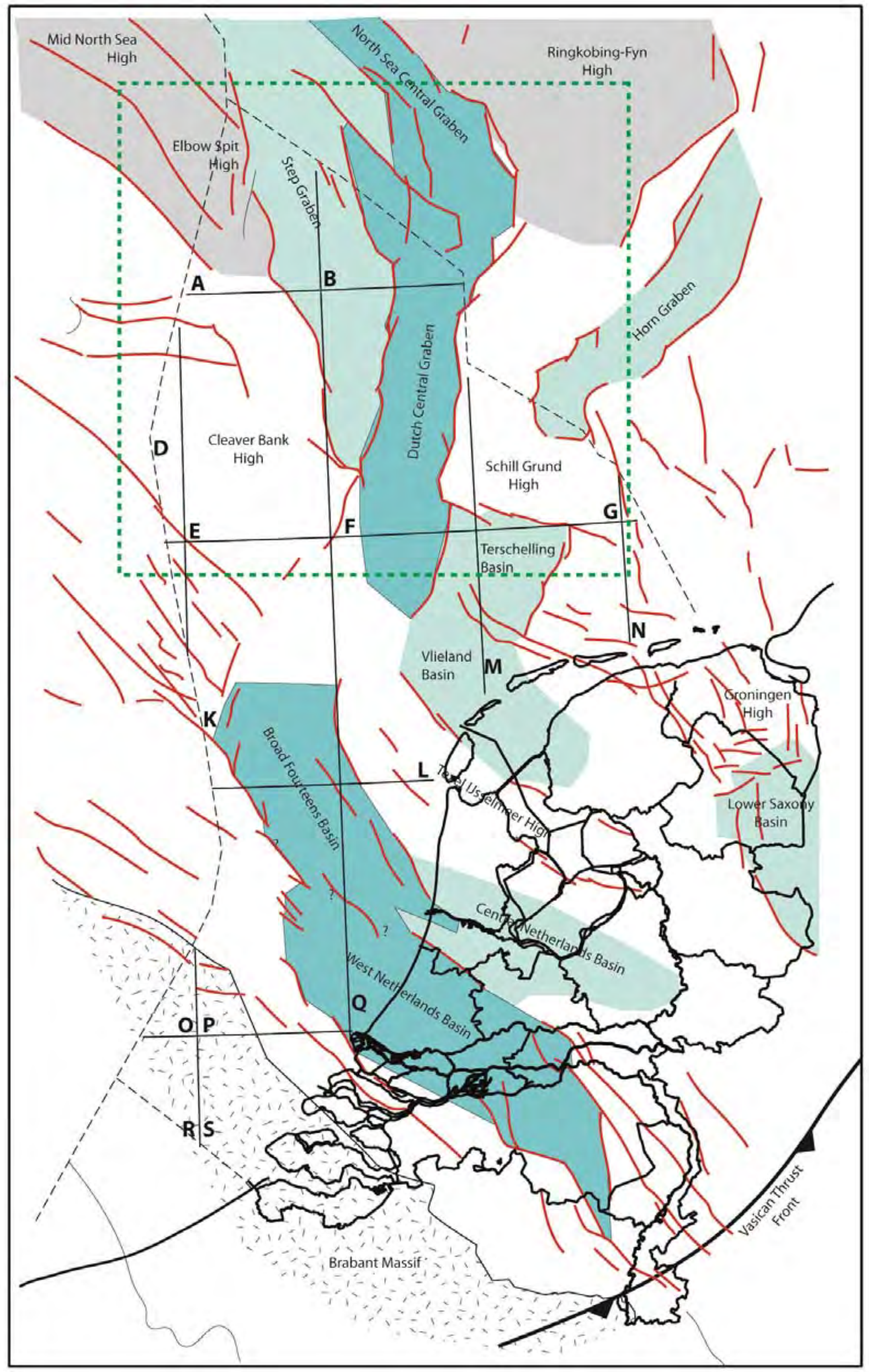

Figure 1: Structural elements in the Netherlands on- and offshore (after De Jager 2007).

The geometry of these lows and highs is largely the result of Mesozoic tectonics (Atlantic extension/rifting), but many sources report that these structures were already active during the Palaeozoic (De Jager, 2007; Geluk, 2007; Van Adrichem Boogaert and Kouwe, 1993; Maynard et al., 1997), which is dealt with in more detail in later sections.

2.1 *North Sea Central Graben*

The North Sea Central Graben (or short: Central Graben) together with its northward extension –the Viking Graben- constitutes the main part of the North Sea rifting system. Rifting started in the Triassic under E-W extension and transected the Northern and Southern Permian Basins (Pharaoh, 2010). The North Sea Central Graben has a present-day NW-SE orientation (Fig. 2). It approximately coincides with the boundary of Avalonia (in the South) and the Norwegian Caledonian Highlands (Fig. 2; (Glennie, 1990; Coward, 1990)).

2.2 *Dutch Central Graben*

The *Dutch* Central Graben is the southerly, NNE-SSW trending, extension of the North Sea Central Graben (Fig. 1). The change of orientation may be related to the possible westward extension of the Trans European fault (Glennie, 1997), which runs parallel to the Tornquist Line (Fig. 2) and coincides with the boundary between Avalonia and the Fenno-Scandian craton.

The Dutch Central Graben experienced increased subsidence during the Triassic, indicated by thickened Triassic sequences and infilling primarily by Jurassic marine sequence (Fig. 3) (De Jager, 2007).

According to various source a proto-Dutch Central Graben was already active during the Late Palaeozoic (De Jager, 2007; Van Adrichem Boogaert and Kouwe, 1993). Such claims however find limited support in isopach data (Van Adrichem Boogaert and Kouwe, 1993).

The Graben inverted during the Late Cretaceous.

2.3 *Step Graben*

The Step Graben is a parallel feature to the west of the Dutch Central Graben (Fig. 1) that subsided at a slower pace and therefore contains a thinner Triassic-Jurassic sequence (De Jager, 2007). In contrast with the Dutch Central Graben, the Step Graben is viewed as a Mesozoic rift structure and no Palaeozoic activity is expected to have occurred (De Jager, 2007; Van Adrichem Boogaert and Kouwe, 1993). The Step Graben served as a slowly subsiding shoulder platform to the main Dutch Central Graben during Mesozoic rifting (Fig. 3).

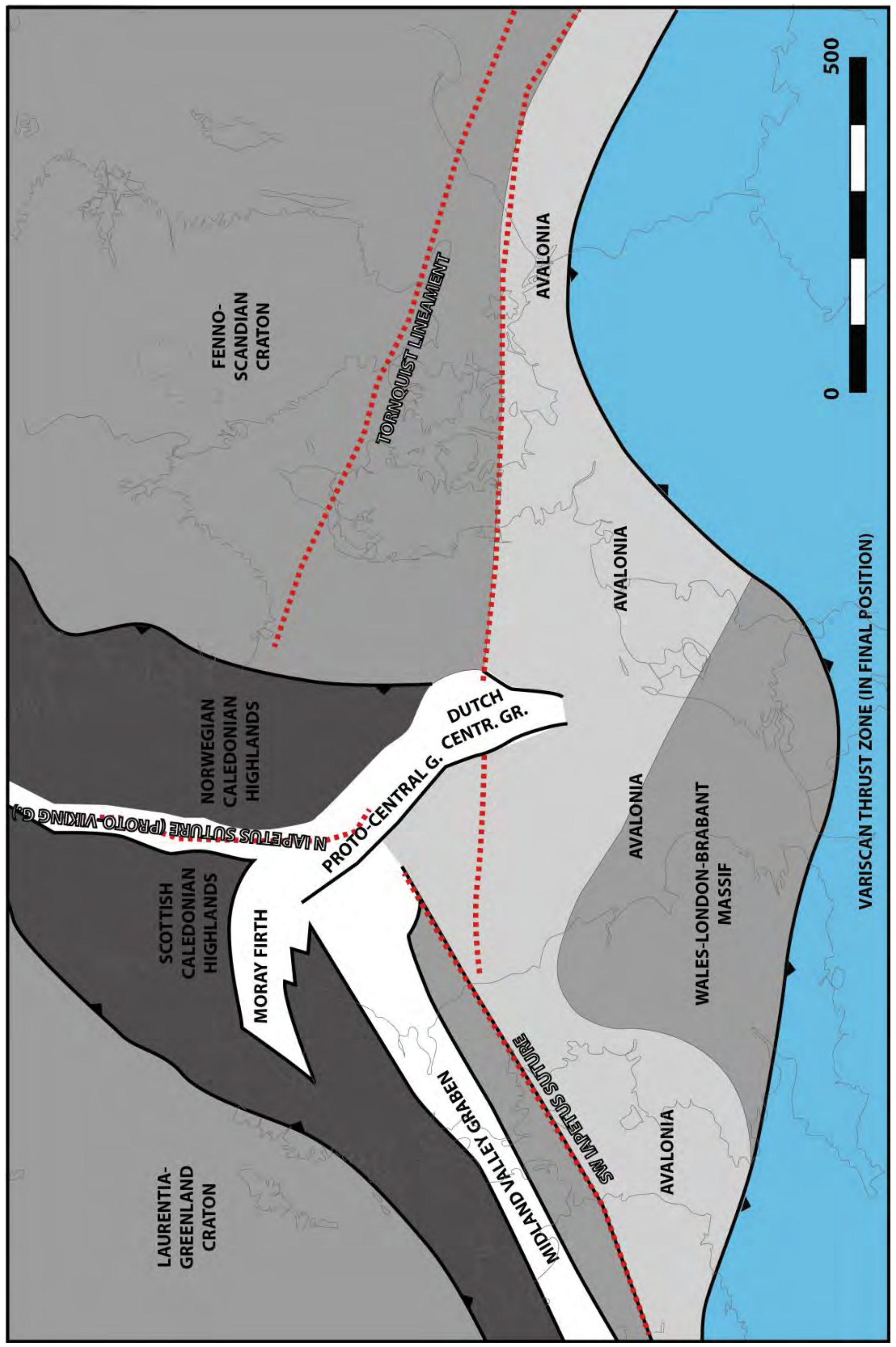

Figure 2: Palaeozoic tectonic framework of NW Europe with Caledonian and Variscan orogenic situations depicted (after Glennie 1990).

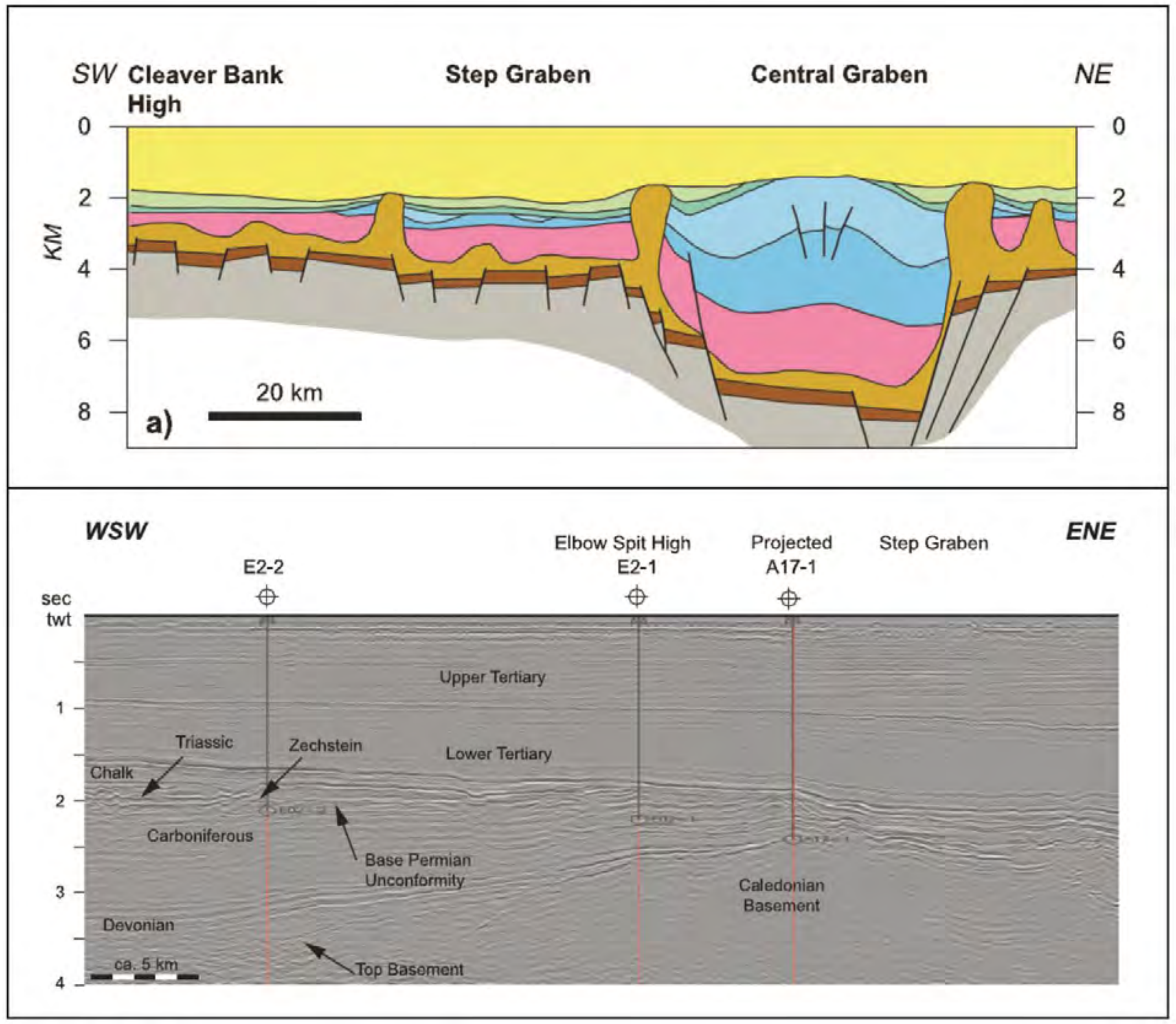

Figure 3: Cross-sections through the Dutch Central Graben/Step Graben/Cleaver Bank Platform rift systems, and accross the Elbow Spit High. Taken from De Jager (2007).

2.4 *Mid North Sea High-Ringkøbing-Fyn High*

These two highs formed an E-W aligned low-relief area primarily during the Permian and Triassic. Its orientation may be related to the E-W aligned Trans European Fault zone lineament. The structural ridge was transected by the (proto?) Dutch Central Graben extensional system. During the Carboniferous, the Mid North Sea High was an area of slow subsidence (Cope et al., 1992).

2.5 *Elbow Spit High*

The Elbow Spit High is a SSE trending extension of the Mid North Sea High that protrudes into Dutch territorial waters. The area experienced deposition throughout the Carboniferous but, due to Mesozoic (rift-shoulder) uplift, the Lower Carboniferous is now truncated and overlain by Cretaceous deposits (Fig. 3).

2.6 *Cleaver Bank Platform/ Schill Grund Platform*

The Cleaver Bank Platform was a slowly subsiding structure during the (Late) Permian and Triassic. It was a stable platform during the Jurassic/Cretaceous and served as a rift shoulder to the Dutch Central/Step Graben extension system (Fig. 2 & 3). According to Quirk (1993) this high is bounded at its northwestern and southeastern sides by major Caledonian NW-SE trending lineaments.

During the Carboniferous, the area was part of the main coal basin and experienced uniform subsidence (Quirk, 1993), but strata may thin over the high (Van Adrichem Boogaert and Kouwe, 1993).

The Schill Ground Platform is a southerly extension of the Ringkøbing-Fyn High, which served as the eastern rift shoulder of the Dutch Central/Step Graben rift system.

Note that these platforms were known as highs previously and have recently been renamed by Kombrink et al. (2012).

3 Large-scale tectonic framework and evolution during the Caledonian and Variscan orogenic cycles

3.1 *Introduction*

The Palaeozoic sedimentary evolution within the NW European basin system was primarily controlled by the Caledonian and Variscan orogenic cycles. Figure 2 is a composite map (Glennie, 1990) for the Late Palaeozoic, showing the main elements and their orientation for both orogenic systems.

The map shows how the NW European Palaeozoic basin system coincides with the Avalonian microcontinent, which itself is enclosed between the Fenno-Scandian and the Laurentian continental masses in the NE and NW. The collision of those two continents gave rise to the Caledonian orogen (Ziegler, 1990), and a number of slivers of continental crust in the South making up the Variscan internides (Fig. 2).

In the following section a summary of events is given.

3.2 *Pre-Caledonian and Caledonian orogeny*

Before the collision of Baltica and Laurentia during the Late Ordovician, the Avalonian microcontinent, later to become the NW European Palaeozoic basin system, moved rapidly northward, from a near South Pole position, only to collide with the Caledonian landmass (Stampfii et al., 2002). Earlier, in its southern position, the Avalonian microcontinent was part of an island arc system, with active subduction occurring in the northern Proto-Tethys domain (Fig. 4).

The main phase of Caledonian orogeny took place during the Late Ordovician and Silurian, and includes the closure of the N-S oriented Iapetus Ocean, due to the E-W directed collision of Laurentia (W) and Baltica (E) (Fig. 2). This resulted in the formation of a symmetric NS aligned orogenic ridge with thrusts on either side (Glennie, 1990; Ziegler, 1990). Subsequent orogenic inversion resulted in uplift of the system and formation of two highland ridges located E and W of the Iapetus suture (Scottish and Norwegian Caledonian highlands). The suture zone later became the site of rifting when the Viking Graben later opened (Glennie, 1990; Coward, 1990).

These highlands would be the main source for sediment to the NW European Palaeozoic basin system during Devonian and Carboniferous, and to a lesser extent, Permian times (e.g. Cope et al., 1992; Ziegler, 1990; Glennie, 1998; Besly, 1998)

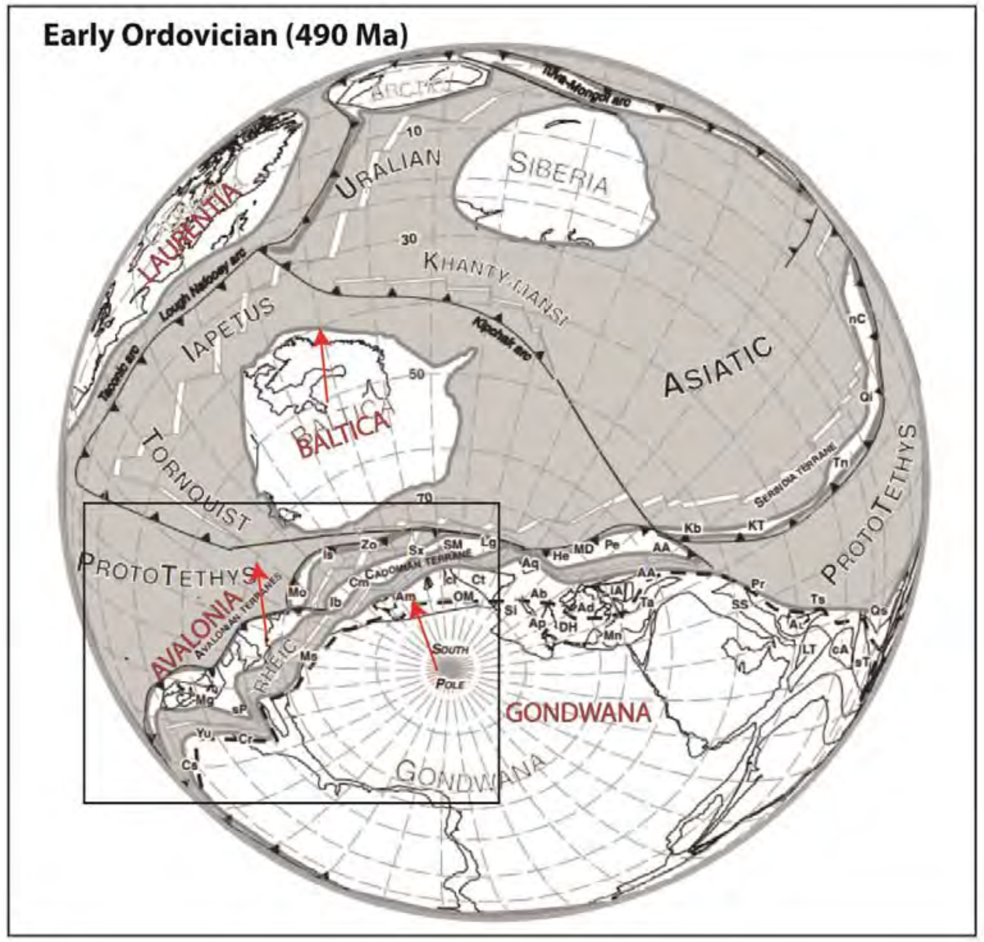

Figure 4: Palaeogeography during the Early Ordovician (taken from Stampfii et al., 2002)

3.3 Variscan orogeny

Northward movement of Gondwana, which moved at a slower pace than Baltica and Avalonia (Glennie, 1990; Stampfii et al., 2002), ultimately resulted in an N-S collision and the formation of the Laurussian megacontinent (Fig. 2). In NW Europe, this continent-continent collision started during the Late Carboniferous (Namurian), only to culminate during the Late Westphalian (C/D) (Coward, 1990; Ziegler, 1990; Leeder et al., 1990). Initially, during the Late Devonian and Early Carboniferous, the NW European Basin, which is viewed as a back-arc extensional basin at that time (Coward, 1990; Ziegler, 1990; Leeder, 1987; Leeder, 1982), was located to the north of a number of elongate microcontinental slivers. These microcontinents had detached from the northern margin of Gondwana during the Ordovician (Glennie, 1990; Ziegler, 1990; Stampfii et al., 2002) and collided with Avalonia well ahead of Gondwana (Coward, 1990). The Rheic Ocean, located between these continental slivers and Gondwana (Fig. 4), quickly narrowed by the approach and subduction of Gondwana.

The Rheic Ocean had disappeared entirely at the start of the Namurian (~330 Ma) when the actual continental collision commenced (Ziegler, 1990). It would take some time however until enough topography had been created for the Variscan orogen to become a major sediment source.

The culmination of thrusting took place during the Late Carboniferous (Westphalian C/D) resulting in the Variscan thrust belt becoming a sediment source to the NW European Basin system, which up to then had mainly received sediments from the northern Caledonides. The compressional phase, associated with folding and uplift in the foreland basins, was associated with major thrusting (Coward, 1990; Leeder and Hardman, 1990; Waters et al., 1994).

3.4 Late Variscan strike-slip and orogenic inversion

Once the continent-continent collision was completed during the Late Carboniferous, strike slip movements increasingly accommodated ongoing compressional forces between Gondwana and Laurussia, as the collision between the continents was not head-on but occurred at an angle (Glennie, 1990). Laurussia's effective net movement was to the NW, resulting in dextral slip along the major NW-SE lineaments (Fig. 2), such as the Tornquist line and Transeuropean Fault zone, as well as minor lineaments and faults of similar orientation.

According to Ziegler (1990), the regional stress pattern in Western and Central Europe changed fundamentally at the transition from Westphalian to Stephanian, with the principle horizontal compressional stress-axis rotating from north-south to east west. During the Stephanian and Autunian, a complex system of conjugate sinistral and dextral shear faults came into place, causing the formation of transtensional and pull-apart basins, as well as transpressional deformation.

The strike-slip regime that was active during the Stephanian may have been responsible for the scarcity of Stephanian deposits through the Variscan foreland (Ziegler, 1990), much of which, in addition, has been reinterpreted as Late Westphalian (Besly et al., 1993). Those few (sub)basins that possibly did accumulate Stephanian deposits (e.g. proto-Dutch Central Graben) may represent pull-apart basins in an overall transpressive system.

Contemporaneously with the early Stephanian rotation of compressional stress from north-south to east-west, the Oslo Graben came into existence (Ziegler, 1990) and magmatic activity (300 Ma) was associated with this event (Ziegler, 1990). Possibly the Horn Graben, i.e. the southward extension of the Oslo Graben also developed at that time. However, Stephanian and Autunian deposits are missing in those grabens, possibly pointing at thermal elevation (Ziegler 1990). At the same time, the east-west trending Mid North Sea-Ringkøbing-Fyn High was uplifted.

This phase of strike-slip tectonics ultimately brought about the collapse of the Variscan mountain range, when the Variscan orogen and its foreland became transected by major sinistral and dextral wrench faults (Ziegler, 1990). The main elements of this system comprised the Tornquist-Teisseyre and the Bay of Biscay fracture zones, with the area located in the middle being dissected by a complex conjugate fault shear system. The principle factor controlling the Late Carboniferous tectonic change from overall compressional to strike slip was likely the dextral translation of North Africa relative to Europe (Ziegler, 1990).

The Variscan foreland was inverted, possibly because of isostatic unroofing, causing truncation of the thick Late Carboniferous sequence, typically to Westphalian A/C depth (Van Buggenum and Den Hartog Jager, 2007). Westphalian D sediments seem to be preserved only in areas where Westphalian C/D compression resulted in the creation of (syndepositional) lows (Leeder and Hardman, 1990; Waters et al., 1994).

The Early Permian is represented in most of NW Europe as a major (Saalian) unconformity, representing some 20-30 My (Ziegler, 1990; Glennie, 1990; Geluk, 2007). It represents erosion associated with a long-lasting post-orogenic phase of volcano-thermal event. Volcanic activity centered in Germany (Ziegler, 1990; Heeremans, 2004), but was more widespread (Martin, 2002) and is evidence of the transtensional nature of Early Permian strike-slip deformation (Glennie, 1990).

At the end of the Autunian (earliest Permian), the dextral wrenching that affected the Variscan foreland gradually abated and a phase of subsidence began, ultimately resulting in the formation of the Northern and Southern Permian basins (Glennie, 1997; Ziegler, 1990; Corfield et al., 1996). These two basins are separated by the above-mentioned Stephanian-Autunian Mid North Sea-Ringkøbing-Fyn trend. Subsidence was primarily governed by thermal relaxation following Stephanian/Autunian wrenching and involved little faulting (Ziegler, 1990). The Variscan fold belt was still characterized by considerable relief and became progressive degraded, supplying sediment to the Northern and Southern Permian Basins.

In the following section, the sedimentary development of the study area throughout the Late Palaeozoic is described using the above-described tectonic framework.

4 Integration of data

For a number of periods paleogeographic maps are presented using literature-collected data on basin structure, sediment sourcing, sediment transport routes and various other aspects.

The main purpose was to analyze the detailed tectono-sedimentary history of the Dutch northern offshore area within a wider tectonic framework to gain insight into the history of the Dutch Central Graben system and its vicinity. More specifically insight into the early tectonic development of the system and the possibility of the development of related reservoir rocks (Late Westphalian/Stephanian/Rotliegend sandstones) and source potential (late Westphalian to Stephanian coal beds) of Carboniferous and Permian age.

Maps are presented for the following approximate periods:

i. Dinantian/Namurian (Fig. 5)
ii. Westphalian A-early B (Fig. 6)
iii. Westphalian B- Early C (Fig. 7)
iv. Westphalian C/D (Fig. 9)
v. Stephanian (Fig. 11)
vi. Rotliegend (Fig. 13)

Each map is accompanied by a description of main observations and conclusions in the following section.

4.1 Dinantian/Namurian

During this period, the NW European Basin system experienced back-arc extensions as a result of subduction of remnant oceanic plate (Rheic Ocean) wedged in between Avalonia and northward drifting Gondwana (Coward, 1990; Leeder, 1987; Leeder, 1982). The basin is characterized by a remarkable arc-shaped block-and-basin structure (Corfield et al., 1996), which fits the back-arc extension situation (Fig. 5), but the origin of which is commonly attributed to reactivation of Caledonian faults (Collinson, 2005). Note, however, that the observed arc-structure is also in line with an early Ordovician oceanic arc, associated with Proto-Tethys oceanic underplating underneath Avalonia (*inset* in Fig. 4).

Rifting occurred from the Late Devonian onward, until continental collision commenced at the start of the Namurian, resulting in tectonic inversion (Fraser et al., 1990).

The Dinantian basins were dominated by carbonate and (black) shale deposition (Besly, 1998; Collinson, 2005; Fraser and Gawthorpe, 1990), in line with the equatorial palaeoposition. Shallow water carbonates accumulated in platform positions on top and adjacent to footwall fault blocks, under syndepositional tectonic control (Leeder, 1987; Leeder and Gawthorpe, 1987). However, clastic sediments were supplied from the north, resulting in dominance of fluvial and deltaic depositional environments there (Cope et al., 1992; Collinson, 2005). Clastic environments were present at least down to Dutch license blocks D and E and UK blocks 41-44 (De Jager, 2007; Van Buggenum and Den Hartog Jager, 2007; Collinson, 2005).

These clastic systems include major stacked fluvial systems, such as the Fell Sandstone system (Turner et al., 1993), the sandstone-dominated deposits of which are 100s of metres thick in places (Collinson, 2005). In more distal areas, deposits are of fluvio-deltaic origin and comprise cyclothemic (coal-bearing) 10m-scale alternations of fluvial sandstones and deltaic shales/coal (Collinson, 2005; Fielding, 1988).

During the Namurian, the same block-and-basin topography was in place and became progressively filled, due to a strong increase of (primarily fine-grained) sediment influx, which is thought to be related to the onset of continental collision (Besly, 1998; Corfield et al., 1996; Fraser et al., 1990). This influx of clastics from the south resulted in choking of the carbonate-producing system, possibly due to lack of light penetration. The Namurian depositional system was characterized by clay-dominated deeper-water deltaic systems (in the basins) and large feeder channels (Fig. 5; in yellow), flowing across the structural blocks and on top of infilled basins (Collinson et al., 1993).

Palaeocurrent data were collected from various sources, as well as info on sandstone distribution patterns, and plotted in Fig. 5 (Cope et al., 1992; Fielding, 1988). These data point at a northern sediment source, very likely a point source with the point of origin being the southern tip of the proto-Viking Graben, which lines up with the Caledonian Iapetus suture separating the Scottish and Norwegian Caledonian highlands (Fig. 2). This is supported by the sediment composition, which is indicative of an origin in the Norwegian and/or Greenland Caledonides belt (Collinson, 2005). If the sediment indeed came from the proto-Viking Graben, then being a successor-structure to the Caledonian suture line, this may point at early activity of the (later) North Sea rift system.

The Palaeocurrent data point at a dispersal pattern away from the estimated point source, but with an overall westward component (Fig. 5). The Namurian feeder channels, mapped by Collinson et al. (1993), show especially a strong tendency to flow away from the Norwegian Caledonian highlands. This may point at higher subsidence rates in the western part of the basin, and may involve a subdued-high position of the area, later to become the North Sea Central Graben/Step Graben/Dutch Central Graben rift system. Hence, the sediment dispersal system seems to indicate that any Carboniferous extension in that system had not been initiated yet.

On the other hand, De Jager (2007) mentions the presence of a "Devonian Seaway", as an element of accelerated subsidence, across the Netherlands in the Late Devonian and Dinantian reconstructions of (Ziegler, 1990), and interprets this as a possible early manifestation of the proto-Dutch central Graben. Note however that this "Devonian Seaway" strikes NW-SE, essentially lining up with the later Vlieland Basin (Fig. 1) and is in fact at an (approx. 60°) angle with the later Dutch Central Graben. It lines up fairly well, however, with the Step Graben system. This may hint at early activity of the latter system, which is also seen in Westphalian depositional patterns (see next sections).

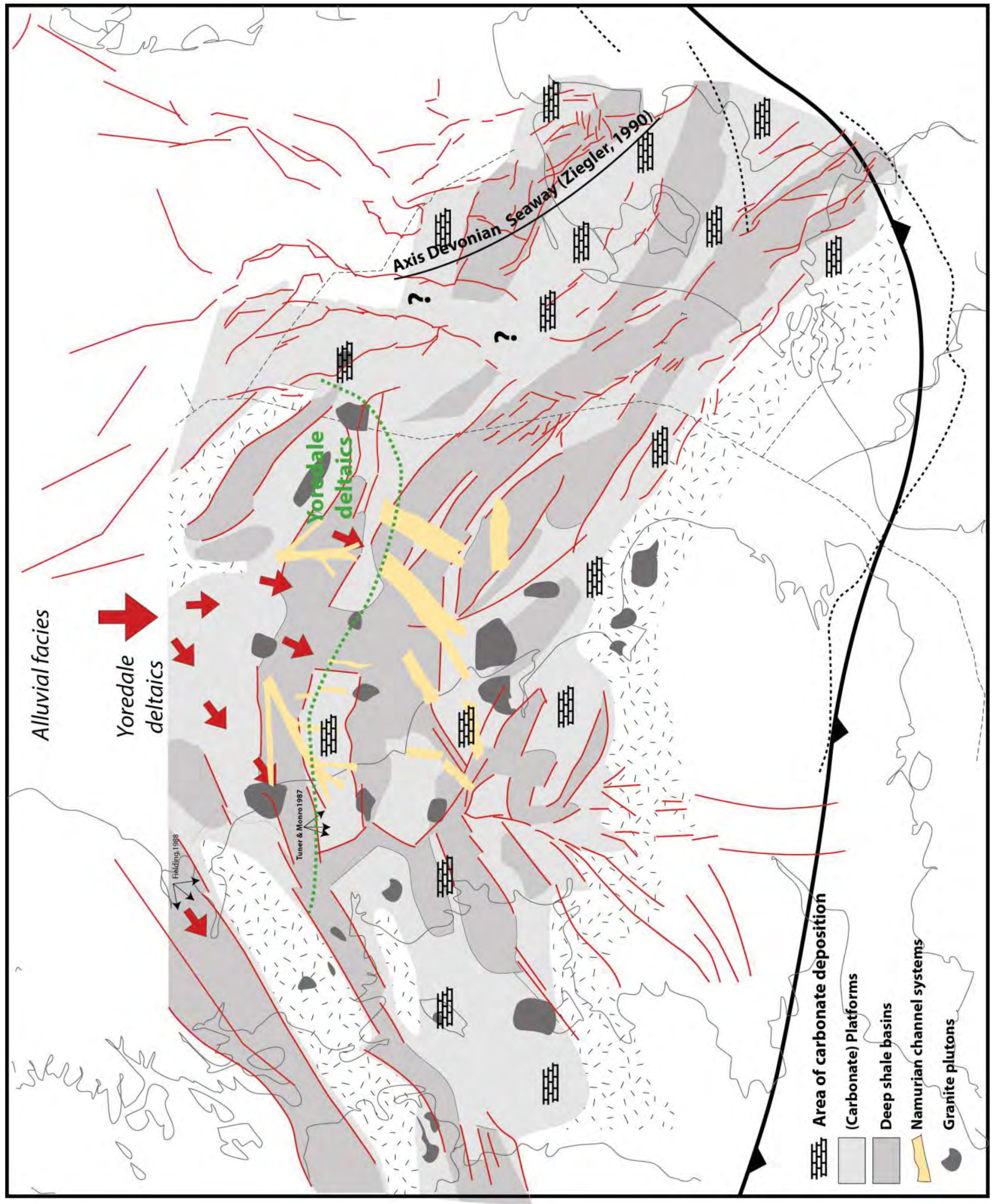

Figure 5: Palaeogeographic map for the Dinantian/Namurian period. Red arrows indicate overall sediment transport directions. Faults compiled from Corfield et al. (1997), De Jager (2007) and Glennie (1997) and Stemmerik (2000). Namurian channel systems from Collinson (1993).

4.2 *Westphalian A-Early B*

With the start of the Westphalian, a period of thermal subsidence commenced (Fraser and Gawthorpe, 1990), which is reflected in a much more uniform subsidence pattern and increased regional correlatability of depositional sequences. During the final stages of the Namurian, all remaining block-and-basin topography had been filled, causing leveling of the depositional surface all across the NW European basin system (Besly, 1998; Leeder and Hardman, 1990). This allowed the formation of extensive coal beds, and deposition throughout the Westphalian A- early C was dominated by regular alternations of coal beds, (marginal marine) deltaic shales and fluvial sandstones (Collinson et al., 1993; Fielding, 1984b; Fielding, 1984a; Guion and Fielding, 1988), driven by glacio-eustatic sea-level fluctuations (Greb et al., 2008; Heckel, 2008; Van den Belt et al., 2012).

During the Early Westphalian, the Variscan thrusts were still remote and the developing orogen had not become a major sediment source area yet (Besly, 1998; Collinson et al., 1993). Only during the Westphalian C would major sandstones be deposited in the southern parts of the Variscan foreland (Jones and Glover, 2005; Drozdzewski, 1993).

Fluvial sandstone deposition was common, however, in the northern parts of the NW European Basin system, especially in its northwestern parts (Fig. 6). This is reminiscent of the Dinantian situation, although the coarse-clastic depositional area became more extensive and the point source seemed to have widened to a line source covering primarily the Scottish Caledonian highland, i.e. the area to the west of the proto-Viking Graben (Fig. 2).

Throughout the western part of the Southern North Sea and onshore U.K. deltaic sequences contain common intercalated fluvial sandstones (Van Adrichem Boogaert and Kouwe, 1993; Besly, 1998; Collinson et al., 1993; Collinson et al., 1993). However, thick fluvial intercalations are rare to absent in most of the Dutch offshore and onshore. Such thick sands are restricted to the westernmost quadrants of the offshore (Fig. 6). Examples of the absence of thicker sandstones are found in wells published in the Dutch stratigraphic nomenclature (Van Adrichem Boogaert and Kouwe, 1993), e.g. M01-01, Steenwijkerwold-1, Goldhorn-1, in (Besly, 1998) and in TNO (2009), e.g. wells in the G17/18 license blocks.

The pronounced east-west contrast concerning fluvial sourcing indicates a structural control along a ridge that parallels the proto-Dutch Central Graben system. Palaeocurrent data from Cope et al. (1992) suggest that the sediment dispersal directions may have paralleled this divide (Fig. 6). It may point at a more elevated position of the proto-Central Graben and possibly of the area east of it. However, Lower Westphalian intervals are very thick in wells from the northern Dutch onshore (Van Adrichem Boogaert and Kouwe, 1993), which suggests that it is not the entire eastern area that is more elevated but that the elevated zone may indeed be elongate.

The proto-Step Graben itself, especially its western part may have been an already subdued element, but data in the Lower Westphalian is too imprecise to accurately map fluvial sandstone distribution.

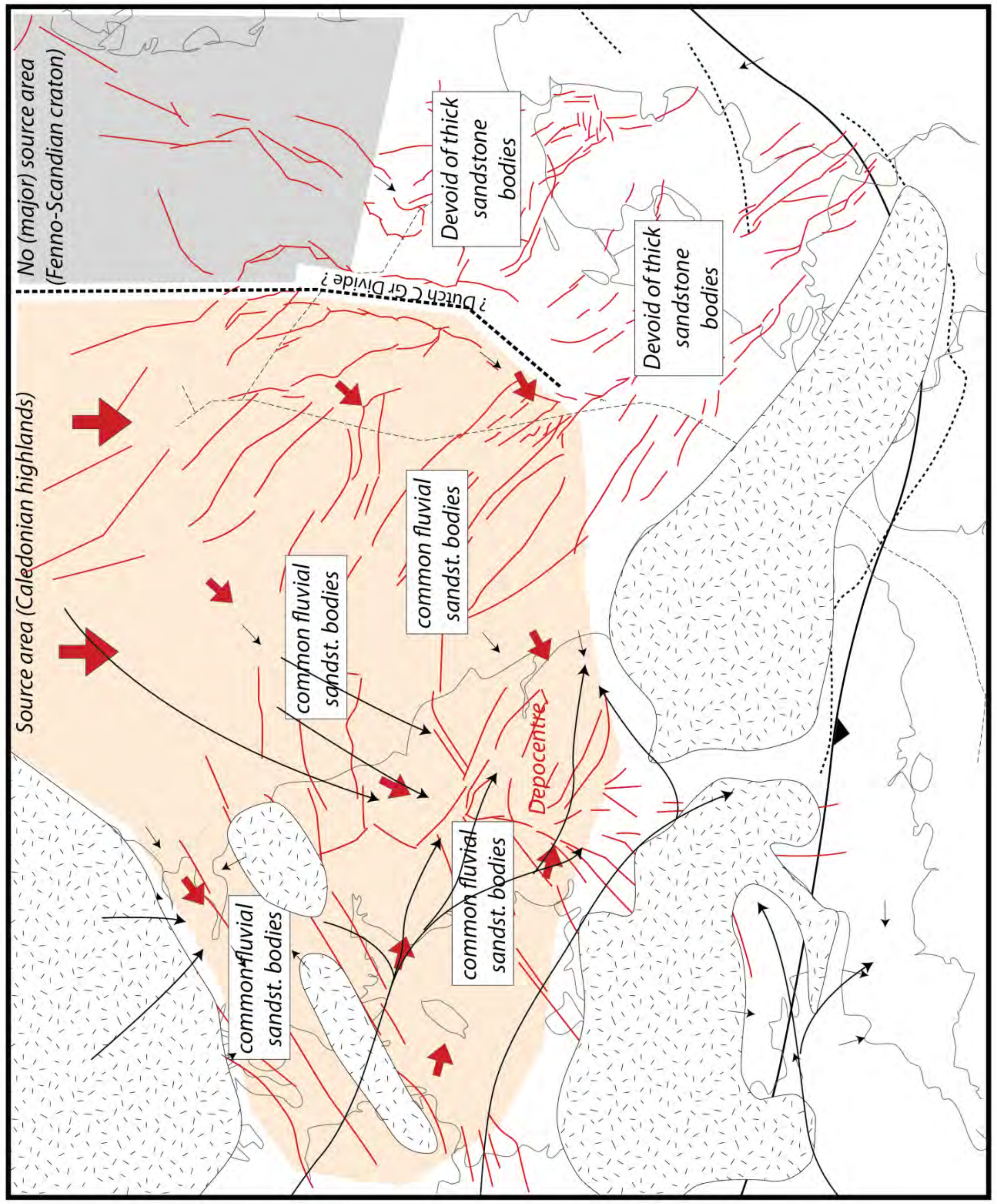

Figure 6: Palaeogeographic map for the Westphalian A- Early B period. Red arrows indicate overall sediment transport directions. Yellow indicates presence of common fluvial sandstone sourced from N. Black arrows show local (measured) palaeocurrents from (Cope et al., 1992) and various other sources (e.g. Besly & Kelling, 1988; Van Adrichem Boogaert & Kouwe, 1993; Collinson et al., 2005).

4.3 *Westphalian B-Early C*

Although the overall sedimentary style during the Westphalian B and Early C is comparable to that of the Westphalian A (dominated by cyclothemic fluvio-deltaic sediments), a drastic and rapid reorganization of fluvial sediment dispersal is observed.

The northern Caledonian highlands remained the main source area, but major fluvial systems seem to have retreated largely from the Southern North Sea. This is quite clear in wells from the D and E blocks (Fig. 8; Van Adrichem Boogaert and Kouwe (1993)). Not far, above the Westphalian A-B boundary the sandstone-dominated sequence is abruptly overlain by a mudstone and coal-dominated sequence; this is observed regionally. More to the west, however, mainly onshore UK, fluvial sedimentation continued well into the Westphalian C (Rippon 2005), O'Mara and Turner 1999).

Hence, somewhere during early Westphalian B, the boundary between the western fluvial dominated and the eastern sand-starved areas shifted westward abruptly. Because many Westphalian sequences in the UK onshore are deeply truncated, the exact boundary is not accurately established, but it seems to line up approximately with the southward extension of the proto-Viking Graben.

A possible explanation for the retreat of fluvial systems out of the eastern Southern North Sea might be the initiation of extension in the proto-North Sea Central Graben (Fig. 7). Note that it links up to the NW with the proto-Viking Graben and thus shields the eastern part of the Southern North Sea from Caledonian sources. Any remaining sand influx onwards came from the Scottish Caledonian highlands and material from the Norwegian Caledonian highlands must have been channeled through the proto-Viking Graben (Fig. 2).

It seems likely that, if indeed the proto-North Sea Central Graben started to subside more rapidly than surrounding areas, it must have attracted much of the sand influx derived from Norwegian Caledonian highlands. Therefore, the Central Graben area probably contains higher net-to-gross sequence than the coal-bearing Westphalian B/C forms the eastern Southern North Sea. Whether this also involved subsidence of the (later) Step Graben is uncertain.

4.4 *Late Westphalian C-D*

The culmination of Variscan thrusting brought about a major reorganization in the NW European Basin system. Thrust loading caused rapid subsidence in the south-east, resulting in the formation of a a-symmetric foreland basin along the Variscan thrust front (Ruhr Basin) that received a lot of sand from the mid Westphalian C onwards (Jones and Glover, 2005; Drozdzewski, 1993; Glover et al., 1996; Dreesen et al., 1995). These areas remained sites of peat accumulation and are coal-bearing up into Early Westphalian D (Cope et al., 1992; Jones and Glover, 2005). Further to the north Late Westphalian, coal diminishes in abundance and is not present roughly above the line Liverpool-Den Helder. There seems to be a northward protrusion of coal occurrence in the vicinity of the Dutch Central Graben (Fig. 9), which might be related to accelerated subsidence in that area.

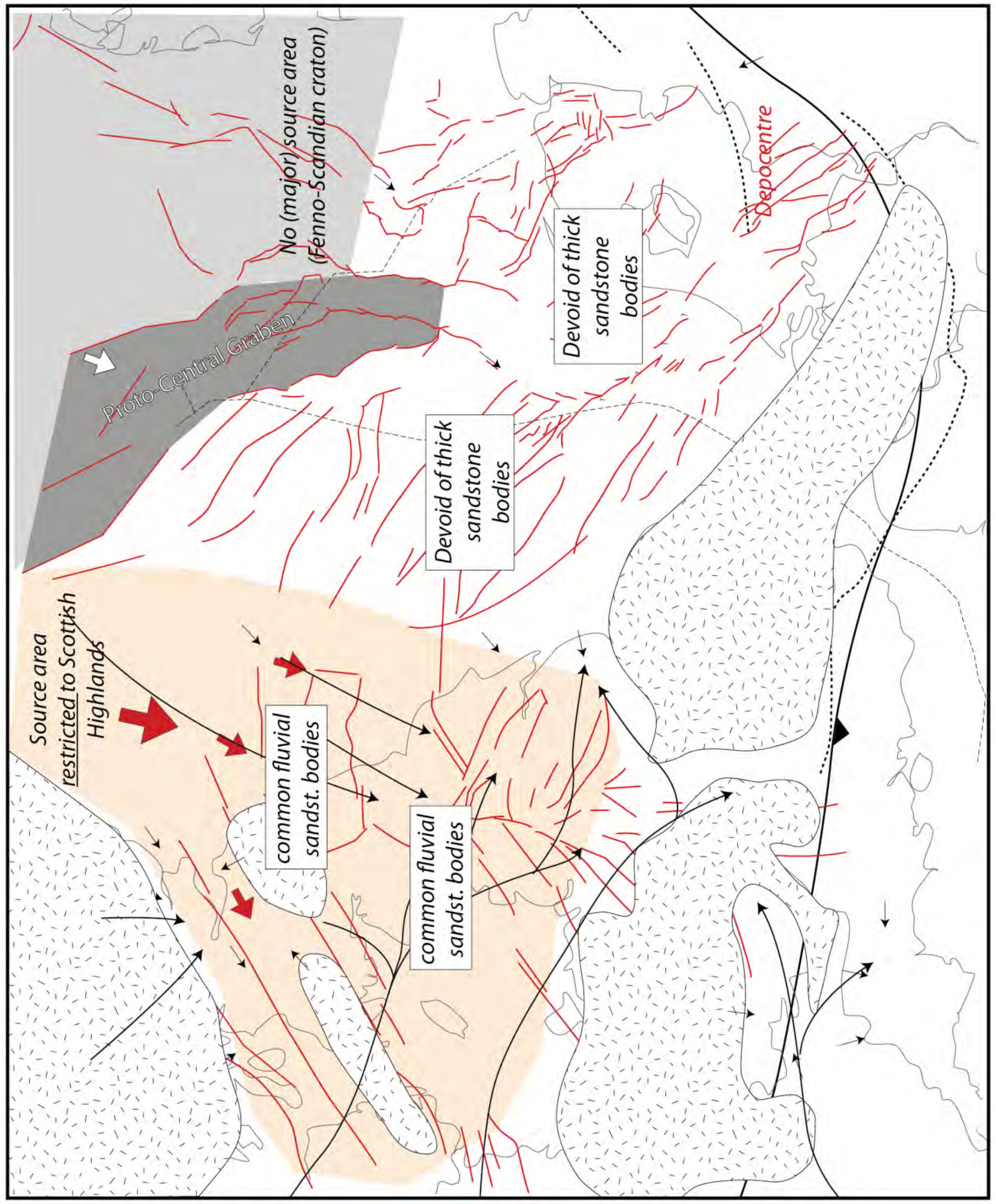

Figure 7: Palaeogeographic map for the Westphalian B- Early C period. Red arrows indicate overall sediment transport directions. Yellow indicates presence of common fluvial sandstone sourced from N. Black arrows show local (measured) palaeocurrents from (Cope et al., 1992) and various other sources (e.g. Besly & Kelling, 1988; Van Adrichem Boogaert & Kouwe, 1993; Collinson et al., 2005).

In the northern parts of the basin, the Late Westphalian-C and Westphalian D are developed as red-beds (Cope et al., 1992; Besly, 2005). Also in the south such red-beds occur (Jones and Glover, 2005), but these overlie much thicker coal-measures sequences. In the north, the red-beds typically (erosionally) overlie Westphalian B/C coal-measures (Leeder and Hardman, 1990; Besly et al., 1993; TNO, 2009; Jones et al., 2005). This is related to the Late Westphalian inversion phase recognized in the NW European basin system as inversion faults/folds (Leeder and Hardman, 1990; Waters et al., 1994; Peace and Besly, 1997).

The red-beds are interpreted as the deposits of fluvial channels and their overbank/substrate (Besly, 2005; Besly and Fielding, 1989) that developed under *well-drained* conditions (contrasting with the waterlogged-conditions for the coal measures). The transition from grey coal measures to red beds is typically abrupt or takes place in short vertical intervals (Quirk, 1993; TNO, 2009) and supports the idea that the facies transition was structurally controlled. It was originally attributed to northward continental movement into the subtropical climate zone (Glennie, 1990; Besly, 1998), but the abruptness of the change and its coincidence with the culmination of tectonic deformation may point at a tectonic cause. Red bed-beds occur in troughs in between mildly folded and cannibalized Westphalian A-B strata, with those older strata being reworked into the younger red-bed sequences in the surrounding low(er) lying areas (Leeder and Hardman, 1990). The formation of red beds is then probably related to deposition well above ground-water level due to folding of the northern foreland to well above base level. More to the south, in the vicinity of the Variscan thrust zone, where subsidence rates were much higher (Drozdzewski, 1993), the sediment surface possibly remained at base level thus allowing peat growth and preservation (to become coal) well into the Westphalian D.

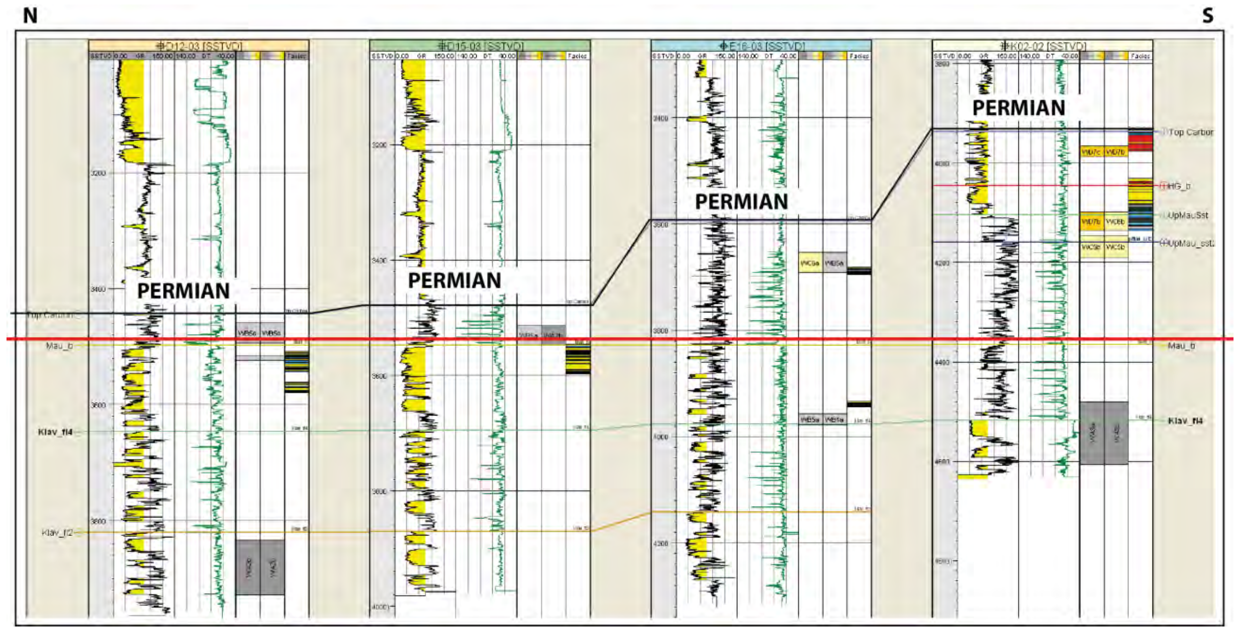

Figure 8: N-S correlation panel showing the abrupt upward transition from fluvial-dominated Westphalian A to coal/shale-dominated westphalian B/C (red line). From TNO (2009).

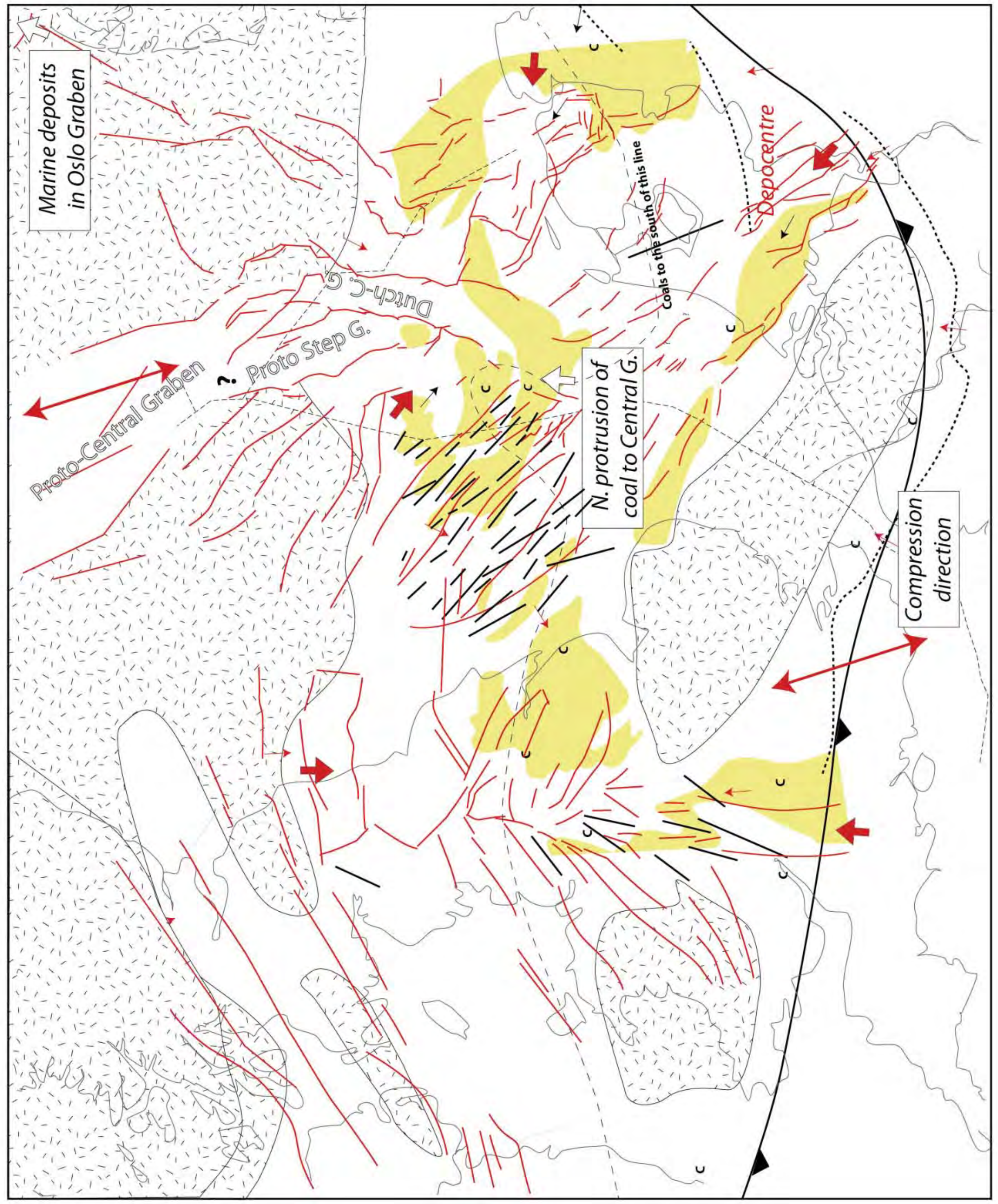

Figure 9: Palaeogeographic map for the Late Westphalian C-D period. Red arrows indicate overall sediment transport directions. Black arrows show local (measured) palaeocurrents from various sources e.g. (Cope et al., 1992)**. C-markers and dashed line indicate occurrence of late coal in southern parts of the basin. Solid black lines indicate faults and folds (re)activated during late Westphalian inversion. Double red arrows indicate interpreted compression direction. Refer to text for complete list of data sources (e.g. Leeder and Hartman, 1990, Water et al., 1994).**

The nature of Late Westphalian deformation has been dealt with in a number of publications and points at inversion of older basin structures by mild folding and faulting (Besly, 1998). Axes of compression have been documented in Staffordshire, onshore UK (Waters et al., 1994) and in the Southern North Sea (Leeder and Hardman, 1990). These axes are indicated in Fig. 9 as black solid lines that line up very well with existing (older) fault systems. In Fig. 10, these axes are plotted as overlays on the Dinantian block-and-basin structure, showing a good match in orientation. This supports the reactivation theory and indicates that the orientation of these structures is a not a direct reflection of the Late Westphalian compression direction.

The variation in the inversion axes of two distinct areas (west UK and SW North Sea), each with different orientation (NW-SE and NNE-SSW) give an approximate indication of the overall compression direction being NNW-SSE (Fig. 8/10, double red arrows). This direction parallels the orientation of the proto-Step Graben/North Sea Central Graben system. Depending on the overall stress situation, this may have permitted extension in the WNW-ESE direction in the proto-Central Graben system.

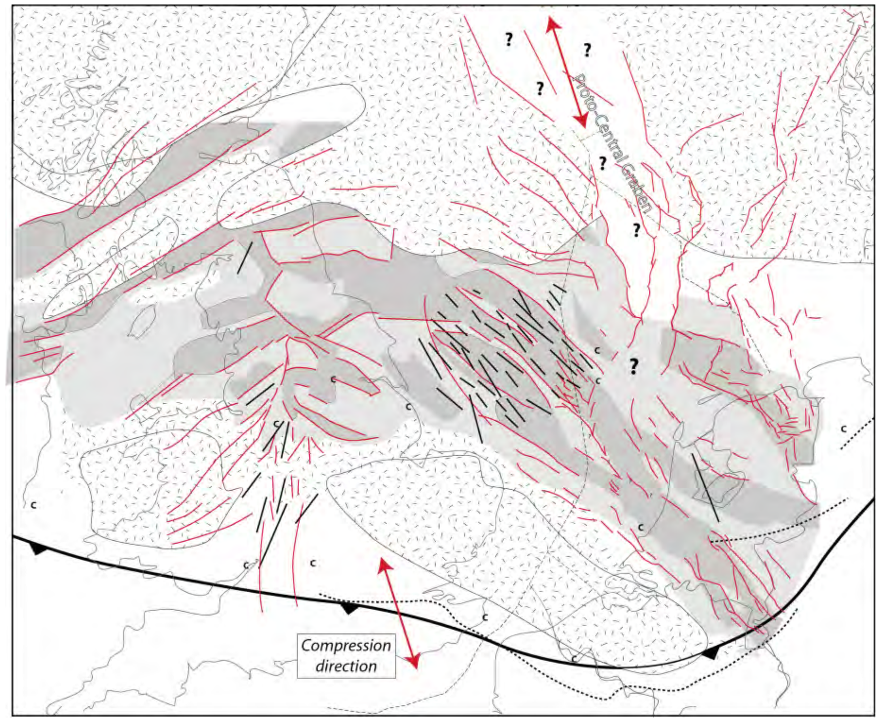

Figure 10: Late Westphalian inversion axes (black solid lines) overlain on Dinantian block-and-basin structure. See Figure 9 for references.

A number of publications deal with hydrocarbon fields within the red-bed sequence of the Southern North Sea, such as in the Ketch and Schooner formations (Jones et al., 2005; Mijnssen, 1997), but such studies give little further insight into the depositional environments of these red-bed deposits or their distribution and correlatability.

4.5 *Stephanian*

Little is known about the palaeogeographic situation in the NW European basin system during the Stephanian. This is due to two reasons: 1) It concerns the youngest Carboniferous

strata that were removed during Permian (Saalian) erosion, and 2) due to the highly oxidized red-bed character of the sediments hampers palynological is hampered.

Trough time sediments in a number of areas have been assigned a Stephanian age (Fig. 11), such as in the UK, Netherlands and Germany. All these sediments, however, have been reinterpreted as Westphalian D, or earliest Stephanian (Cantabrian) at best (Besly et al., 1993). As an example of such uncertainty, the deposits of the red-bed key well De Lutte-6, in the eastern onshore Netherlands have been interpreted initially as primarily Westphalian D with possible remnant Stephanian at the top (Van de Laar and Van der Zwan, 1996), then to dominantly Stephanian (Van Waveren et al., 2008), and then back to Westphalian D (Van Hoof et al., 2012).

Currently, the only succession with reliable indications of Stephanian age, based on palynology, is found at the base of a long cored section of calcrete-rich red-beds in well F10-2 (TNO, 2009). This basal unit comprises coal-measure type deposits, just below the red-beds and based on the presence of *Vittatina costabilis* and a high number of Striate bisaccate pollen in combination with abundant Lycospora spp. these strata are interpreted as not older than Stephanian. Besides the palynological content, the presence of common carbonate concretions within the overlying (upper) red-bed sequence may point at a non-Westphalian D origin (cf. Besly et al., 1993).

The well in question, F10-2, is positioned in the southernmost tip of the proto-Step Graben and therefore any Stephanian deposition (and preservation) may be related to continued subsidence of the proto-North Sea Central Graben/Step Graben system, that seems to have started during the early Westphalian B (see previous section).

All that is known about the depositional style in the NW European Basin during the Stephanian is what is known from well F10-2. In essence, it resembles the depositional style of the Westphalian D red-beds, i.e. in terms of channel thickness and stacking, and red-bed soil character. The only difference is the presence of calcrete soils in the top section (TNO, 2009), something not observed in red-beds from the Southern North Sea (Besly et al., 1993). It must be noted that red-beds in well De Lutte-6, interpreted as Westphalian D (Van Hoof et al., 2012) contain calcrete levels as well, which could point at a possible Stephanian upper part.

Additional indications of extensional tectonics in the area are given by the presence of volcanics within the graben systems (Fig. 11; Ziegler, 1990).

Also of interest is the possible occurrence of Stephanian or late Westphalian D coal beds (as source rocks of relatively shallow burial) within areas of accelerated subsidence, such as the proto-North Sea Graben system. There are indications that deposition under waterlogged conditions continued longer within the proto-Step Graben than in other parts of the NW European Basin system (TNO, 2009). Known occurrences of Stephanian coal are from intramontane in France and Germany, to the south of the Variscan thrust (Ziegler, 1990), such as the Saar-Nahe Basin (Lang, 1976; Schäfer, 1989). However, these coals are found in overall grey claystones. Coals are absent in the overlying Late-Stephanian red-bed part of the Saar-Nahe succession.

In general, it must be noted that any other Stephanian coals (e.g. in USA and Spain) are from basins that were located in a more southerly, near-equatorial palaeoposition during the Stephanian (Fig. 12). This remark holds for the Saar-Nahe Basin as well.

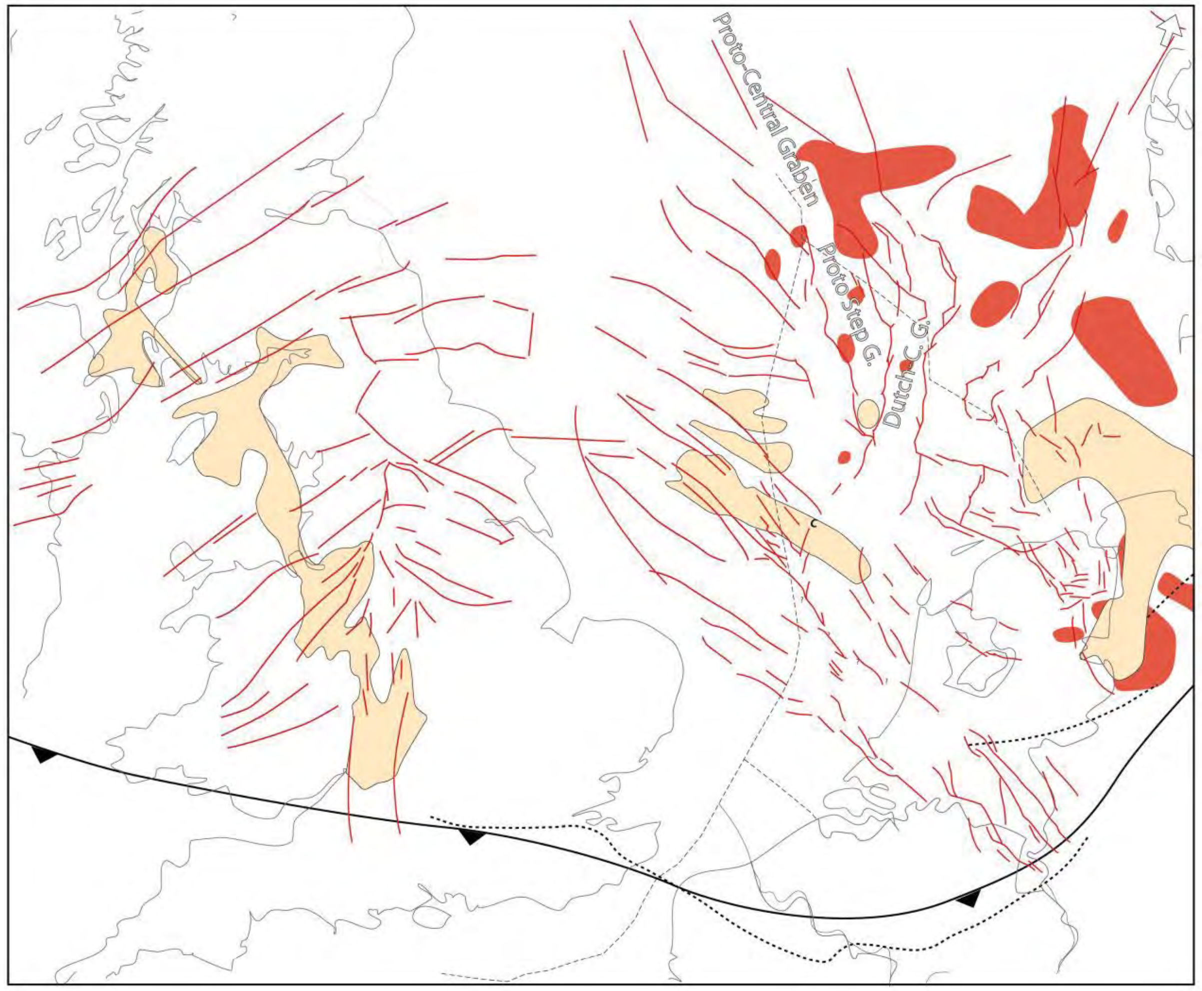

Figure 11: Map for the Stephanian showing areas at some time been interpreted as Stephanian in yellow (Ziegler, 1990), but mostly reinterpreted as Westphalian D (Besly, 1993). Stephanian volcanic indicated in red. Faults compiled from Corfield et al. (1997), De Jager (2007) and Glennie (1997) and Stemmerik (2000).

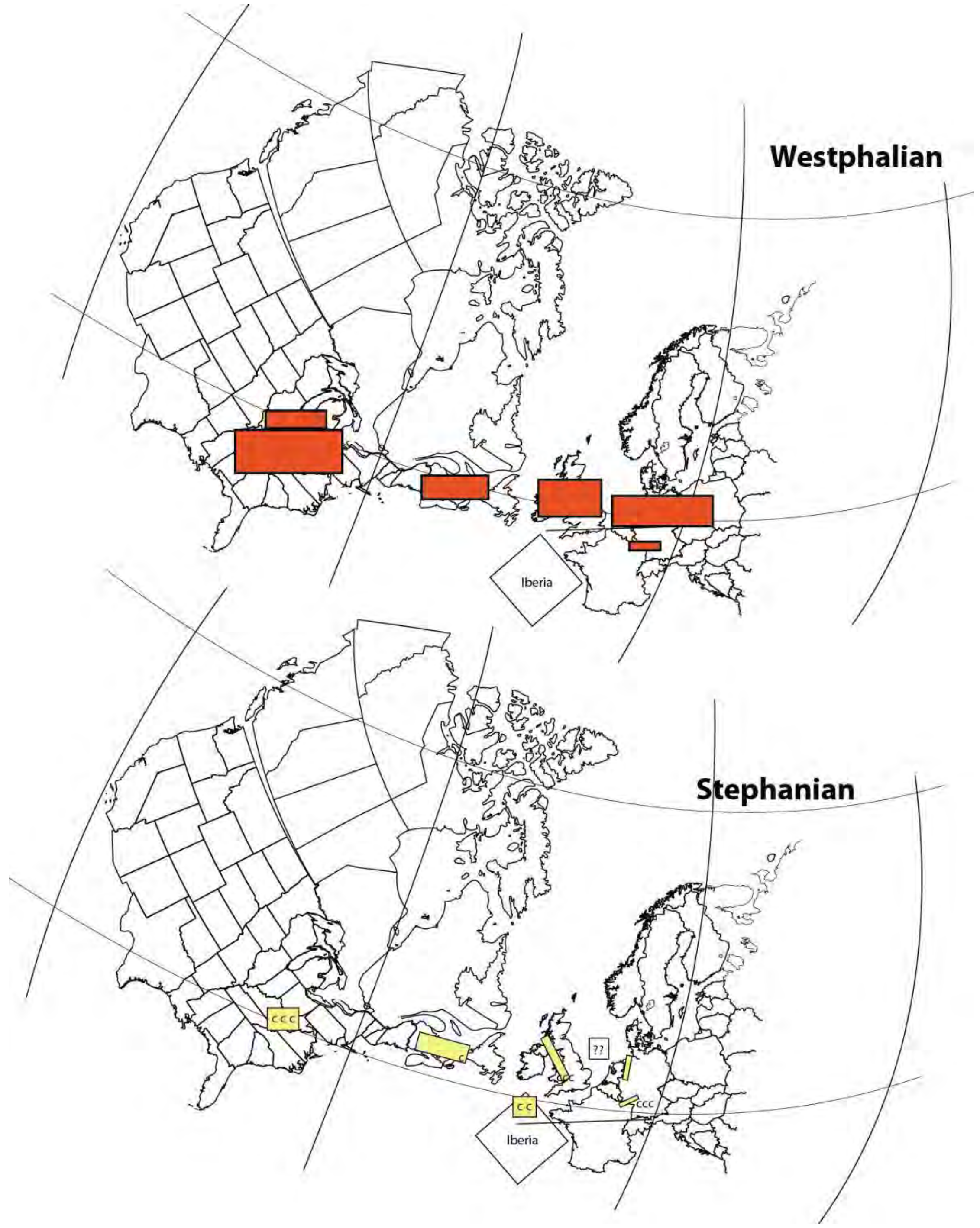

Figure 12: Palaeogeographic reconstructions of Carboniferous basins (Blakey, 2012). Westphalian basins all contain coal; only *equatorial* Stephanian basins contain coal. From many sources.

4.6 *Rotliegend*

Following the long period of Late-Carboniferous inversion and Early to middle Late Permian uplift and erosion (Saalian unconformity), deposition in the study area was reinitiated sometime during the Tartarian (Glennie, 1997). Under a transtensional strike-slip regime the Southern Permian Basin, that had formed much earlier in Germany and progressively widened westward, had extended into the Netherlands, Southern North Sea and eastern U.K. (Geluk, 2007; Glennie, 1990; Glennie, 1997; Glennie, 1998; Gast et al., 2010).

In the Netherlands on- and offshore an up to some 300 metres thick Rotliegend sequence is present, within a wide band of primarily arid fluvial sands and (reworked?) aeolian sands along the southern basin margin. Marginal-lake deposits and desert-lake shales/evaporites were deposited in the north (Gast et al., 2010; Verdier, 1996; George and Berry, 1993; George and Berry, 1997). In the far NE of the Dutch offshore, the lake sequence thickens to more than 600 m (Geluk, 2007; Van den Belt and Van Hulten, 2011).

The overall facies pattern is shown in Fig. 13. Sandy facies were primarily derived from the Variscan orogen in the south, and to a lesser extent from highs in the U.K. (Geluk, 2007; Glennie, 1998; Verdier, 1996). This is obviously related to the position of the main source areas, but the overall direction of (stable) palaeowinds, blowing from the E and NE (Glennie, 1998; Verdier, 1996), also resulted in stacking-up of sands against elevated topography in the south and southwest (Van den Belt and Van Hulten, 2011; Mijnlieff and Geluk, 2011).

Although in many maps sandy facies are drawn along the northern edge of the Southern Permian Basin (Ziegler, 1990), there is little evidence for much sandy development there (Verdier, 1996), as explicitly reflected in a recent map by (Geluk, 2007). There are a few explanations for the paucity of sands along the northern edge:

First, the Mid North Sea high, located to the north is not likely to have been a significant source area (Verdier, 1996). This is supported by the observation that the "high", which probably is better referred to as a platform, was covered by carbonate platforms during the subsequent Zechstein carbonate-evaporite phase, unlike the other potential source areas further to the north and east (Fig. 13; (Geluk, 2007)). Hence, it seems that the Mid North Sea High had only minor topographic relief and therefore it had little sourcing potential. Verdier (1996) attributed it to the fact that the Caledonian highlands, which were a major source during the Carboniferous, had attained an overall lack of topographic relief.

Secondly, based on the wind directions (blowing from E/NE) sand stacking against topography would typically occur against southerly and westerly highs. The presence of (thin) Lower Slochteren sandstones in the northwest corner of the basin (Fig. 13, from (Geluk, 2007)) is attributed to a minor western source area (i.e. the western margin of the Southern Permian Basin) possibly introducing sand along the northern fringe via fluvial fans systems. Regarding the overall wind direction, it seems that aeolian systems would generally counteract sediment dispersal along the northern fringe. It is noted that Lower Slochteren reservoir, recently discovered in the northern fringe (Cygnus development, see Fig. 13; field location marked with asterisk(*)), might be explained as a *western* fringe sand, although a thin northern fringe could be in place.

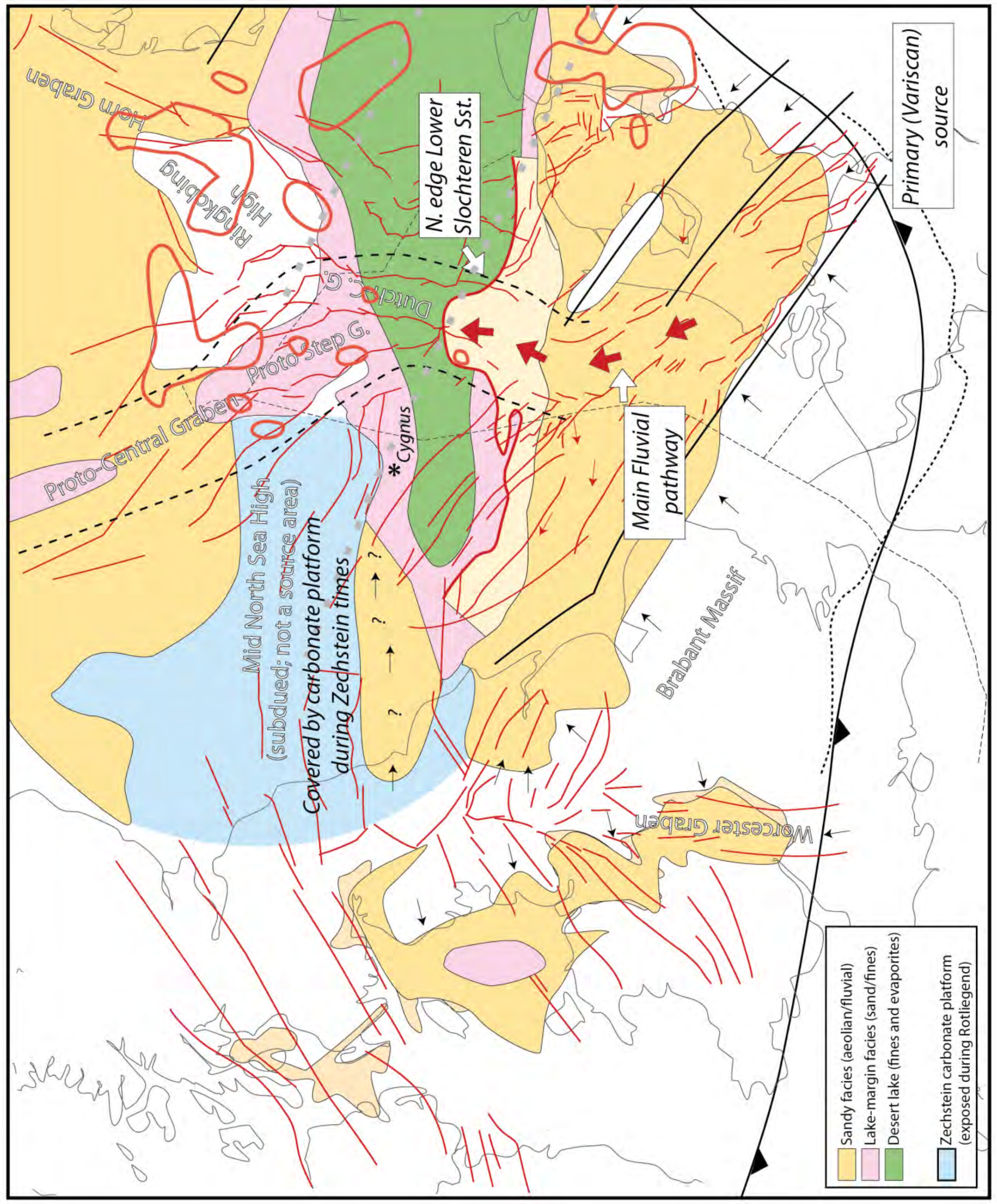

Figure 13: Palaeogeographic map for the Rotliegend (Permian) showing facies belts (yel: sands, pnk: basin margin, grn: desert lake) (Geluk, 2007; Glennie, 1990/1997). Palaeocurrents (black arrows) and main fluvial pathway (red arrows) indicated (George and Berry, 1993/1997; Van den Belt & Van Hulten, 2011). Closed orange lines: Permian volcanics (Ziegler, 1990).

In the Southern North Sea, a number of sedimentary trends are observed that seem to confirm continued activity of the proto-Central North Sea/Step Graben system. This includes a basin-margin sands protrusion along the line of the proto-Step Graben (Fig. 13), and Zechstein salts being thicker there as well (Geluk, 2007). In addition, a major fluvial axis is observed, active particularly during deposition of the Lower Slochteren (George and Berry, 1993; George and Berry, 1997; Van den Belt and Van Hulten, 2011) and running along a SE-NW to N-S trend across the Dutch offshore. This seems to parallel the proto-West Netherlands/Broad Fourteens basins and then turning north toward the proto Step Graben, where Lower Slochteren sands have been shed much further into the basin than more to the east or west (Fig. 13; (Van den Belt and Van Hulten, 2011)).

5 Conclusions

The above analysis has resulted in an improved understanding of the evolution of the northern offshore area during the Late Palaeozoic, which primarily concerns the early activity and tectono-sedimentary evolution of the proto-Central North Sea/Step Graben system from the Early Westphalian onwards.

In short, this history is illustrated in Figure 14.

Main conclusions/interpretations are summarized as follows:

- The evolution of the proto-Central North Sea/Step Graben system seems to have strongly controlled the distribution of fluvial sands into the NW European basin system during the Carboniferous and Permian:
    - Initially, during the Dinantian and Namurian, a point source existed that roughly coincided with the southern tip of the proto-Viking Graben.
    - Towards the Westphalian A, the Caledonian highlands seem to have developed towards a more extensive line source, but the area east of the Step Graben did not receive significant fluvial sand. This suggests that the proto-Step Graben system may have acted as a divide rather than a low.
    - During the Early Westphalian B fluvial systems abruptly retreated from most of the Southern North Sea, which might be related to the initiation of the proto-Central/Step Graben system as an extensional system. Accelerated subsidence may have caused fluvial systems to stay within the system (potential reservoir) and no longer prograde out into the basin.
    - The Late Westphalian compressional direction seems to parallel the general direction of the graben system, allowing for extension during the Variscan culmination. This may explain the presence of thick Westphalian D and possibly Stephanian strata in the Step Graben. Furthermore, accelerated subsidence may have allowed longer accumulation of peat in these grabens as subsidence may have kept the sediment surface at ground-water level (unlike in the main basin).
    - During the Permian, the graben system remained active as a low, as reflected in the major fluvial pathway running N-S toward the Step Graben system.
- Thick Rotliegend "northern fringe" sands can be expected towards the west, due to a combination of overall palaeowind direction (blowing (south)westward) and the absence of northern source.
- The results of this study show that any previous conclusions about Palaeozoic activity of a proto-Dutch Central Graben may possibly apply to the proto-Step Graben.

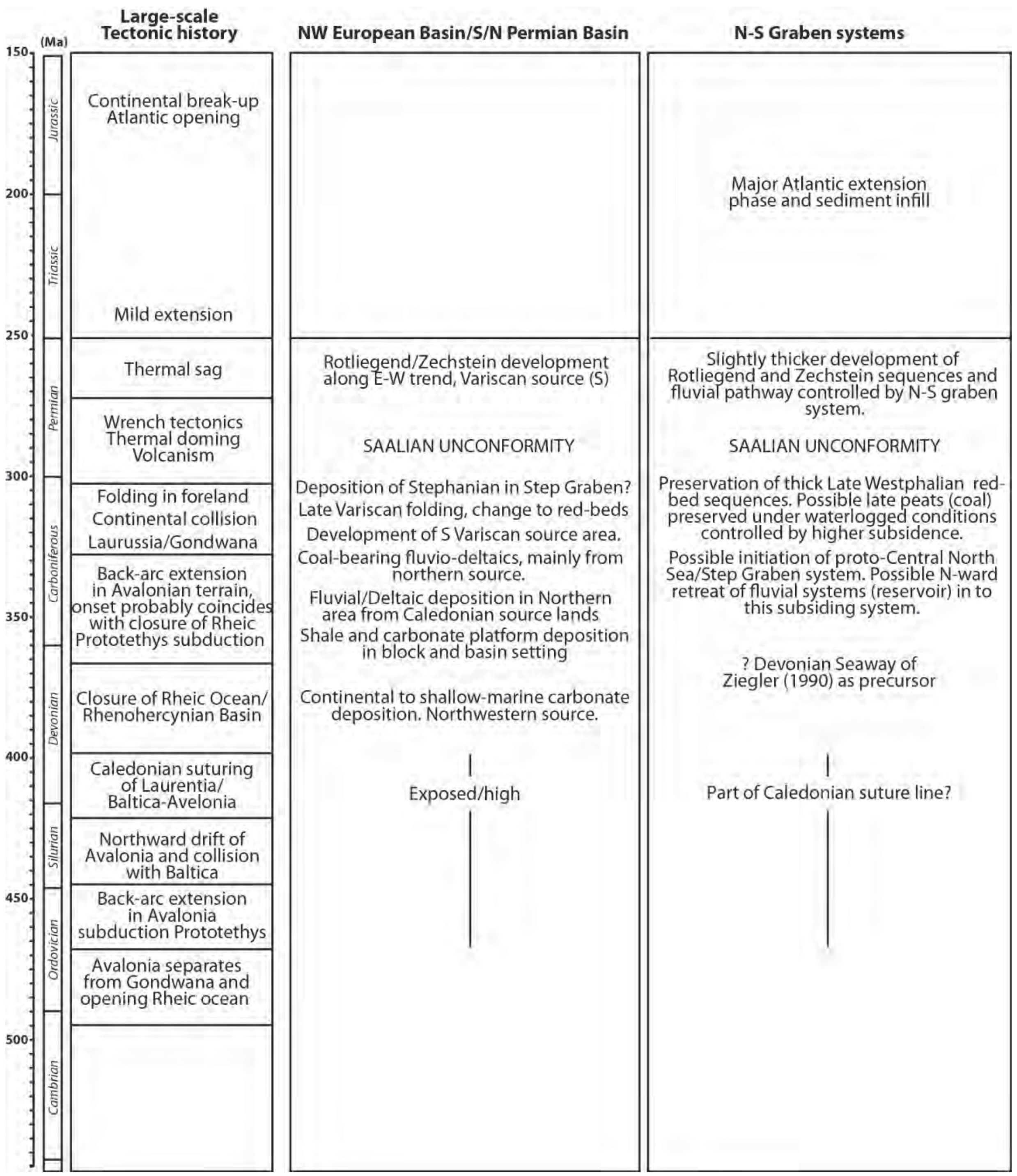

Figure 14: Summary of main tectono-sedimentary events in the NW European basin system and Cross Graben systems. Refer to text for references.

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2.1 The Grensen Formation

During the course of the project the TNO research team identified a possible time equivalent of the Lower Rotliegend on the northern side of the Mid North Sea High. Referred as the Grensen Formation by Martin *et al.* (2002), this siliciclastic interval is located in the Eastern part of the offshore UK sector around the Auk and Flora Fields (see). Martin et al. (2002) identify the Grensen Formation as the interval located between the Upper Flora Sandstone and a volcanic interval, referred to as the Upper Volcanic Unit (Figure 2-1).

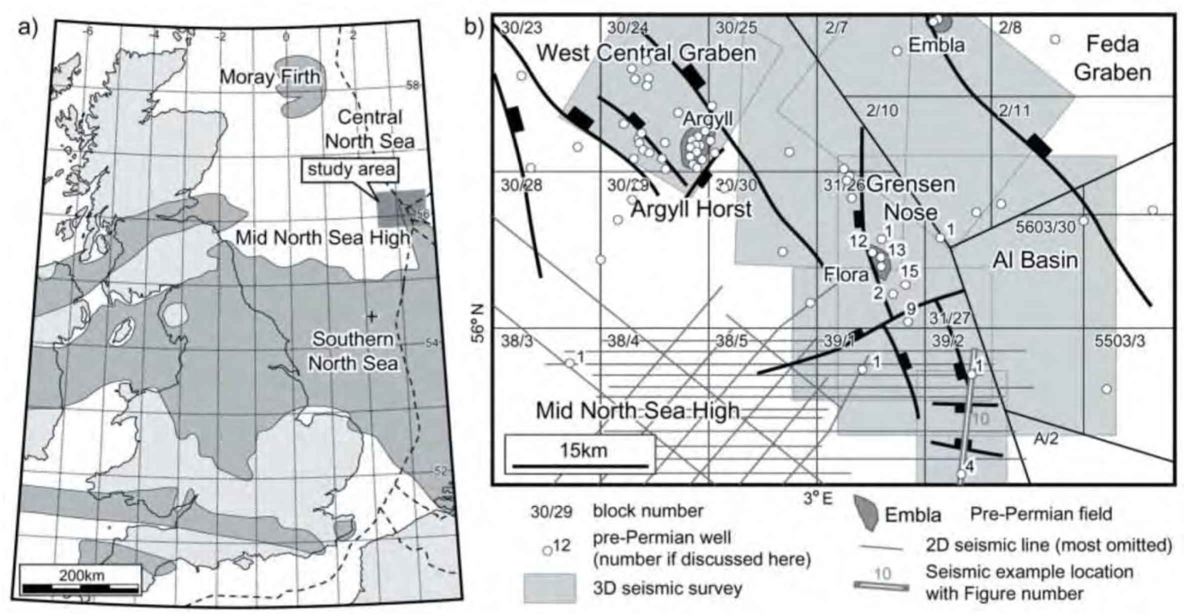


Figure 2-1: a) Location of the Flora and Argyll Fields, Eastern Offshore UK. Shading represents known distribution of the Carboniferous sediments, after Maynard et al. (1997) and Gerling et al. (1999). b) Map of Grensen Nose vicinity showing seismic sections, wells that penetrated pre-Permian strata, major structures and oilfields in Pre-Permian strata. Martin et al. (2002).

Listed below are the main key points regarding the Grensen Formation compiled from Martin et al (2002):

- Stratigraphic context: Lies conformably below the Upper Volcanic Unit (299 +/- 1,6 Ma). Unconformable (Asturic U/C) with the Westphalian Upper Flora Sandstone.
- Age: Stephanian (Menning et al., 2006) or Asselian (Permian) (Gradstein et al., 2004).
- Lithology: Low net/gross succession, interbedded mudstone, siltstone and sandstone (no core).
- Sediment transport direction (dipmeter): Unidirectional palaeocurrents toward the NE (low variance), indicative of a change in basin configuration (E-SE direction for older strata).
- Depositional environment: Fluvial or alluvial depositional settings, arid climate.

The main relevant question concerning the Grensen Formation for this project is to know how this formation relates to the Dutch Northern Offshore and specifically the study area?

The age of the Grensen Formation is debatable, it can be Stephanian or Early Permian. Martin et al. (2002) date the volcanics above the Grensen Formation at 299 +/- 1.6 Ma, and define the base of the Grensen Formation as an unconformity referred as Asturic Unconformity. The absolute age of the Carboniferous-Permian boundary varies depending on the chronostratigraphical charts used, which introduce a discrepancy between various publication such as Heeremans et al (2004) and Waters et al. (2011) that gives a Stephanian age to the Grensen Formation, while the Gradstein (2004) chronostratigraphical chart would possibly allocate the Grensen Formation to the Asselian (Permian). Another problem is related to the error bars on age dating using K-Ar dating method, which introduce uncertainties in the age of the Upper Volcanic Unit (299 +/- 1.6 Ma) (Martin et al., 2002).

However, the Grensen Formation's lithology, depositional environment, sediment dispersal pattern,
heavy mineral assemblage and, its similarities with the Basal Rotliegend Clastics in the Northern Offshore of the Netherlands, suggest that the Grensen Formation is most likely equivalent to the Lower Rotliegend, as present in the Northern Offshore of the Netherlands. Martin et al. (2002) wrote that "the Grensen Formation is genetically distinct from the Carboniferous units. The Grensen Formation is more similar in lithology to the strata of the Lower Rotliegend Group". Hayward et al. (2003) mentioned that "the Grensen Formation is barren of organic material, but heavy mineral assemblages indicate a clear association with the Permian and the interval has therefore been assigned a Lower Rotliegend Group."

Therefore, our conclusion concerning the Grensen Formation is that it is equivalent to the lowest part of the Lower Rotliegend within the Southern Permian Basin. The Upper Volcanic Unit of Martin et al. (2002) would be equivalent to the intra volcanics identified in the Lower Rotliegend of the Southern Permian Basin (sometimes referred to as Emmen Volcanics or RVVE).

Recently other authors (Lundmark et al., 2014) arrived independently at the same conclusions referring to the Grensen Formation as the "lower Rotliegend Grensen Formation".

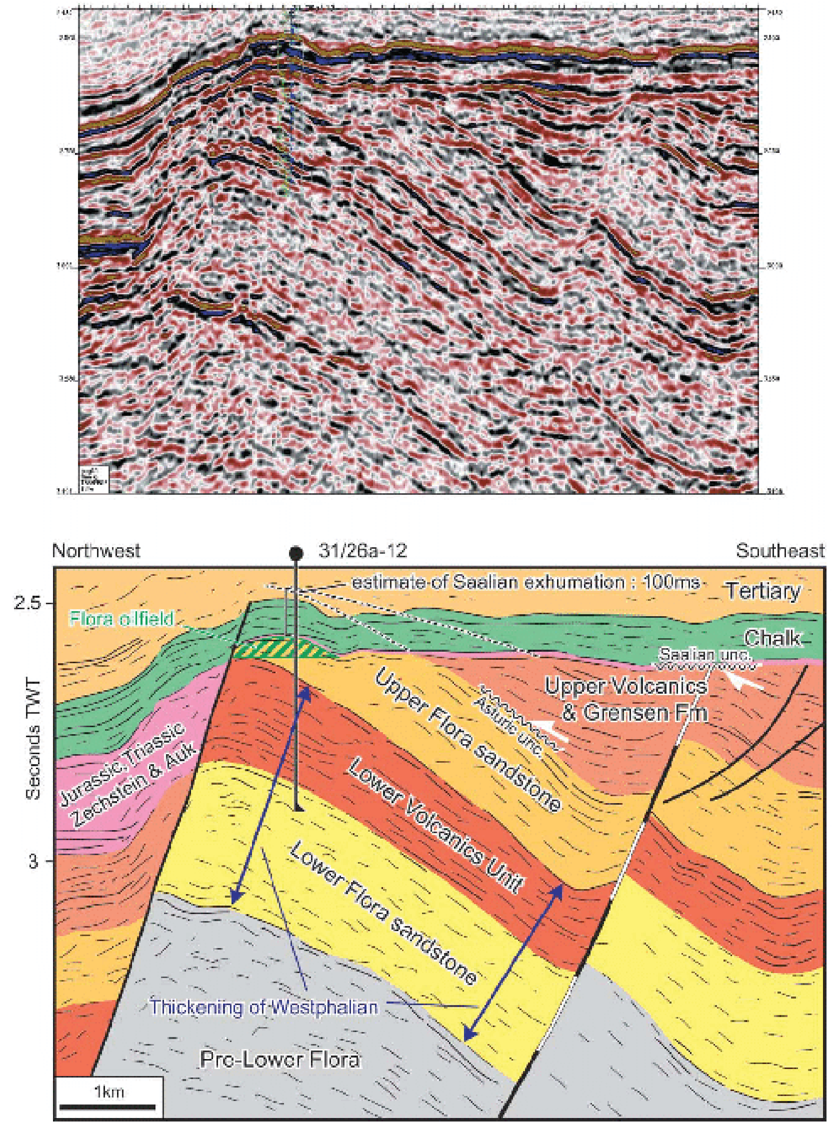


Figure 2-2: Typical seismic section through the Grensen Nose (location shown in Figure 2-1). This section passes through Flora Field discovery well 31/26a-12. The seismic interpretation shows the main stratigraphic units controlled by various well penetrations in the study area. The Flora Field and two key unconformities are highlighted. Also shown is a projection of the eroded strata above the present crest of the fault block to estimate the amount of crestal erosion. The extensional fault within the Grensen Nose is shown as a dashed line; each black or white interval corresponds to c. 3000 m, or 1000 ft, to give an estimate of interval thickness. Vertical exaggeration in the section as a whole is approximately three times horizontal. Martin et al. (2002).

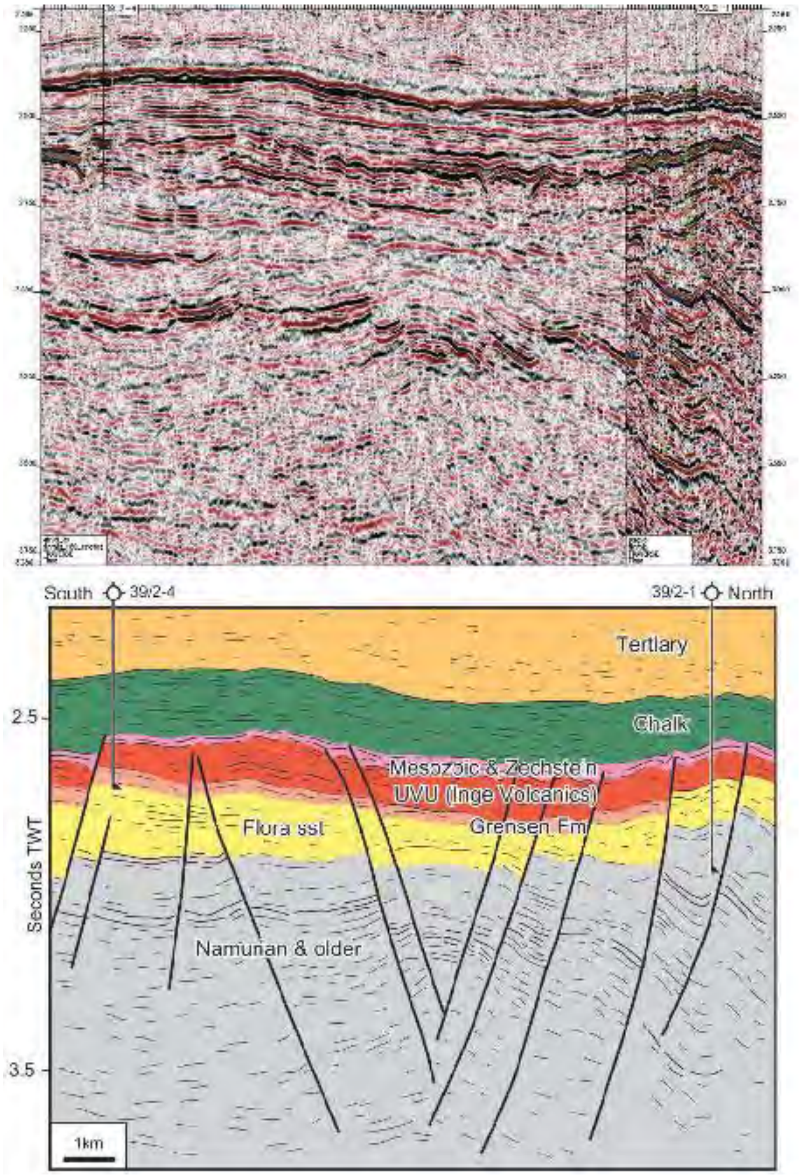


Figure 2-3: Seismic section and seismic interpretation trending north–south through block 39/2; location is shown in . The seismic section changes character near 39/2-1 because the line steps from one survey to another. Three-dimensional seismic mapping shows that the extensional faults seen in this area trend east–west. Martin et al. (2002).

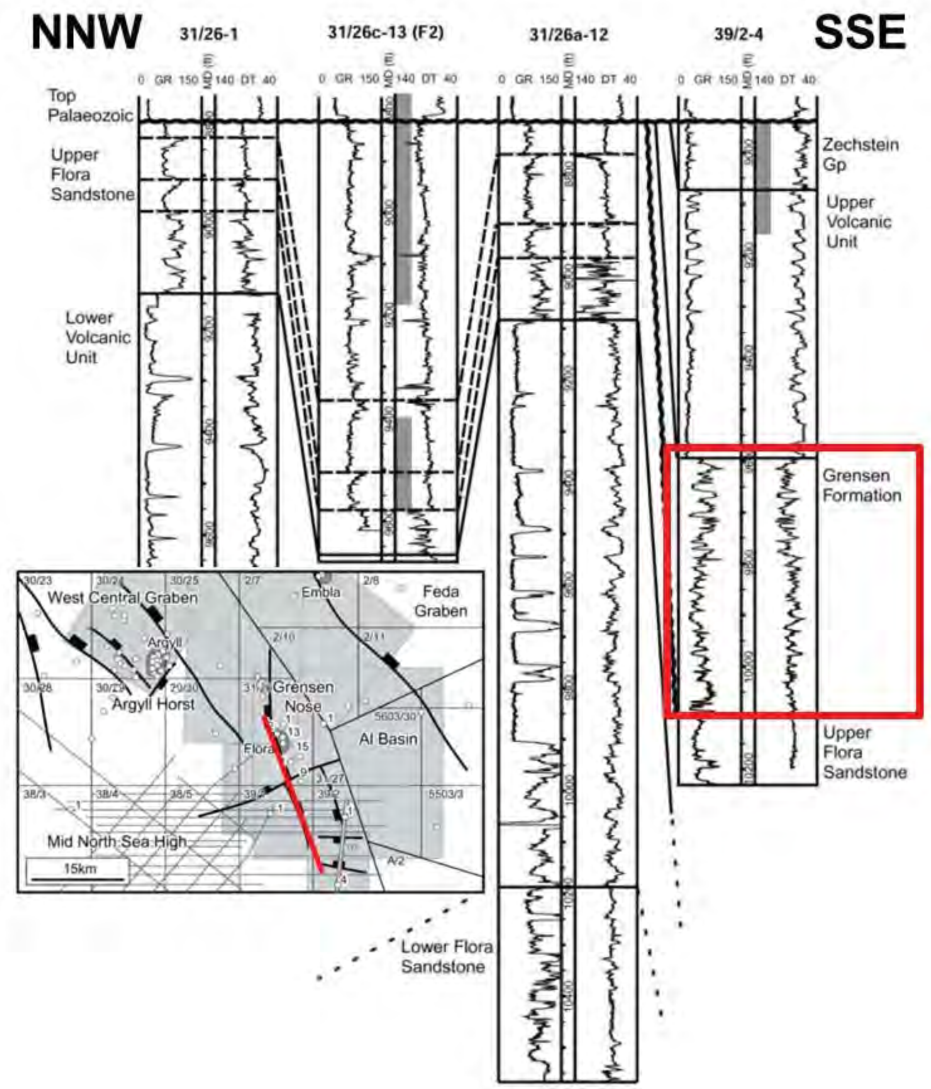


Figure 2-4: NNW to SSE well correlation across the Grensen Nose illustrating those wells with significant preserved thickness of Upper Carboniferous–Lower Permian section. Datum is base of the Mesozoic sequence. Hatched column indicates conventional core coverage. Location of wells is shown in Fig. 1b. Wells 31/26-1, 31/ 26a-12 and 31/26c-13 lie in the Flora Field. Modified from Martin et al. (2002).

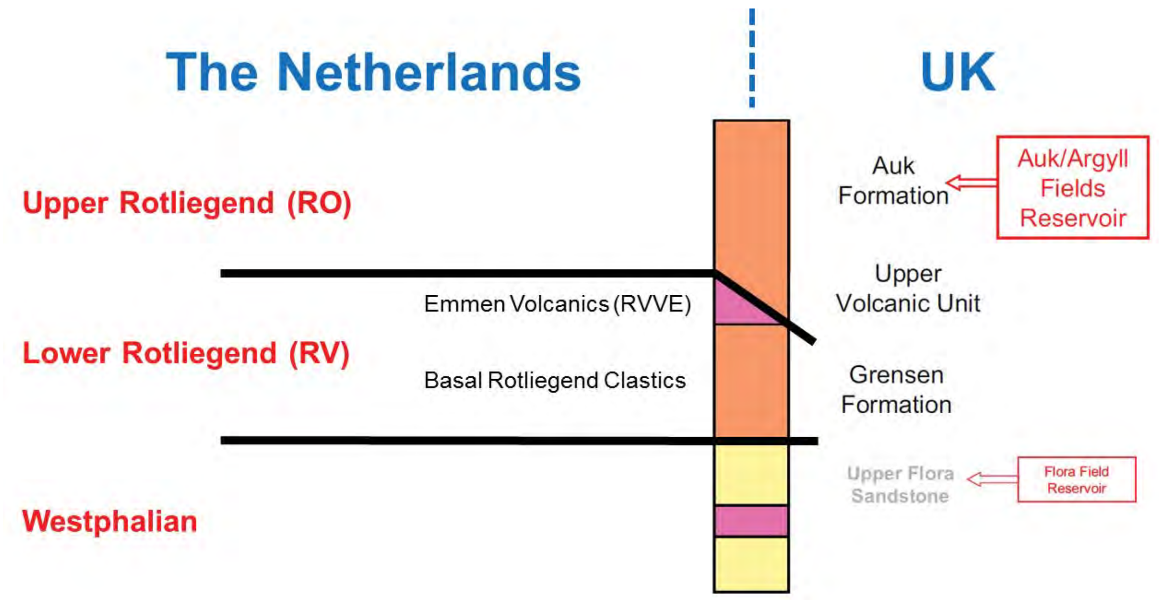


Figure 2-5: Lower Permian lithostratigraphical equivalence between Dutch Northern Offshore and the UK Eastern Offshore. Modified from PGL (2005) report

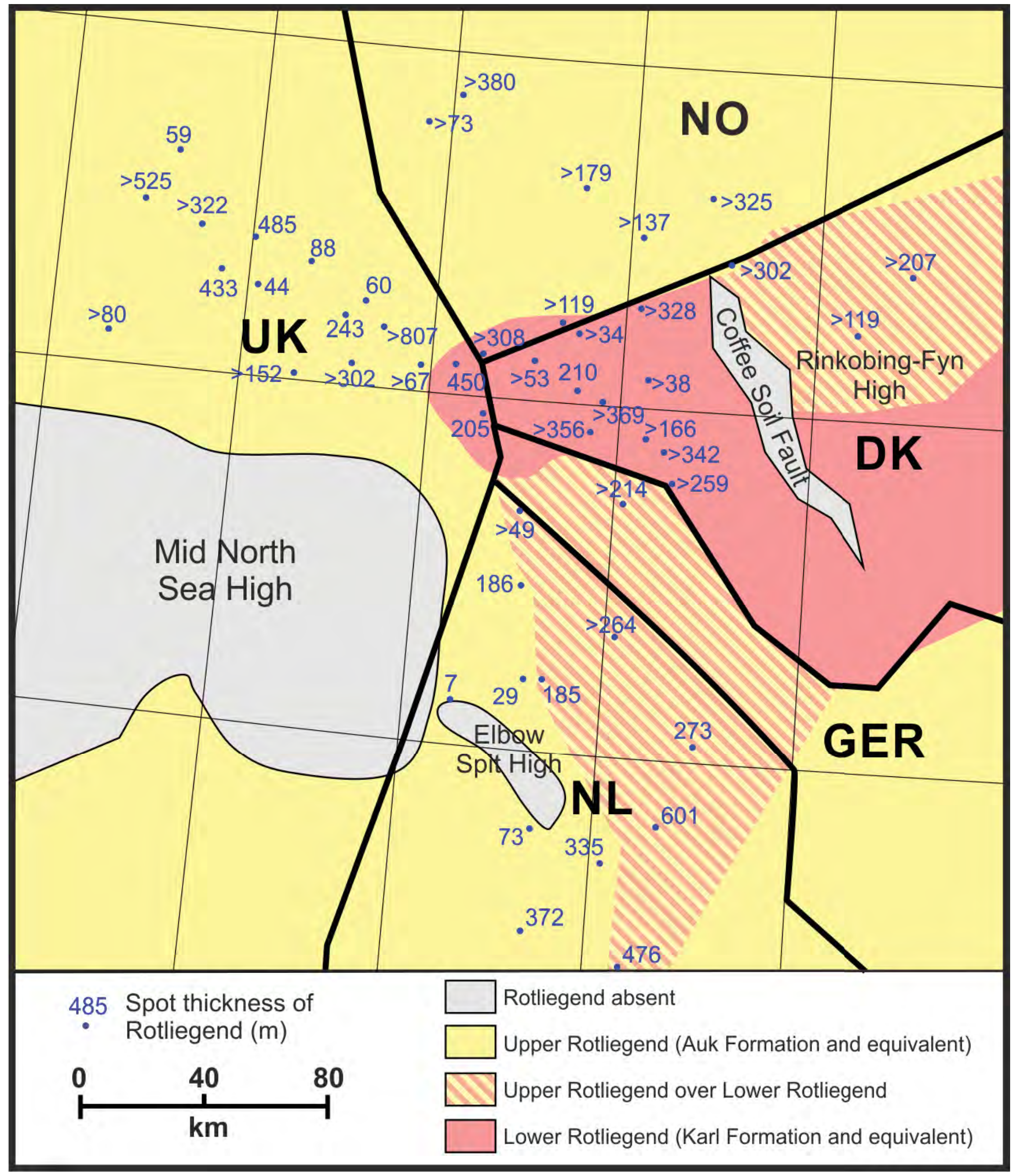
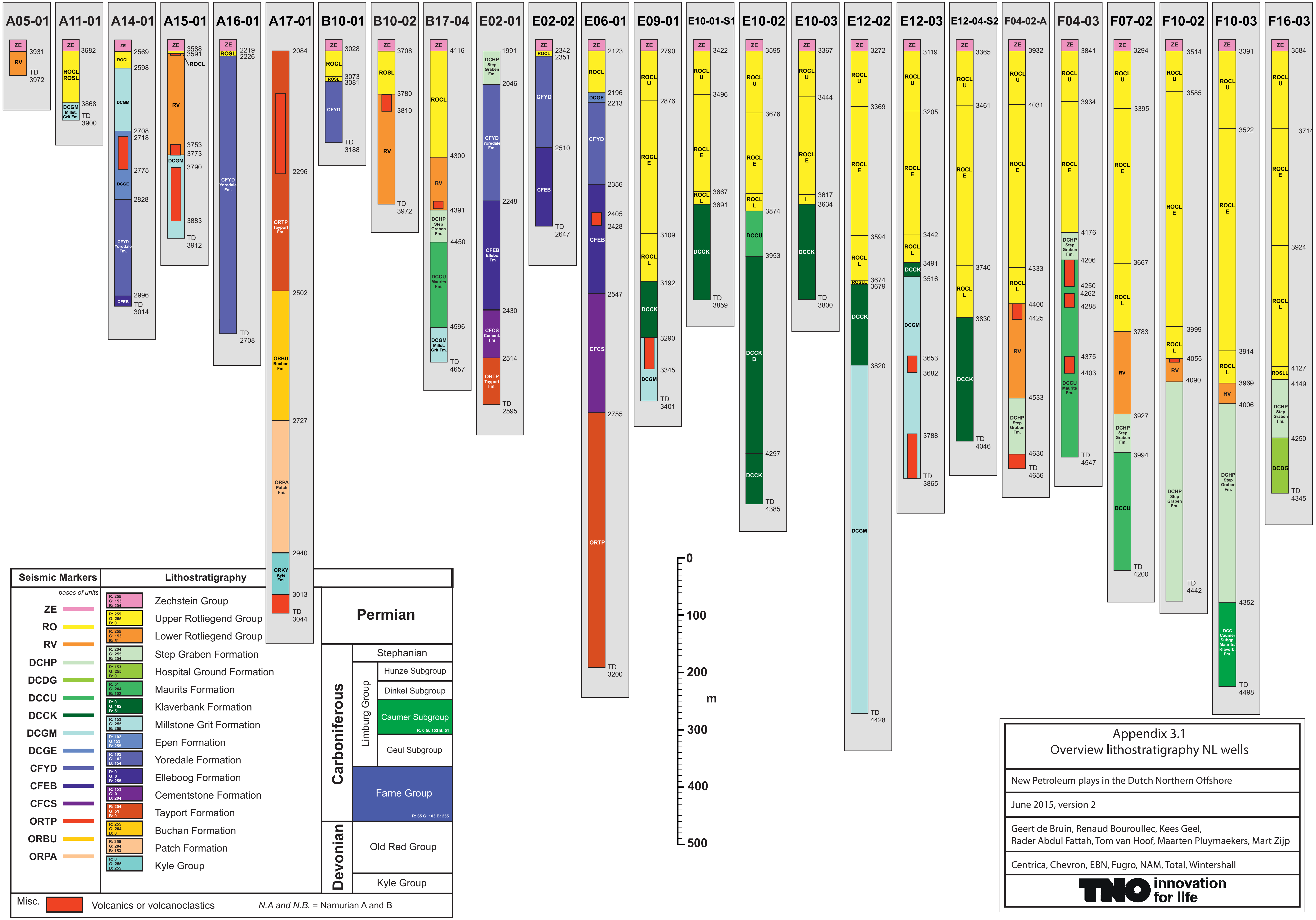


Figure 2-6: Map of the Rotliegend in the Central North Sea. This map combines published results from Glennie et al. (2003) (their Figure 8.12), and results from the present study.

3 Well re-interpretation

3.1 Overview of all Dutch Wells
3.2 Overview of lithostratigraphic re-interpretations
3.3 Well reinterpretations



Appendix 3.1
Overview lithostratigraphy NL wells

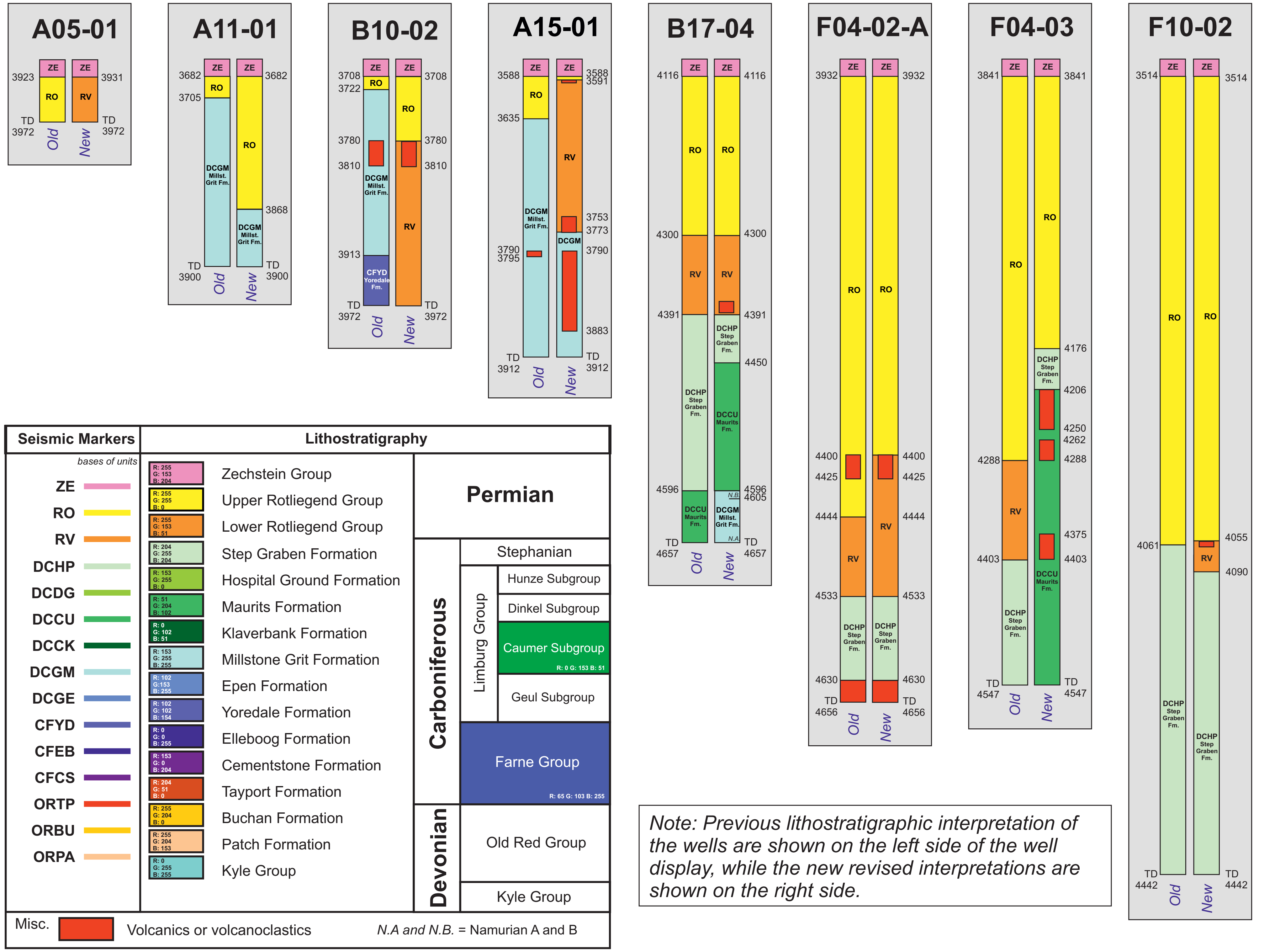
New Petroleum plays in the Dutch Northern Offshore

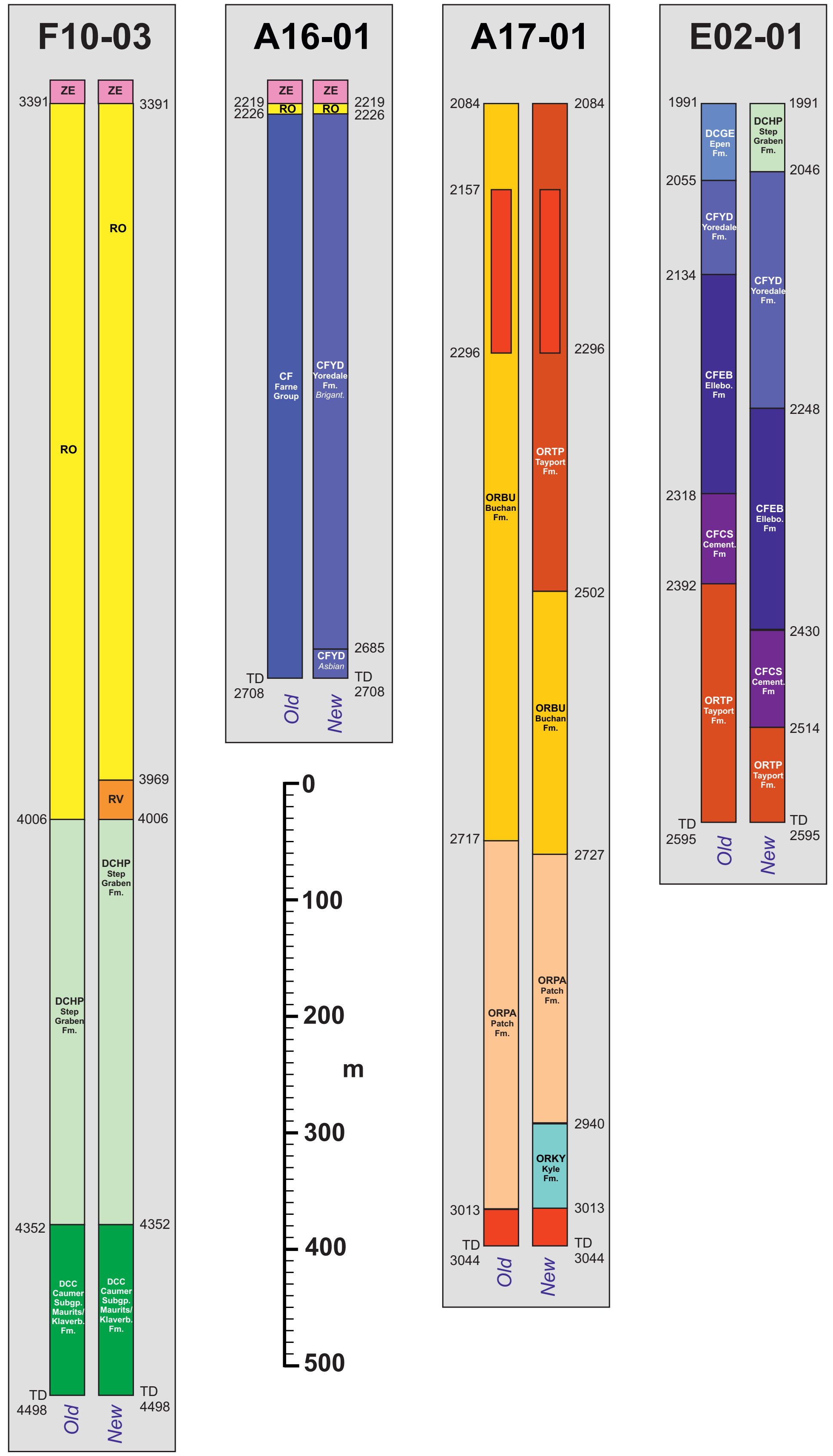
June 2015, version 2

Geert de Bruin, Renaud Bouroullec, Kees Geel,
Rader Abdul Fattah, Tom van Hoof, Maarten Pluymaekers, Mart Zijp

Centrica, Chevron, EBN, Fugro, NAM, Total, Wintershall

TNO innovation for life





The re-evaluation of the some of the pre-Zechstein stratigraphy has been carried out.12 wells have been re-evaluated including 9 wells with Rotliegend-age strata.

NLOG lithostratigraphic subdivision (left side of the well displays) has been critically reviewed and re-interpreted in light of:

- Other NLOG documents, including logs, core descriptions, biostratigraphic reports, and geochemical reports,
- Non-NLOG biostratigraphic information (palynology) provided by Tom van Hoof (TNO),
- Inconsistency in lithostratigraphic interpretation (e.g. anhydrite in Carboniferous), and
- The presence of omitted, misinterpreted or under-estimated volcanics and volcano-clastic intervals.

A few rules were followed to distinguish the presence of Rotliegend (RO) and Lower Rotliegend (RV) in those wells:

- Rule #1: The occurrence of in-situ anhydrite below the base Zechstein indicates the presence of Rotliegend (notably Upper Rotliegend). Exception: Buchan Formation
- Rule #2: The volcanics or volcano-clastic intervals identified above the base Permian U/C and below the base Zechstein are interpreted as Lower Rotliegend Volcanics (RVVE).

New well interpretations debated by both the Geology and GeoBiology groups. Changes were voted on and implemented into the Petrel master project.

Appendix 3.2
Lithostratigraphic re-interpretation

New Petroleum plays in the Dutch Northern Offshore

June 2015, version 2

Geert de Bruin, Renaud Bouroullec, Kees Geel,
Rader Abdul Fattah, Tom van Hoof, Maarten Pluymaekers, Mart Zijp

Centrica, Chevron, EBN, Fugro, NAM, Total, Wintershall

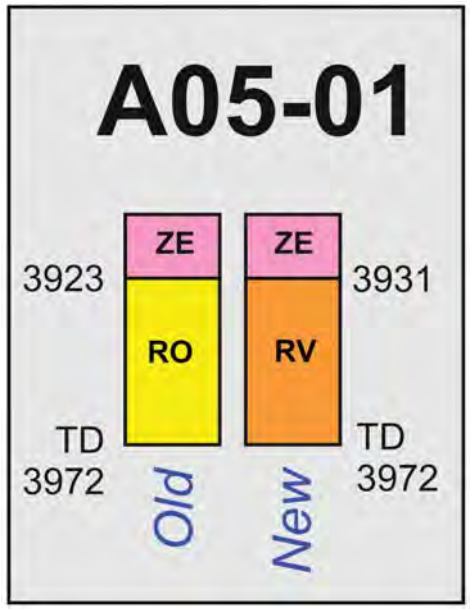
TNO innovation for life

Appendix 3.3 – Reinterpretation of stratigraphy in wells

Note: The reinterpretation of the stratigraphy of twelve wells in the study area was performed. Extensive literature search, including biostratigraphic reports from service and E&P companies were used for this task. However, some additional biostratigraphic analysis should be done for a few wells (e.g. A17-01 and E02-01) to clarify some of the Devonian and Carboniferous stratigraphy in this part of the basin.

A05-01

Summary of changes



Existing lithostratigraphy (Amerada Hess 1999)

Top (m)	Bot (m)	Stratigraphic unit
0.0	1225.3	Quaternary-Pliocene
1225.3	1606.3	Miocene
1606.3	2542.0	Eocene-Horda
2542.0	2557.9	Balder
2557.9	2591.4	Sele
2591.4	2630.4	Lista
2630.4	2654.2	Maureen
2654.2	2670.0	Ekofisk
2670.0	2685.3	Ekofisk Tight
2685.3	2692.9	Tor
2692.9	2735.3	Tor Porous Zone
2735.3	3096.2	Tor Tight Zone
3096.2	3435.1	Triassic
3435.1	3918.5	Zechstein
3918.5	3971.8	Rotliegendes

New interpretation

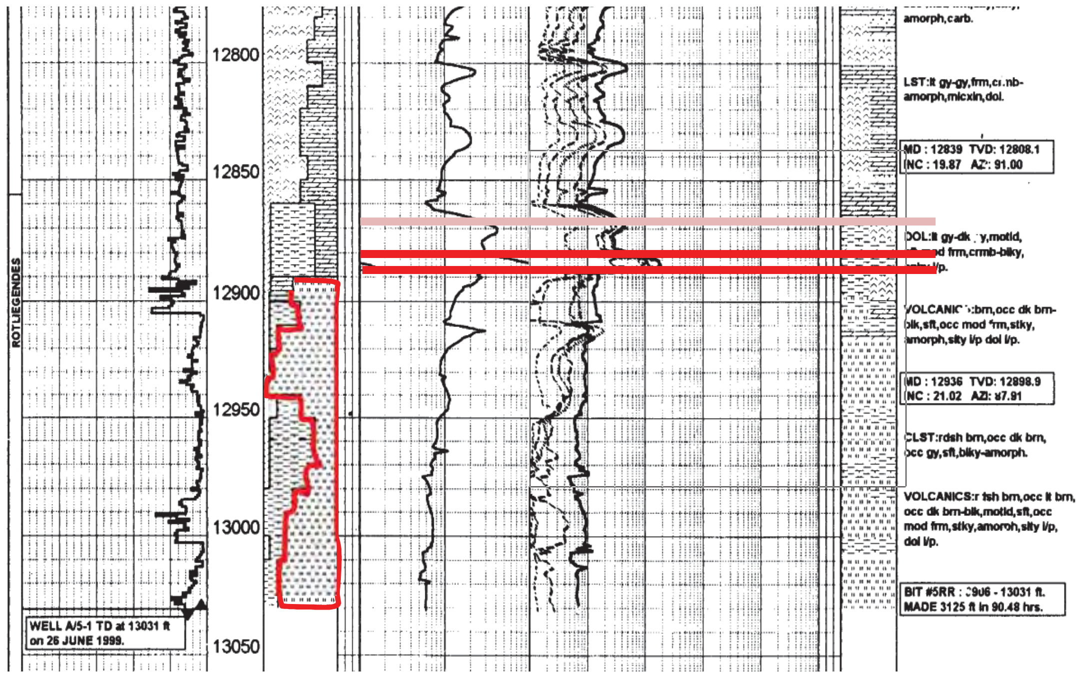
Two major changes were applied:

1) The Upper Rotliegend was previously interpreted on NLOG database between 3923 and 3972 m (TD). Recently added documents on NLOG (e.g. Spectral gamma ray log (1999), see below) show that the base Zechstein is at 3931 m (12896 ft) rather than 3923 m (12971 ft) as previously interpreted. Presence of Kupferschiefer was inferred from the difference between SGR and CGR, indicating a high Uranium content.

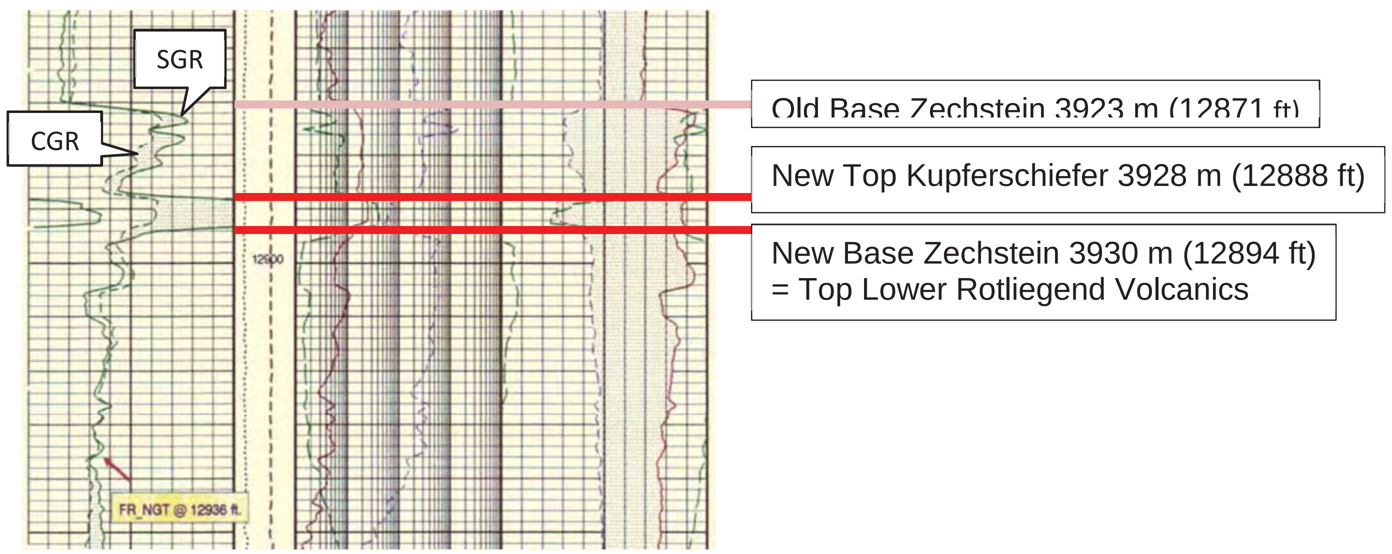
2) Lower Rotliegend strata have been interpreted in this well based on the presence of volcanics (tuffs) between 3931 m (12896 ft) and 3970 m (13027 ft) on the Master Log (1999). The new interpretation attributes all of the interval between 3931 and 3972 m to Lower Rotliegend rather than Upper Rotliegend.

A05-01

Masterlog (1999)

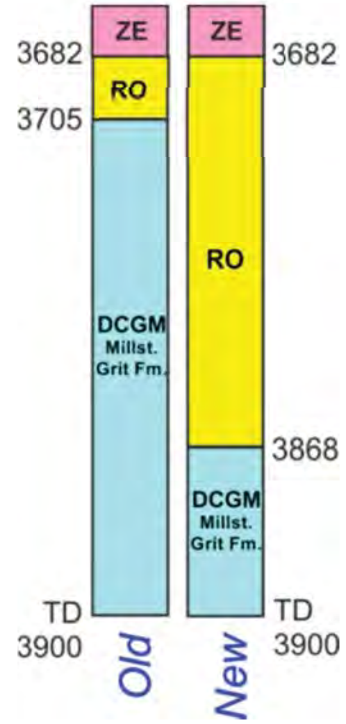


Spectral GR log (1999)



A11-01

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	A11-01	
Diepte in meter t.o.v.	Rotary Table	
Einddiepte (m)	3900	
Lithostratigrafie		
Datum interpretatie	2000-02-03	
Bron	KARTERING DIEP - RGD - 1997	
Diepte stratigrafische eenheden (gemeten langs het boorgat)		
Stratigrafische eenheid	**Bovenkant van interval**	**Onderkant van interval**
North Sea Supergroup	0	2406
Ekofisk Formation	2406	2482
Ommelanden Formation	2482	2872
Upper Holland Marl Member	2872	2909
Kimmeridge Clay Formation	2909	2918
Main Claystone Member	2918	3105
Zechstein Upper Claystone Formation	3105	3127
Z4 Salt Member	3127	3145
Z4 Pegmatite Anhydrite Member	3145	3146
Red Salt Clay Member	3146	3151
Z3 Salt Member	3151	3383
Z3 Anhydrite/Carbonate Member	3383	3428
Grey Salt Clay Member	3428	3431
Z2 Roof Anhydrite Member	3431	3434
Z2 Salt Member	3434	3644
Z2 Basal Anhydrite Member	3644	3650
Z2 Carbonate Member	3650	3657
Z1 Anhydrite Member	3657	3675
Z1 Carbonate Member	3675	3681
Coppershale Member	3681	3682
Silverpit Formation	3682	3705
Millstone Grit Formation	3705	3900

New interpretation

The base Rotliegend is interpreted on the NLOG database at 3705 m.
However, six levels of anhydrite below 3705 m suggest that more Rotliegend strata is present at this location. Possible casing issues bringing shallower anhydrite materials down into the borehole has been rejected as an explanation for anhydrite occurrences due to the log responses of these anhydrite streaks suggesting an in situ setting.
Therefore, the interval between 3705 to 3868 m is now attributed to Upper Rotliegend rather than Millstone Grit Formation, which doesn't have any proven evaporites. The original composite log from 1981 shows 174 m of Rotliegend strata and the new TNO interpretation now allocates 186 m of Rotliegend (Upper Rotliegend).

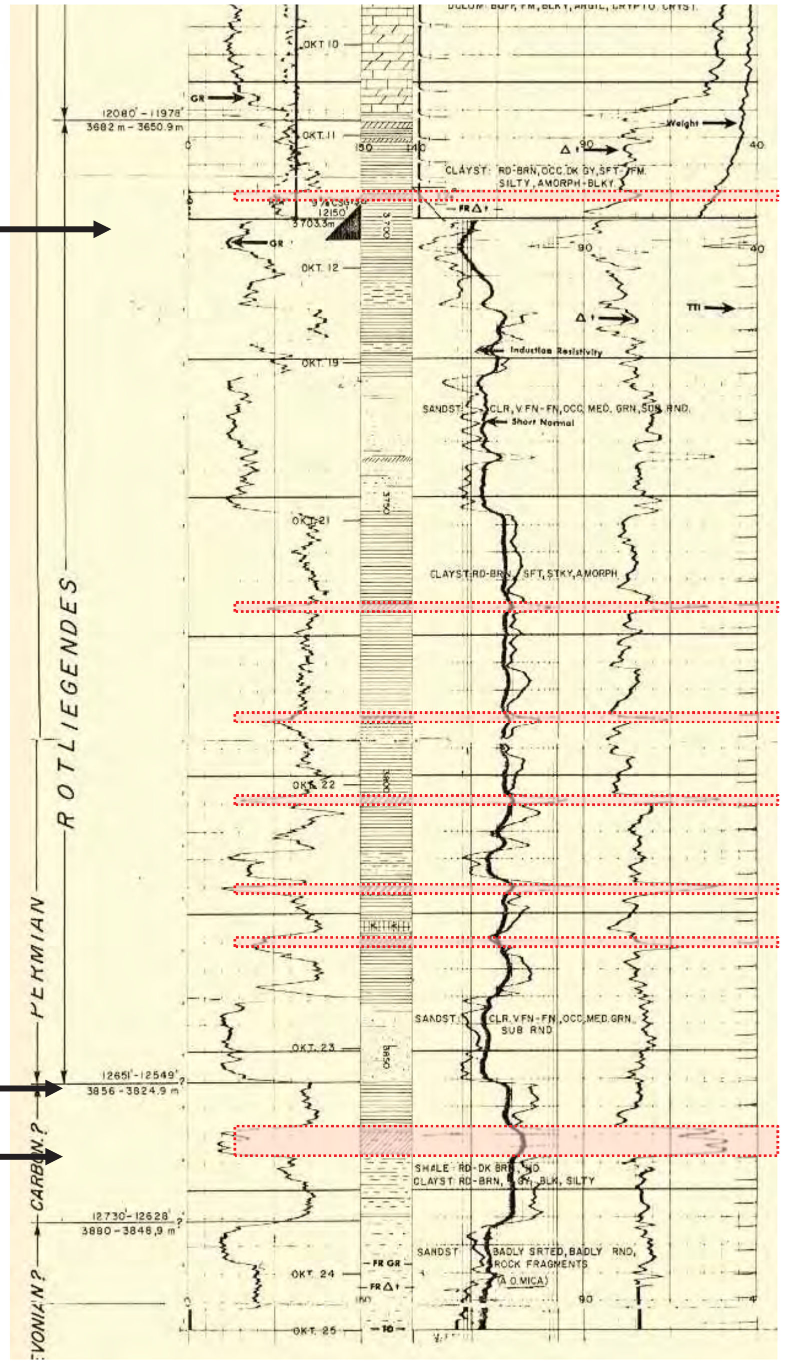
A11-01

NLOG base Rotliegend

- 23 m of Rotliegend in the NLOG lithostratigraphic report (1997).
- 174 m of Rotliegend in the original composite well log (1981).
- Possibility of casing issues to explain the presence of anhydrite in the cuttings has been rejected.

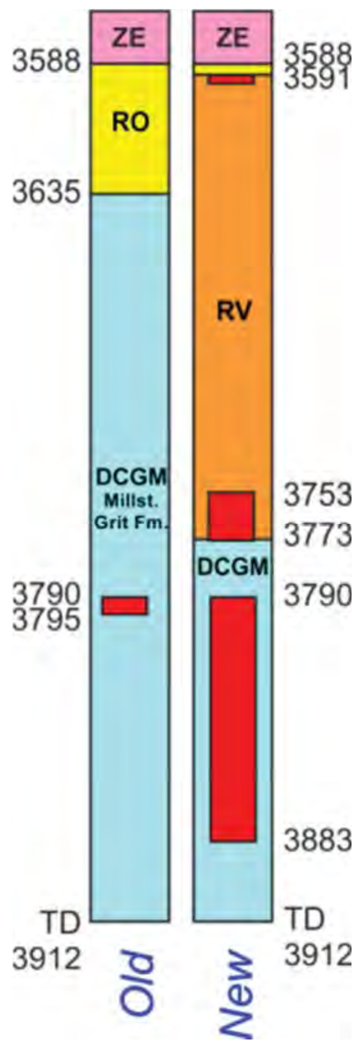
Original base Rotliegend (1981)

New base Rotliegend



A15-01

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Z1 Carbonate Member	3580	3587
Coppershale Member	3587	3588
Silverpit Formation	3588	3635
Millstone Grit Formation	3635	3790
VOLCANIC DYKE	3790	3795
Millstone Grit Formation	3795	3912

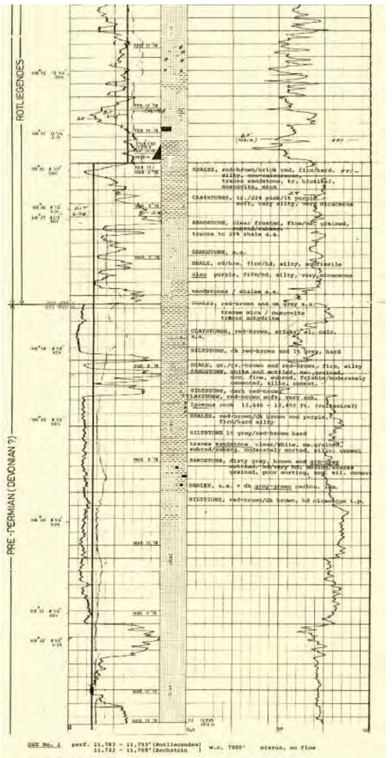
New interpretation

The interval between 3773 and 3753 is interpreted as volcanoclastics. The lithology described in the composite log (1973) between 3635 and 3753 m is attributed to lower Rotliegend based on the bed's colour (brown) and bed thickness configuration (not like the massive nature of the Millstone Grit, which was previously interpreted for this interval).

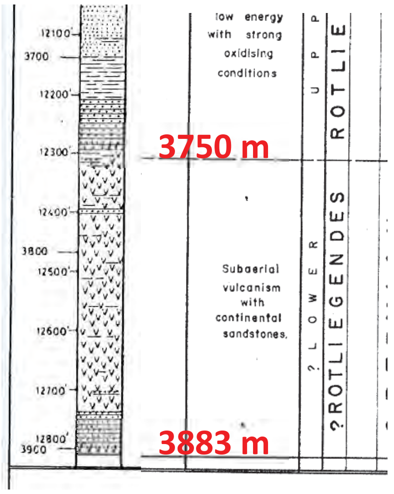
Thick gabbro (93m) added within the Millstone Grit Formation based on the information from the composite log.

A15-01

Composite Log (1978)



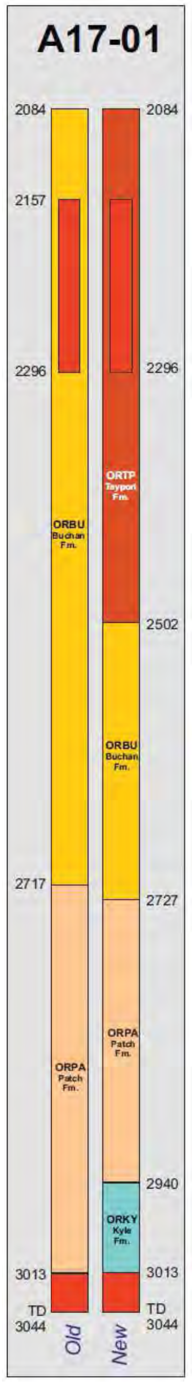
Stratigraphic Log (1978)



Lithology (cuttings) (1979)

A17-01

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	A17-01
Diepte in meter t.o.v.	Rotary Table
Einddiepte (m)	3044
Lithostratigrafie	
Datum interpretatie	2013-12-11
Bron	KARTERING DIEP 2013 (QC)
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)	

Diepte stratigrafische eenheden (gemeten langs het boorgat)

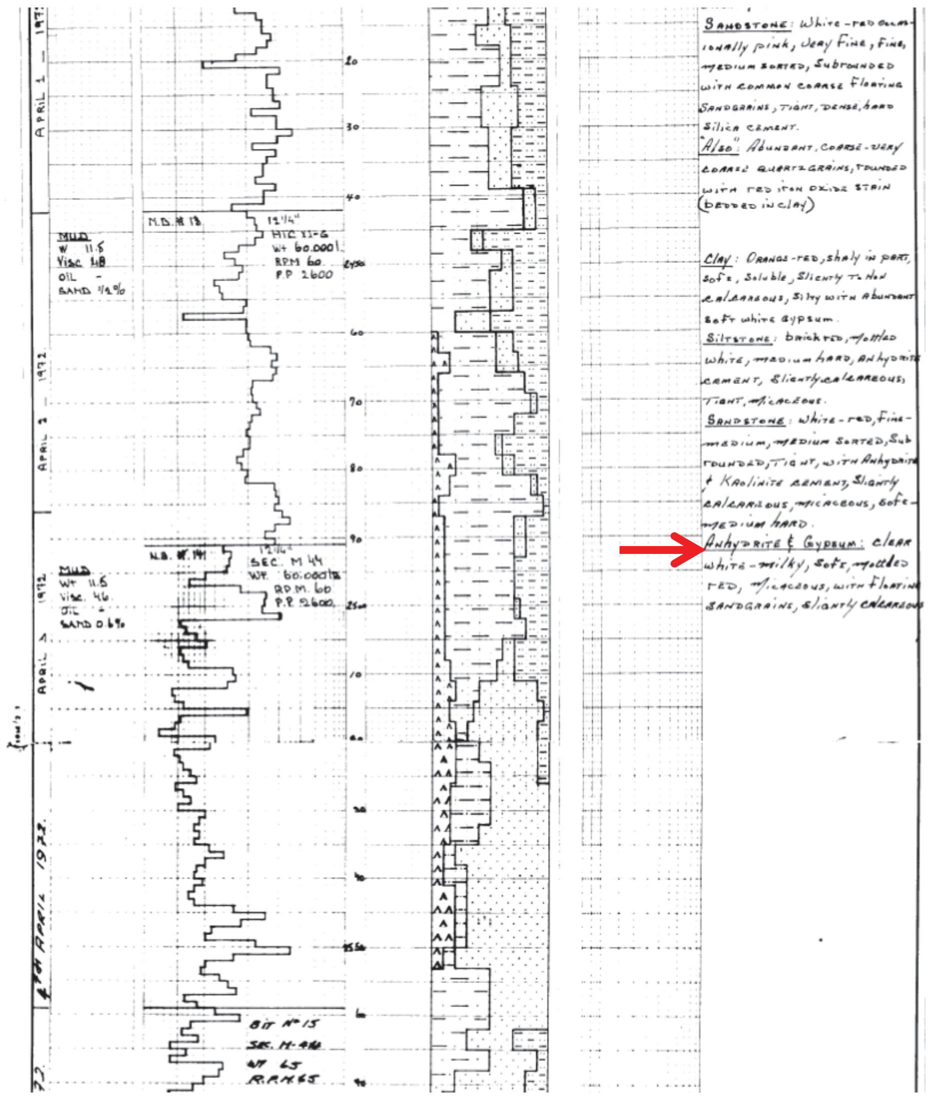
Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
Upper North Sea Group	0	1040	
Lower North Sea Group	1040	1910	
Ekofisk Formation	1910	1921	
Ommelanden Formation	1921	2084	
UPP. BUCHAN	2084	2157	
Rhyolite Member	2157	2296	
LOW. BUCHAN	2296	2717	
Patch Formation	2717	3013	
PLUTONIC ROCK	3013	3044	TD

New interpretation

Several changes have been applied to this well. These changes are also present in the Petroplay TNO report (TNO NTIG 05-155-C).

1) Tayport Formation (ORTP) was added between 2084 and 2502 m based:
   a. the Mobile report from June 1972 indicating Devonian age for the interval between 2070 and 2084 m,
   b. the Halliburton 5C 1993 Report indicating late Famennian for the interval between 2084 and 2583 m,
   c. the presence of Gypsum (attributed to Tayport Formation) at 2493 m and between 2295 and 2500 m, and
   d. the base of Tayport is interpreted at 2502 based on wireline log information.
2) Buchan Formation now interpreted between 2583 and 2727 m, based on the Petroplay TNO report indicating an early – middle Famennian age.
3) Base Patch Formation brought down from 2717 to 2727 m based on geochemistry (Bow Valley report , 1992).
4) Kyle Formation added between 3013 and 2940 m based on the Petroplay report.

A17-01



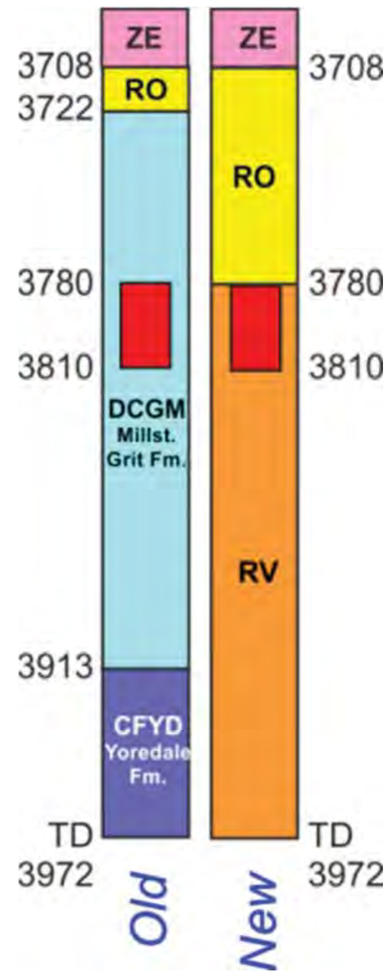
Exception to Rule # 1:

Rule #1: "The occurrence of **in-situ anhydrite** below the base Zechstein indicates the presence of Rotliegend (notably Upper Rotliegend)."

The lower part of the Tayport Formation show occurrences of anhydrite and gypsum but in minor amounts compared to the Rotliegend.

B10-02

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	B10-02-SIDETRACK1
Diepte in meter t.o.v.	Kelly Bushing
Einddiepte (m)	3972
Lithostratigrafie	
Datum interpretatie	2000-02-02
Bron	KARTERING DIEP - RGD - 1997
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)	

Diepte stratigrafische eenheden (gemeten langs het boorgat)

Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
Lower North Sea Group	1439	1981	UKO
Ekofisk Formation	1981	2027	
Ommelanden Formation	2027	2378	
Solling Claystone Member	2378	2431	
Detfurth Claystone Member	2431	2457	
Lower Detfurth Sandstone Member	2457	2462	
Volpriehausen Clay-Siltstone Member	2462	2545	
Lower Volpriehausen Sandstone Member	2545	2557	
Lower Buntsandstein Formation	2557	2833	
Zechstein Upper Claystone Formation	2833	2844	
Z5 (Ohre) Formation	2844	2849	
Z4 Salt Member	2849	2915	
Z4 Pegmatite Anhydrite Member	2915	2916	
Red Salt Clay Member	2916	2917	
Z3 Salt Member	2917	3125	
Z3 Anhydrite/Carbonate Member	3125	3201	
Grey Salt Clay Member	3201	3202	
Z2 Roof Anhydrite Member	3202	3207	
Z2 Salt Member	3207	3677	
Z2 Basal Anhydrite Member	3677	3680	
Z2 Carbonate Member	3680	3685	
Z1 Anhydrite Member	3685	3701	
Z1 Carbonate Member	3701	3707	
Coppershale Member	3707	3708	
Slochteren Formation	3708	3722	
Millstone Grit Formation	3722	3780	
EXTRUSIVE ROCK	3780	3810	
Millstone Grit Formation	3810	3913	
Yoredale Formation	3913	3972	TD

New interpretation

Total reinterpretation down to TD. RO and RV interpreted based on presence of tuff and anhydrites and on biostratigraphic data.

Evidence for Upper Rotliegend:
Presence of a 3 m thick in situ anhydrite between 3764 and 3767 m, attributed to RO.

Evidence for Lower Rotliegend

- Presence of tuff between 3780 to 3810 m,.
- Presence of a Permian-age species (*Lueckisporites*) at 3858 m (as documented in the Nam Report) support the idea that the lower part of the stratigraphic consist of Basal Rotliegend Clastics.
- Sandstone with anhydrite cement at 3840 m and at 3965 m
- Sandstone are brown and red colour (3940 m, not usually found in the Millstone Grit Formation or Yoredale Formation but rather indicative of Rotliegend depositional setting (dry continental red beds).

Note: The biostratigraphic report from Robertson (1982) also support a Rotliegend age for the strata located between the Zechstein (3708 m) and TD (3972 m).

B10-02

Several cuttings below the NLOG base Rotliegend (3722 m) show anhydrites.

3807 – 3814 m VOLCANIC TUFF: mottled grey, red, purple, green, very hard, highly siliceous, very argillaceous, ferruginous, fractured, with minor interbeds of
CLAYSTONE: as above

3814 – 3819 m CLAYSTONE: orange brown, light grey, moderately firm, non calcareous, locally slightly silty, with very thin stringers of
SANDSTONE: light grey, purplish grey, very fine, friable, poor visible porosity, non calcareous.

3819 – 3821 m SANDSTONE: predominantly loose sand, quartz, fine, subround to subangular, well sorted, occasionally loosely cemented by silica, friable, noncalcareous, slightly micaceous, locally stained red & purple, locally ferruginous, fair visible porosity, no show, with traces
ANHYDRITE: white, soft, amorphous

3821 – 3824 m CLAYSTONE: varicoloured, red brown, purple, green, moderately firm, locally silty, non calcareous, locally subfissile.

3824 – 3827 m CLAYSTONE: becomes darker to redish grey, firmer, micaceous & subfissile

3827 – 3833 m SANDSTONE: as above ... redish grey, quartzose, fine, sub... non calcareous, locally ... matrix, locally poor

...AYSTONE: orange brown, red brown, ...
calcareous, locally silty & sandy, loc...

3833 – ... m ... ately firm, non-

SANDSTONE: predominantly loose quartz gra...
predominantly medium, angular to subround, ... coarse,
few grains cemented by silica, traces anhyd... angular,
throughout the interval, traces of ... show,
ANHYDRITE: white, soft, amorphous

385... m CLAYSTONE: pale to dark redish brown, soft ... areous,
locally sandy, locally subfissile, with fe... with
SANDSTONE: light grey, redish grey, purp... ly highly
argillaceous matrix, non calcareous, s...
...icaceous.

3866 – 3883 m ... ne, subround firm to ... ic cement, non calcareous, ... comes more argillaceous towards ... light grey, red... ceous; From 3872 – 3873 m one thin band of Anhydrite ... stone at this depth has calcareous cement; further traces Anhydrite throughout the rest of the interval.

3883 – 3908 m CLAYSTONE: pale to dark red brown, soft to firm, non calcareous, commonly very finely sandy, locally subfissile, trace micaceous often with very thin streaks and bands of
ANHYDRITE: white, soft, amorphous
From 3883 to 3903 m there are interbeds of
SANDSTONE: purplish grey, very fine firm to hard, generally argillaceous, locally brittle with calcareous cement; with depth the Sandstone grades to interbeds of
SILTSTONE: (3903 – 3908 m) purplish grey, firm to moderately hard, argillaceous, locally very finely sandy, non calcareous, generally micaceous & subfissile.

3908 – 3914 m CLAYSTONE: light to dark red brown, locally patches of light green soft to firm, non calcareous, locally silty, grading to argillaceous siltone. Wit[h] few thin bands of
ANHYDRITE: white, soft amorphous

3914 – 3916.5 m CLAYSTONE: as above, with good traces of loose iron oxide granules & nodules up to 1 mm in diameter, also several cylindrical fossil fragments with radial marks from a central axis, up to 1 mm in diameter (possible crinoids/corals)

3918 – 3921 m CLAYSTONE: light to dark red brown, firm, non calcareous, with interbeds o[f]
SANDSTONE: grey, pink, very fine to fine, moderately hard, quartz cement, trace calcareous cement, no visible porosity, no show, also traces of Anhydrite and several ferruginous nodules, as above.

3921 – 3923 m SANDSTONE: light grey, pink, red brown, very fine, well sorted, friable silica cement, non calcareous, variable amounts of red argillaceous matrix locally very micaceous, poor visible porosity.

3923 – 3930 m CLAYSTONE: brick red, red brown, moderately firm, non calcareous, often wi[th] thin white bands of
ANHYDRITE, with minor interbeds of
SILTSTONE: redish grey, firm, non calcareous, micaceous, argillaceous, locally very finely sandy, locally subfissile, grades to a silty sandstone

3930 – 3935 m CLAYSTONE: as above, with interbeds of
SANDSTONE: mottled light grey, red brown, very fine, friable to moderately hard, anhydritic, locally micaceous, trace calcareous, variable argillaceous variable argillaceous, no visible porosity, no show.

3935 – 3941 m CLAYSTONE: as above, with thinner interbeds of
SILTSTONE: as above and
SANDSTONE: as above and traces
ANHYDRITE: white, soft, amorphous and clear, crystalline

3941 – 3943 m LIMESTONE: off white to redish brown, soft and chalky to moderately hard and brittle, micro- to cryptocrystalline, trace argillaceous, traces fossil fragments (none identifiable), no porosity.

3943 – 3952.5 m SANDSTONE: mottled light grey, dark brown, very fine, friable, locally anhydritic, locally argillaceous, locally trace calcareous, poor to nil visible porosity, no show, interbedded with
CLAYSTONE: red brown, firm, non calcareous, argillaceous, micaceous, sub fissile.

3952.5 – 3959 m SANDSTONE: predominantly loose clear Quartz grains, fine to medium, well sorted, subround, few grains weakly cemented by silica, friable, anhydrit[ic]

3958 – 3961 m SANDSTONE: very fine to fine, well sorted, subrounded, Quartz cement, with minor
CLAYSTONE: red-brown, firm, blocky, non calcareous

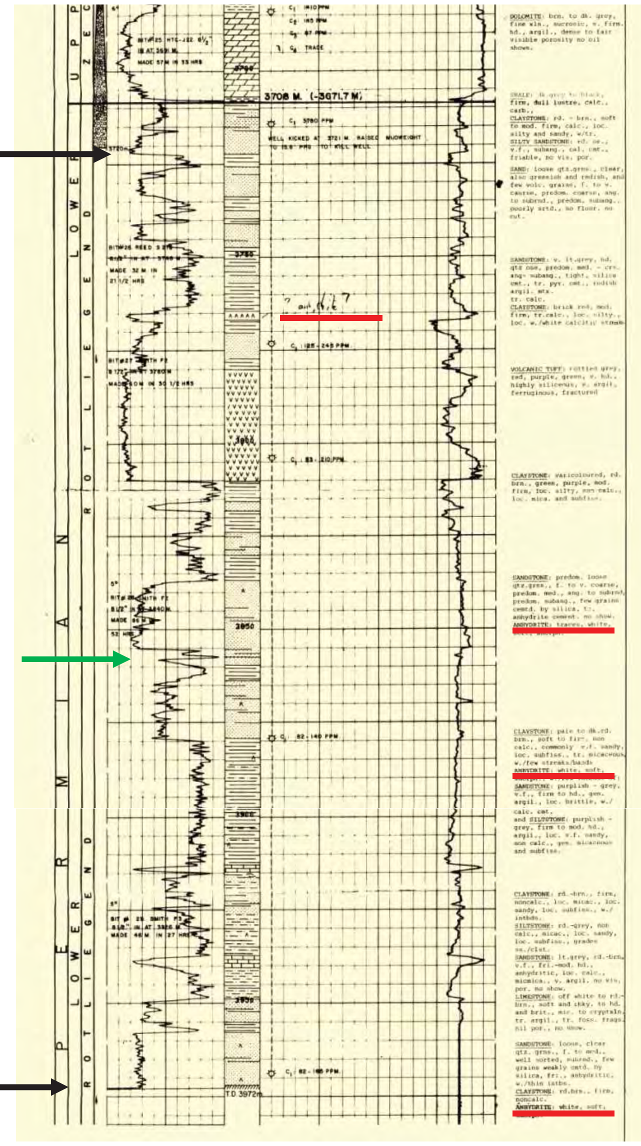
3961 – 3965 m SANDSTONE: loose Quartz sand, predominantly medium, subangular to subrounded well sorted, traces
ANHYDRITE

3965 – 3972 m SANDSTONE: light grey, light brown, very fine to fine, subangular to subroun[ded] Quartz cement, trace argillaceous, trace anhydritic. With thin interbeds of
CLAYSTONE: red-brown, firm, as above, and
ANHYDRITE: white, soft, amorphous

B10-02

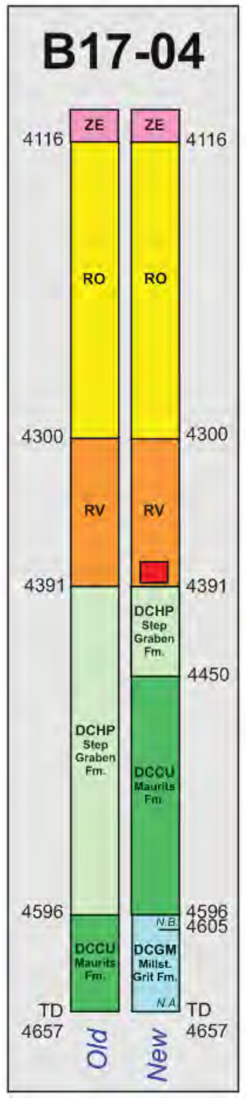
NLOG base Rotliegend

Original and new base Rotliegend



B17-04

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	B17-04
Diepte in meter t.o.v.	Rotary Table
Einddiepte (m)	4657.65
Lithostratigrafie	
Datum interpretatie	2005-03-24
Bron	EINDSLIP
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)	

Diepte stratigrafische eenheden (gemeten langs het boorgat)

Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
Upper North Sea Group	0	1086	
Rupel Formation	1086	1139	
Ieper Member	1139	1280	
Basal Dongen Tuffite Member	1280	1304	
Landen Clay Member	1304	1366	
Ekofisk Formation	1366	1439	
Ommelanden Formation	1439	1542	
Zechstein caprock	1542	1583	
Zechstein salt	1583	4077	
Z2 Basal Anhydrite Member	4077	4082	
Z2 Carbonate Member	4082	4096	
Z1 Lower Anhydrite Member	4096	4106	
Z1 Carbonate Member	4106	4113	
Coppershale Member	4113	4116	
Silverpit Formation	4116	4300	
Lower Rotliegend Group	4300	4391	
Step Graben Formation	4391	4596	UU
Maurits Formation	4596	4657	TD

New interpretation

- The interval between 4450 and 4596 m previously interpreted as Step Graben Formation is now considered Maurits Formation.
- The interval between 4596 and 4657 m (TD) previously interpreted as Maurits Formation is now considered Millstone Grit Formation.

The arguments are as follows:

- A biostratigraphic report by Robertson (1990) assigned a Namurian A age to the interval 4605 m to 4657 m(TD), and a Namurian B age to the interval 4596-4605 m. These ages suggest the Millstone Grit Fm.
- The same report listed the interval 4450-4596 m having an age of Westphalian B or B-C. This points to the Maurits Fm.
- Core (4569 m to 4593 m, or 14990 to 15068 ft) shows an upper conglomerate (3 m thick) and fining upward sandy sequences that are not indicative of the Step Graben Formation but rather an older formation, e,g, the Maurits Fm.
- According to the well site cuttings descriptions, the mudstones change colour from red to grey at 4450 m (14595 ft). So grey formations (e.g. Maurits Fm.) are present from 4450 m and deeper.

- The interval between 4391m and 4450m is unclear. There is no information that unambiguously supports a Step Graben or Maurits interpretation. More work should be done to elucidate this interval. We retained the Step Graben interpretation for this interval because the well-site lithology log indicates red-brown colours for the the majority of the mudstones. Also, the overall low sand content points to a Step Graben interpretation.

B17-04

INTERVAL 15250'-15251': LOWER CARBONIFEROUS, PENDLEIAN

Features of correlatable value:

- the appearance of *Tripartites nonguerickei* at 15250' NC Zone.

Comments:
T. nonguerickei is restricted to the NC Zone.

INTERVAL 15110'-15250': LOWER CARBONIFEROUS, ARNSBERGIAN

Features of correlatable value:

- the appearance of *Crassispora maculosa* at 15110' SO Zone (lower part).
- the appearance of *Tholisporites ?biannulatus* at 15140'.
- the appearance of *Tricidarisporites serratus* at 15181'(SWC).
- the appearance of *Triquitrites comptus* at about 15230' TK Zone.

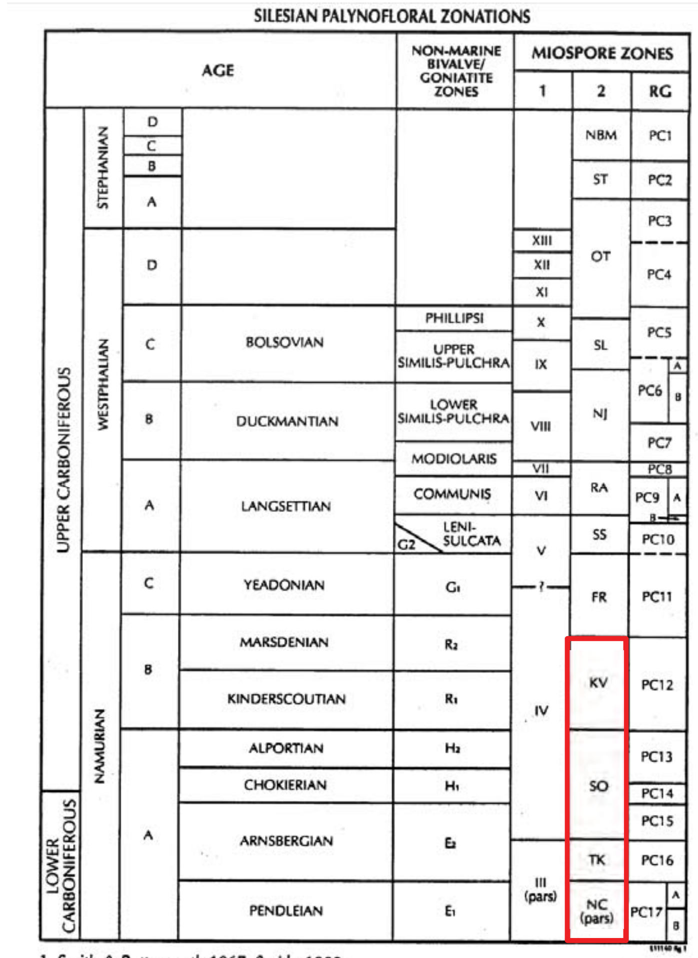
INTERVAL ?15080'(log)-15110': UPPER CARBONIFEROUS, KINDERSCOUTIAN

Stratigraphic Comments:
A regional stratigraphic break is inferred at the top of this interval, separating palynologically productive Namurian sediments from the overlying Tubbergen Sandstone Formation. The extent of missing section cannot be precisely determined because of the lack of biostratigraphic evidence for dating the lower part of the Tubbergen Sandstone Formation.

Palynological Zone:
KV.

Features of correlatable value:

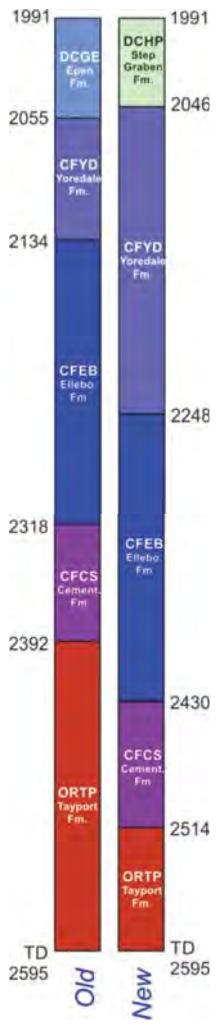
- the presence of common *Spelaeotriletes arenaceus* at 15080'.



1. Smith & Butterworth,1967; Smith, 1988.

E02-01

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	E02-01
Diepte in meter t.o.v.	Rotary Table
Einddiepte (m)	2595
Lithostratigrafie	
Datum interpretatie	1996-07-24
Bron	KARTERING DIEP - RGD - 1997
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)	

Diepte stratigrafische eenheden (gemeten langs het boorgat)

Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
Upper North Sea Group	0	1029	
Middle North Sea Group	1029	1075	
Lower North Sea Group	1075	1824	
Ekofisk Formation	1824	1855	
Ommelanden Formation	1855	1991	
Epen Formation	1991	2055	
Yoredale Formation	2055	2134	
Elleboog Formation	2134	2318	
Cementstone Formation	2318	2392	
Tayport Formation	2392	2595	TD

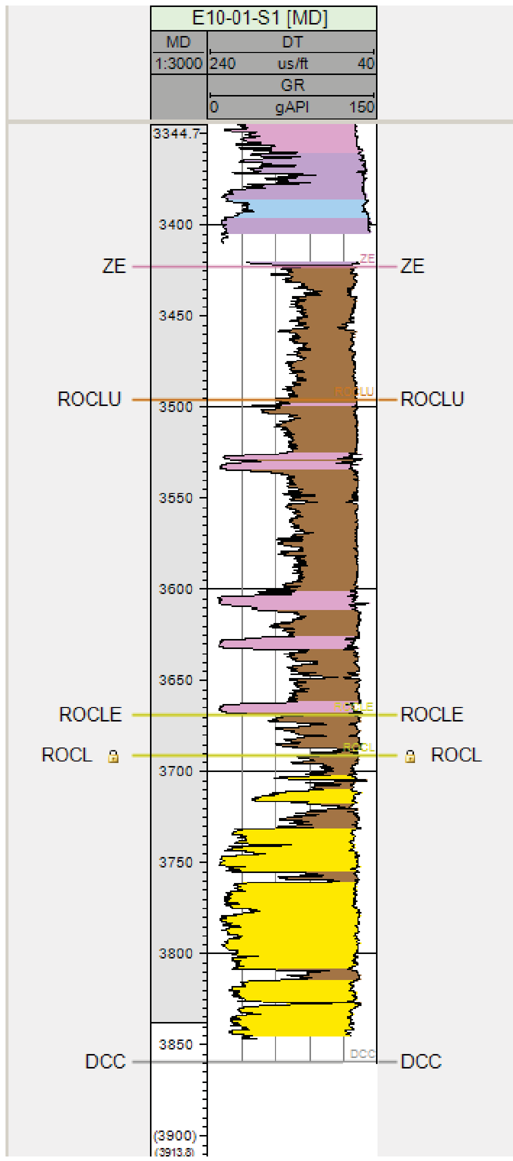
New interpretation

The new interpretation is primarily based on a biostratigraphic report made by Robertson (1985) for NAM (27021999/RRI DNS 85). This report was also used in TNO's Petroplay (2006) report. Changes are:

1. Step Graben Formation added between 1991 and 2046 m, based on additional TNO analyses that yield a Westphalian C or D age.
2. Base Yoredale Formation (Asbian-age) down to 2248 m.
3. Base Elleboog Formation (Holkerian to late Chadian) down to 2430 m.
4. Base Cementstone Formation (Early Chadian to Ivorian) down to 2514 m.

E10-01-S1

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	E10-01-SIDETRACK1
Diepte in meter t.o.v.	Rotary Table
Einddiepte (m)	3859
Lithostratigrafie	
Datum interpretatie	2005-03-24
Bron	EINDSLIP
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)	

Diepte stratigrafische eenheden (gemeten langs het boorgat)

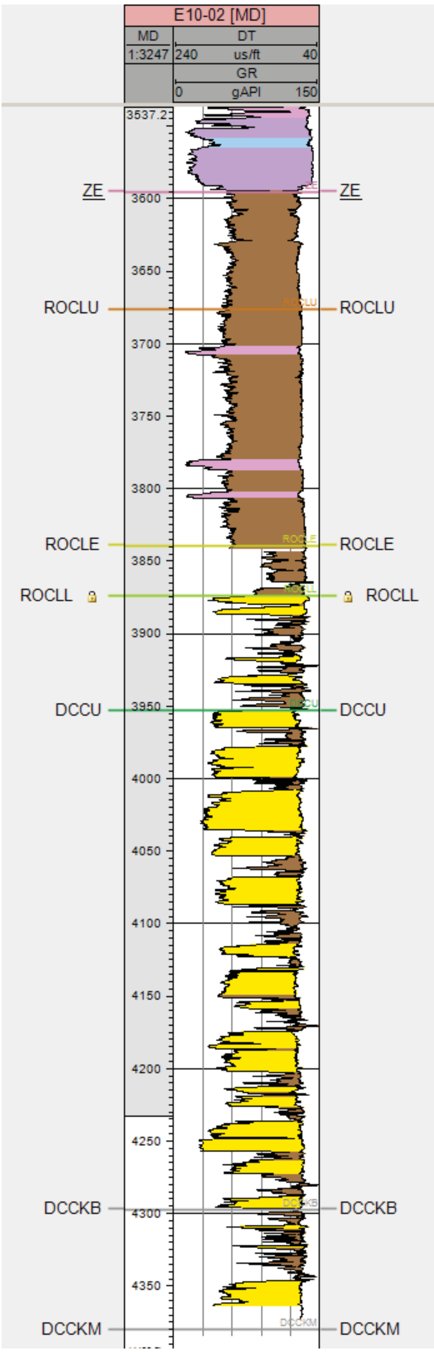
Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
North Sea Supergroup	1168	1527	UKO
Ekofisk Formation	1527	1572	
Ommelanden Formation	1572	2117	
Texel Formation	2117	2148	
Upper Holland Marl Member	2148	2172	
Middle Holland Claystone Member	2172	2185	
Lower Holland Marl Member	2185	2195	
Vlieland Marl Member	2195	2241	
Vlieland Claystone Formation	2241	2255	
Rogenstein Member	2255	2429	
Main Claystone Member	2429	2547	
Zechstein Upper Claystone Formation	2547	2563	
Zechstein Group	2563	2700	
Z3 Salt Member	2700	2876	
Z3 Main Anhydrite Member	2876	2908	
Z3 Carbonate Member	2908	2910	
Grey Salt Clay Member	2910	2911	
Z2 Salt Member	2911	3380	
Z2 Basal Anhydrite Member	3380	3388	
Z2 Carbonate Member	3388	3393	
Z1 Anhydrite Member	3393	3411	
Z1 Carbonate Member	3411	3422	
Coppershale Member	3422	3422	
Silverpit Formation	3422	3691	
Klaverbank Formation	3691	3859	TD

New interpretation

The undivided Silverpit Fm is now subdivided into ROCLU (3422-3496 m), ROCLE (3496-3667 m), and ROCLL (3667-3691 m). The subdivision is based on a comparison and correlation with neighbouring wells that already had a formal subdivision into ROCLU, ROCLE, and ROCLL.

E10-02

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	E10-02
Diepte in meter t.o.v.	Rotary Table
Einddiepte (m)	4385.5
Lithostratigrafie	
Datum interpretatie	1997-01-20
Bron	KARTERING DIEP - RGD - 1997
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)	

Diepte stratigrafische eenheden (gemeten langs het boorgat)

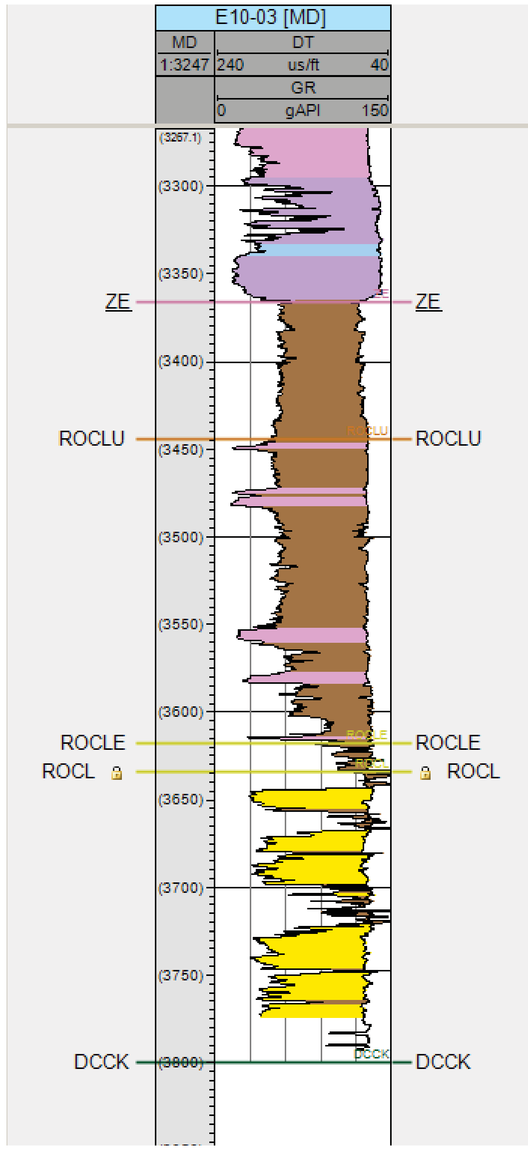
Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
North Sea Supergroup	0	1224	
Ommelanden Formation	1224	1782	
Texel Formation	1782	1823	
Upper Holland Marl Member	1823	1851	
Middle Holland Claystone Member	1851	1865	
Lower Holland Marl Member	1865	1879	
Vlieland Claystone member	1879	1891	
Vlieland Marl Member	1891	1927	
Vlieland Claystone member	1927	1954	
Lower Detfurth Sandstone Member	1954	1969	
Volpriehausen Clay-Siltstone Member	1969	1992	
Lower Volpriehausen Sandstone Member	1992	2050	
Rogenstein Member	2050	2263	
Main Claystone Member	2263	2431	
Zechstein Upper Claystone Formation	2431	2436	
Red Salt Clay Member	2436	2440	
Lower Zechstein salt	2440	3552	
Z2 Carbonate Member	3552	3563	
Z1 Lower Anhydrite Member	3563	3590	
Z1 Carbonate Member	3590	3594	
Coppershale Member	3594	3595	
Upper Silverpit Claystone Member	3595	3703	
Silverpit Evaporite Member	3703	3874	
Maurits Formation	3874	3953	
Botney Member	3953	4297	
Main Klaverbank Member	4297	4385	TD

New interpretation

The lowermost part of the Silverpit Evaporite Member (3839-3874 m) is now assigned to the Lower Silverpit Claystone Mb (ROCLL).

E10-03-S2

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	E10-03-SIDETRACK2
Diepte in meter t.o.v.	Kelly Bushing
Einddiepte (m)	3800
Lithostratigrafie	
Datum interpretatie	2002-10-07
Bron	EINDSLIP
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)	

Diepte stratigrafische eenheden (gemeten langs het boorgat)

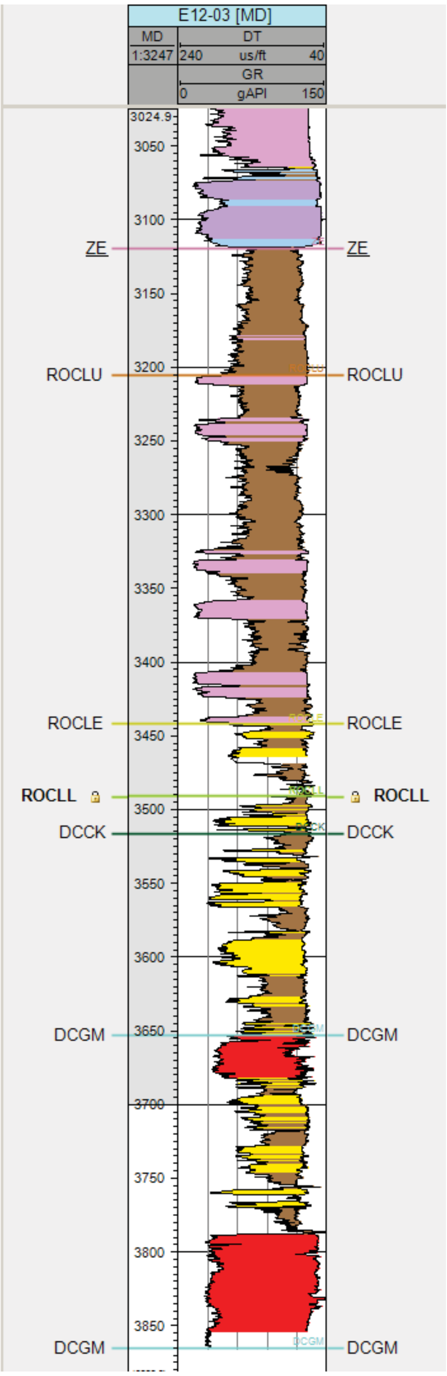
Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
Lower Buntsandstein Formation	2404	2434	UKO
Zechstein Group	2434	3366	
Coppershale Member	3366	3367	
Silverpit Formation	3367	3634	
Limburg Groep	3634	3800	TD

New interpretation

The undivided Silverpit Fm is now subdivided into ROCLU (3366-3444 m), ROCLE (3444-3617 m), and ROCLL (3617-3634 m). The subdivision is based on a comparison and correlation with neighbouring wells that already had a formal subdivision into ROCLU, ROCLE, and ROCLL.

E12-03

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam E12-03
Diepte in meter t.o.v. Rotary Table
Einddiepte (m) 3865

Lithostratigrafie
Datum interpretatie 1996-07-24
Bron KARTERING DIEP - RGD - 1997
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)

Diepte stratigrafische eenheden (gemeten langs het boorgat)

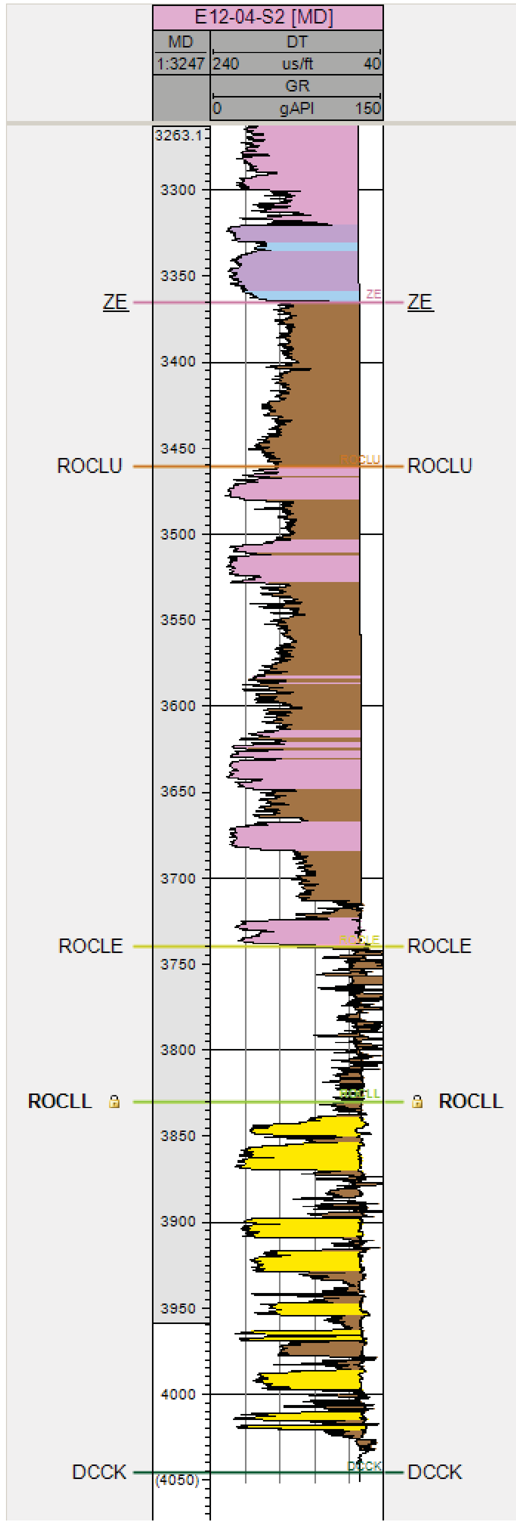
Stratigrafische eenheid	**Bovenkant van interval**	**Onderkant van interval**	**Anomaliecode**
Upper North Sea Group	0	950	
Middle North Sea Group	950	1077	
Lower North Sea Group	1077	1733	
Ommelanden Formation	1733	2138	
Texel Formation	2138	2185	
Upper Holland Marl Member	2185	2203	
Middle Holland Claystone Member	2203	2208	
Lower Holland Marl Member	2208	2219	
Vlieland Marl Member	2219	2277	
Vlieland Claystone member	2277	2319	
Main Claystone Member	2319	2542	
Zechstein Upper Claystone Formation	2542	2569	
Z2 Salt Member	2569	3074	
Z2 Basal Anhydrite Member	3074	3086	
Z2 Carbonate Member	3086	3092	
Z1 Lower Anhydrite Member	3092	3111	
Z1 Carbonate Member	3111	3118	
Coppershale Member	3118	3119	
Upper Silverpit Claystone Member	3119	3223	
Silverpit Evaporite Member	3223	3442	
Lower Silverpit Claystone Member	3442	3491	
Millstone Grit Formation	3491	3653	
IGNEOUS ROCK	3653	3682	
Millstone Grit Formation	3682	3788	
IGNEOUS ROCK	3788	3865	TD

New interpretation

1. The base of the Upper Silverpit Claystone Mb (ROCLU) was shifted up from 3223 to 3205 m, based on a comparison and correlation with neighbouring wells. This means that also the top of the Silverpit Evaporite Member (ROCLE) was changed from 3223 to 3205 m.
2. The upper 25 m of the Millstone Grit Fm (DCGM) is now assigned to the Klaverbank Formation (DCCK; 3491-3516 m), based on an ELF-Aquitain palynological study from 1992 (EP/S/EXP/SED/92.015 RP). This study found Westphalian A miospores at 3492 and 3494.5 m.

E12-04-S2

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam E12-04-SIDETRACK2
Diepte in meter t.o.v. Rotary Table
Einddiepte (m) 4046

Lithostratigrafie
Datum interpretatie 1997-09-10
Bron EINDSLIP
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)

Diepte stratigrafische eenheden (gemeten langs het boorgat)

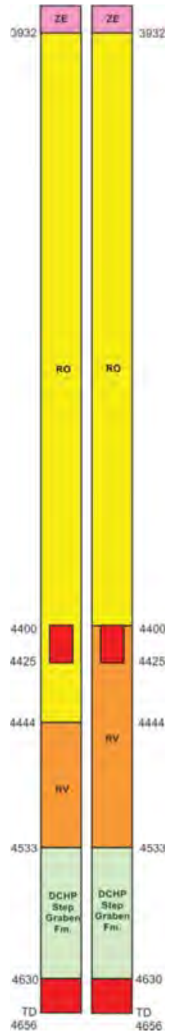
Stratigrafische eenheid	**Bovenkant van interval**	**Onderkant van interval**	**Anomaliecode**
North Sea Supergroup	810	1768	UKO
Ekofisk Formation	1768	1875	
Ommelanden Formation	1875	2233	
Texel Formation	2233	2257	
Upper Holland Marl Member	2257	2265	
Middle Holland Claystone Member	2265	2275	
Lower Holland Marl Member	2275	2283	
Vlieland Marl Member	2283	2310	
Vlieland Claystone member	2310	2384	
Friesland Member	2384	2396	
Lower Buntsandstein Formation	2396	2575	
Zechstein Upper Claystone Formation	2575	2602	
Z4 Salt Member	2602	2710	
Zechstein salt	2710	3321	
Z2 Basal Anhydrite Member	3321	3330	
Z2 Carbonate Member	3330	3338	
Z1 Anhydrite Member	3338	3360	
Z1 Carbonate Member	3360	3364	
Coppershale Member	3364	3365	
Upper Silverpit Claystone Member	3365	3470	
Silverpit Evaporite Member	3470	3740	
Lower Silverpit Claystone Member	3740	3830	
Klaverbank Formation	3830	4046	UU_TD

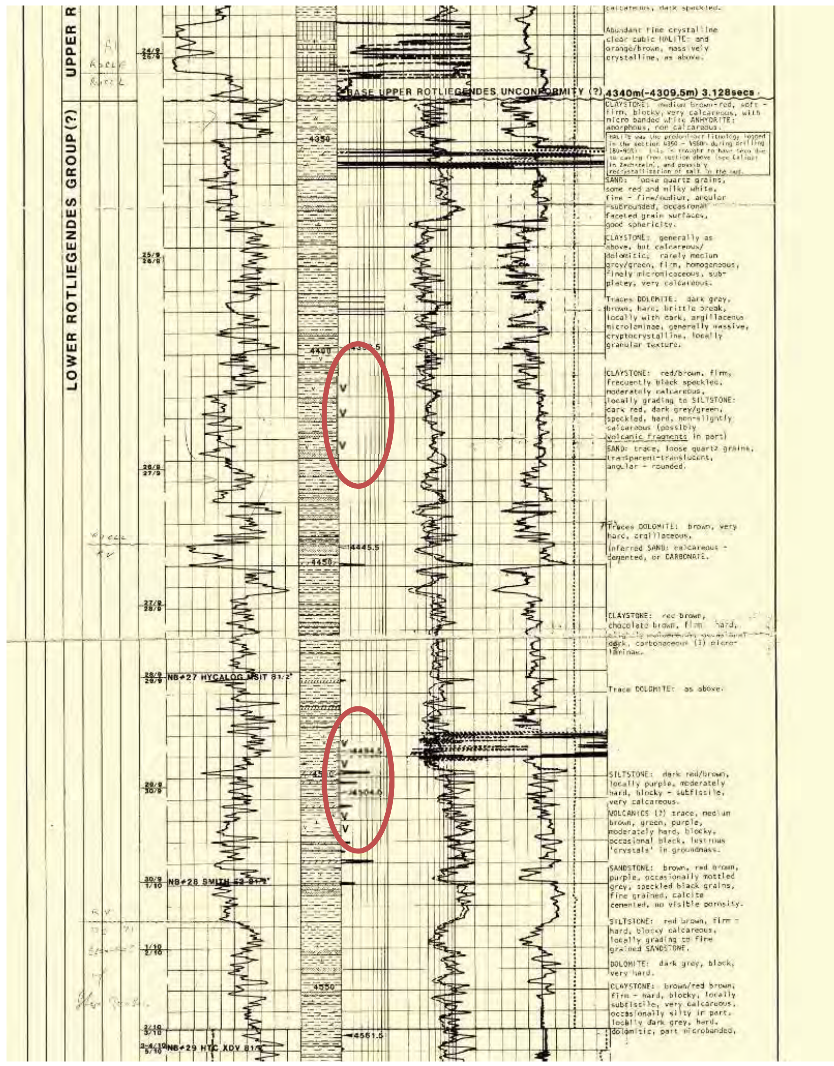
New interpretation

1. The base of the Upper Silverpit Claystone Mb (ROCLU) was shifted up from 3470 to 3461 m, based on a comparison and correlation with neighbouring wells. This means that also the top of the Silverpit Evaporite Member (ROCLE) was changed from 3470 to 3461 m.

F04-02-A

Summary of changes



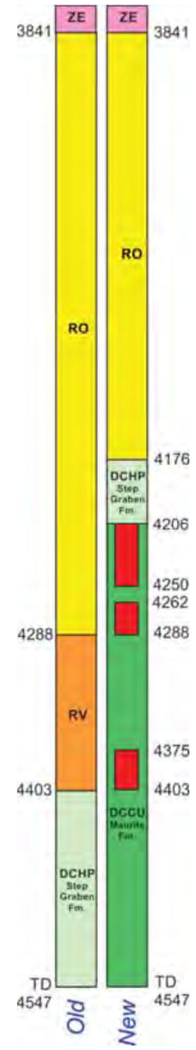


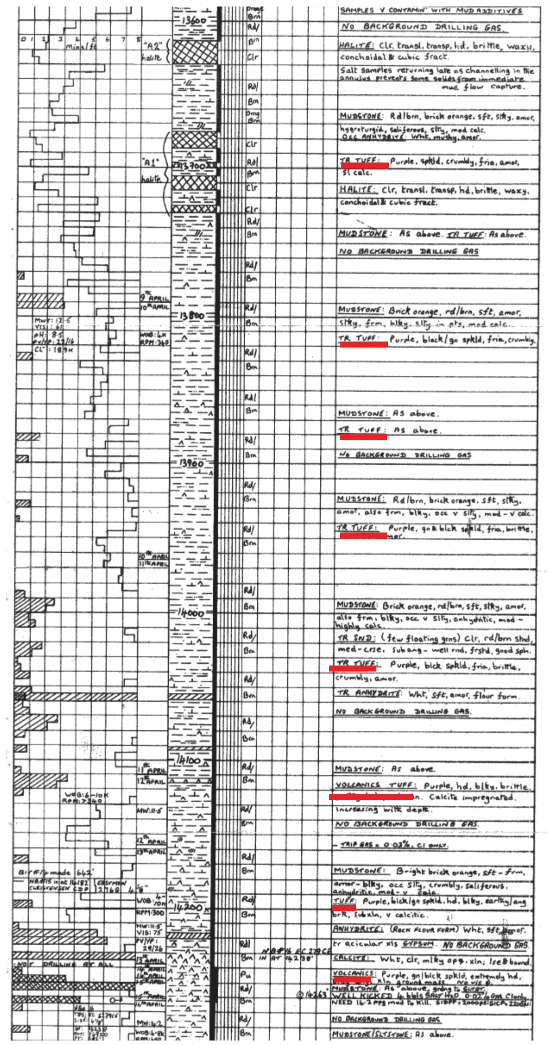
New interpretation

1. Base Upper Rotliegend Group (RO) moved up to 4400 m due to the presence of volcanics between 4425 and 4400m. Those volcanics are interpreted as Lower Rotliegend volcanics.

F04-03

Summary of changes





New interpretation

1. The interval 4176-4206 m, earlier interpreted as Upper Rotliegend, is now Step Graben Formation.
2. The interval 4206-4547 m, earlier interpreted as Upper Rotliegend, Lower Rotliegend, and Step Graben Fm, is now interpreted as Maurits Formation.

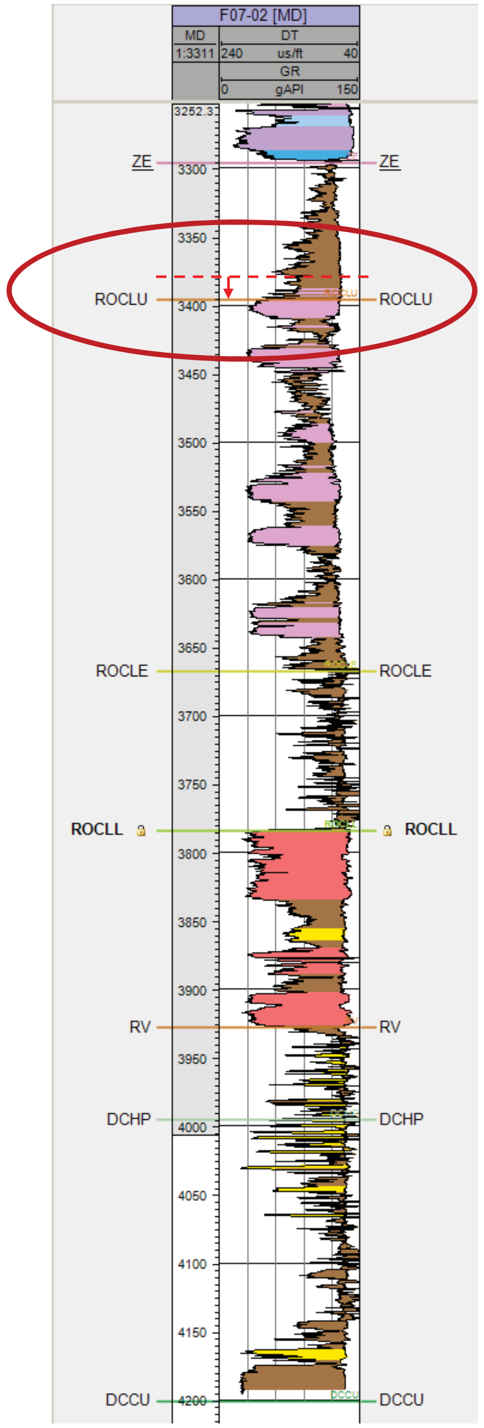
The following arguments were used:

- There are frequent tuffs and volcanics between 4176 and 4343m that should not occur within the Upper Rotliegend Group;
- A biostratigraphic report from Halliburton (1992) indicates:
    1) Westphalian D age between 4206 and 4176 m with *Vestispora fenestrate* (13710), suggesting Step Graben Formation;
    2) Westphalian B-C below 4206 m. The highest occurrences of *Dictyotriletes bireticulatus* indicates an age no younger than early Westphalian C. This suggests that it is Maurits Fm.

Note: The wireline logs characteristics show an unusual stratigraphy compared to typical Westphalian B-C (Maurits Formation), with some alternations of mudstone and thick tuff intervals. This interval is also sand-poor and has no coal.

F07-02

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Boorgatnaam	F07-02
Diepte in meter t.o.v.	Rotary Table
Einddiepte (m)	4200
Lithostratigrafie	
Datum interpretatie	2000-06-20
Bron	EINDSLIP
Conform Adrichem Boogaert & Kouwe (1993) en Munsterman et al (2012)	

Diepte stratigrafische eenheden (gemeten langs het boorgat)

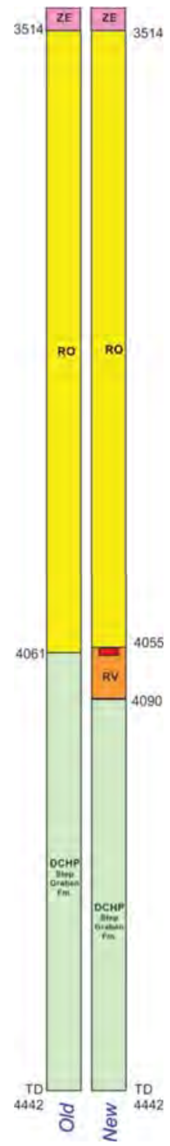
Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
Upper North Sea Group	0	1019	
Middle North Sea Group	1019	1103	
Lower North Sea Group	1103	1557	
Ommelanden Formation	1557	1695	
Texel Formation	1695	1708	
Holland Formation	1708	1761	
Vlieland Claystone Formation	1761	1797	
Hardegsen Formation	1797	1823	
Detfurth Claystone Member	1823	1857	
Lower Detfurth Sandstone Member	1857	1873	
Volpriehausen Clay-Siltstone Member	1873	2001	
Lower Volpriehausen Sandstone Member	2001	2052	
Rogenstein Member	2052	2164	
Main Claystone Member	2164	2389	
Zechstein Upper Claystone Formation	2389	2400	
Zechstein salt	2400	3256	
Z2 Basal Anhydrite Member	3256	3260	
Z2 Carbonate Member	3260	3269	
Z1 Anhydrite Member	3269	3284	
Z1 Carbonate Member	3284	3293	
Coppershale Member	3293	3294	
Upper Silverpit Claystone Member	3294	3374	
Silverpit Evaporite Member	3374	3660	
Lower Silverpit Claystone Member	3660	3783	
Lower Rotliegend Group	3783	3927	
Step Graben Formation	3927	3994	
Maurits Formation	3994	4200	TD

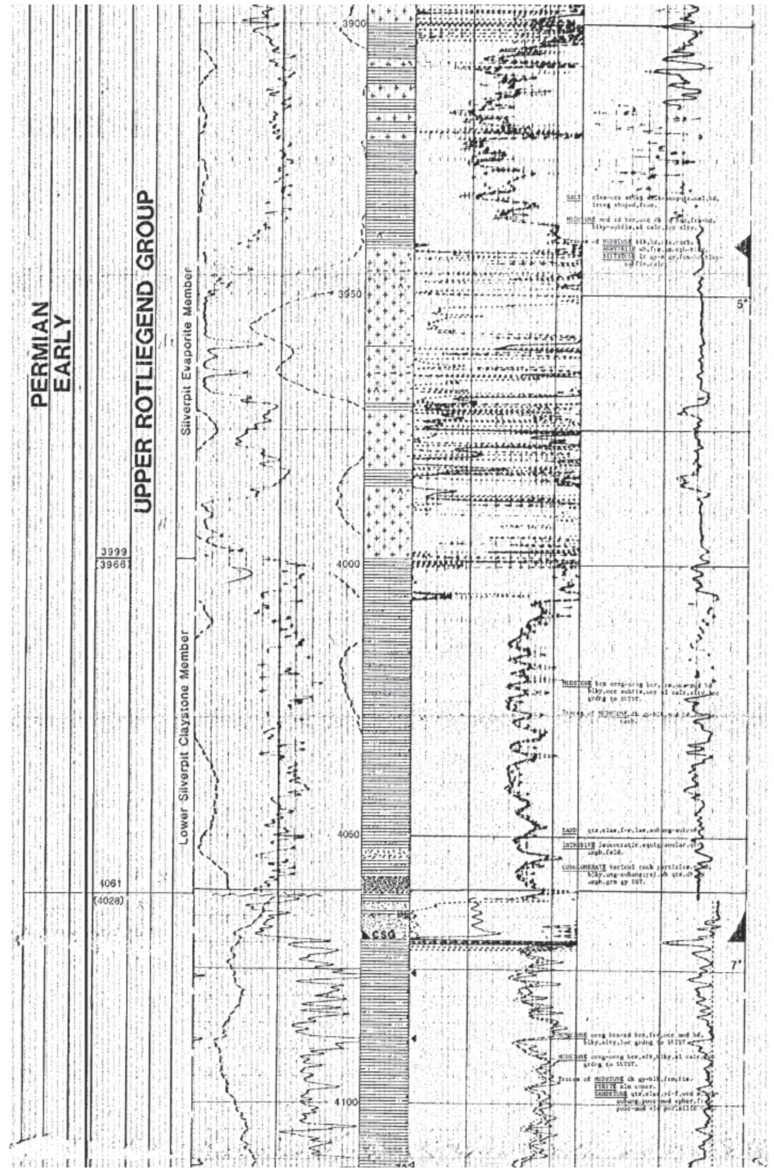
New interpretation

1. The base of the Upper Silverpit Claystone Mb (ROCLU) was shifted down from 3374 to 3395 m, based on a comparison and correlation with neighbouring wells. This means that also the top of the Silverpit Evaporite Member (ROCLE) was changed from 3374 to 3395 m.

F10-02

Summary of changes



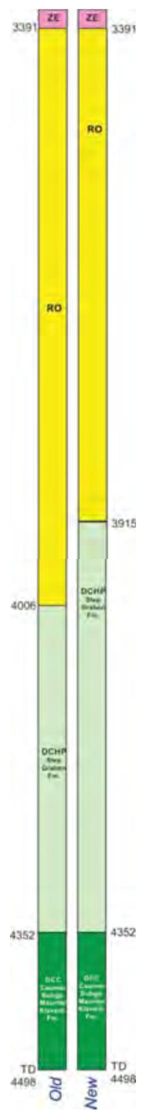


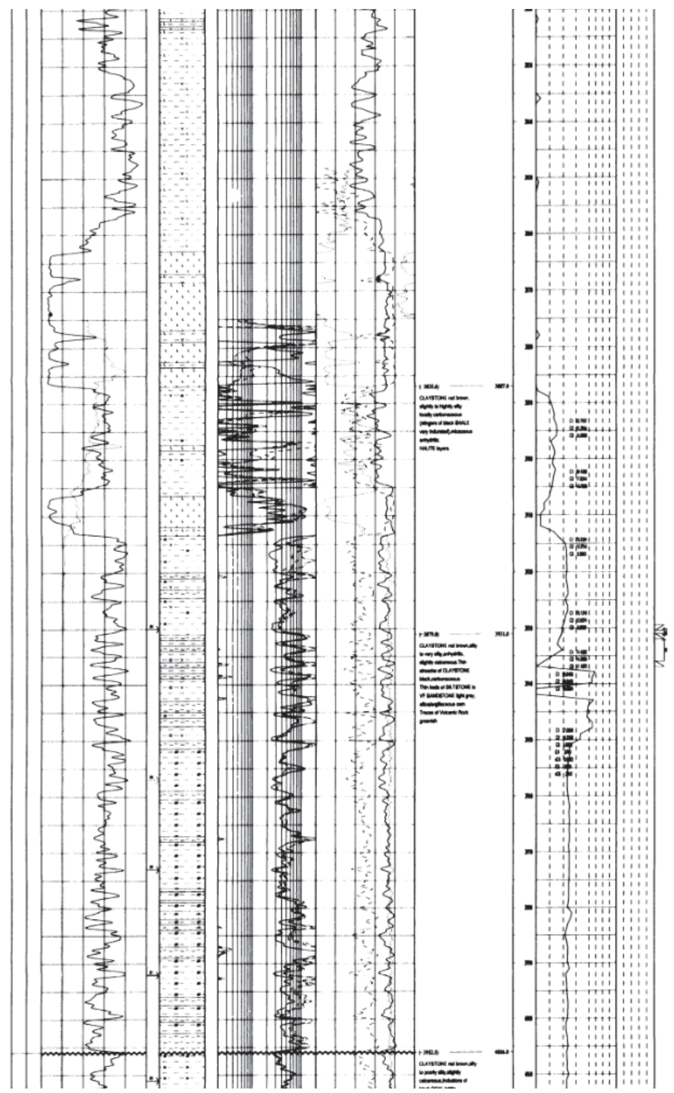
New interpretation

1. The presence of volcanics is interpreted as Lower Rotliegend (RV) in the interval 4055-4090 m. This interval was previously interpreted as partly belonging to the Upper Rotliegend and partly to the Step Graben Formation.

F10-03

Summary of changes





New interpretation

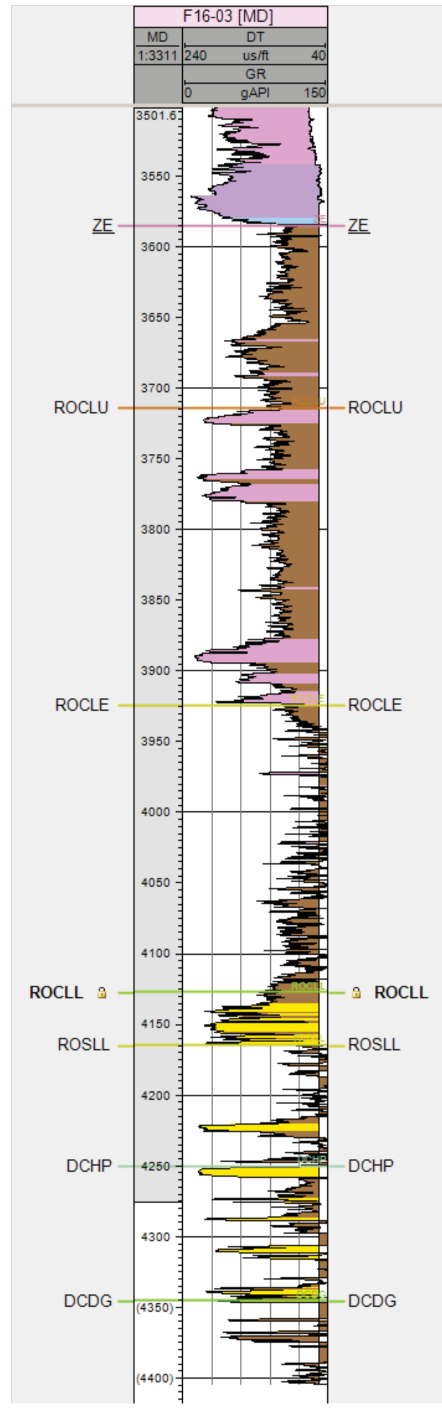
1. The interval between 3915-4006 m is interpreted as Step Graben Fm instead of Upper Rotliegend.
2. Undivided Silverpit Fm is now subdivided into ROCLU (3393-3522 m), ROCLE (3522-3914 m), and ROCLL (3914-3969 m).

The arguments for the Step Graben interpretation are as follows:

- A Late Westphalian C – Westphalian D age is inferred based on the presence of *Thymospora* spp. together with *Potonieisporites* spp. and *Protohaploxypinus* spp. and the LOD *Triquitrites tribullates* at 4348m.
- A Westphalian C age is assigned to the interval between 4435 and 4367m, based on presence of *Raistrickia fulva*.

F16-03

Summary of changes



Existing lithostratigraphy (NLOG 2014)

Diepte stratigrafische eenheden (gemeten langs het boorgat)			
Stratigrafische eenheid	Bovenkant van interval	Onderkant van interval	Anomaliecode
North Sea Supergroup	0	1852	
Ommelanden Formation	1852	2466	
Plenus Marl Member	2466	2467	
Texel Marlstone Member	2467	2564	
Upper Holland Marl Member	2564	2609	
Middle Holland Claystone Member	2609	2627	
Lower Holland Marl Member	2627	2639	
Vlieland Marl Member	2639	2734	
Vlieland Claystone member	2734	2858	
Schill Grund Member	2858	2875	
Scruff Greensand Formation	2875	2882	
Zechstein caprock	2882	2904	UU
Z4 Salt Member	2904	2965	
Z4 Pegmatite Anhydrite Member	2965	2982	
Z3 Salt Member	2982	3253	
Z2 Salt Member	3253	3542	
Z2 Basal Anhydrite Member	3542	3548	
Z2 Carbonate Member	3548	3556	
Z1 Anhydrite Member	3556	3573	
Z1 Carbonate Member	3573	3583	
Coppershale Member	3583	3584	
Upper Silverpit Claystone Member	3584	3717	
Silverpit Evaporite Member	3717	3919	
Lower Silverpit Claystone Member	3919	4127	
Lower Slochteren Member	4127	4155	UU
Step Graben Formation	4155	4250	UU
Hospital Ground Formation	4250	4345	TD

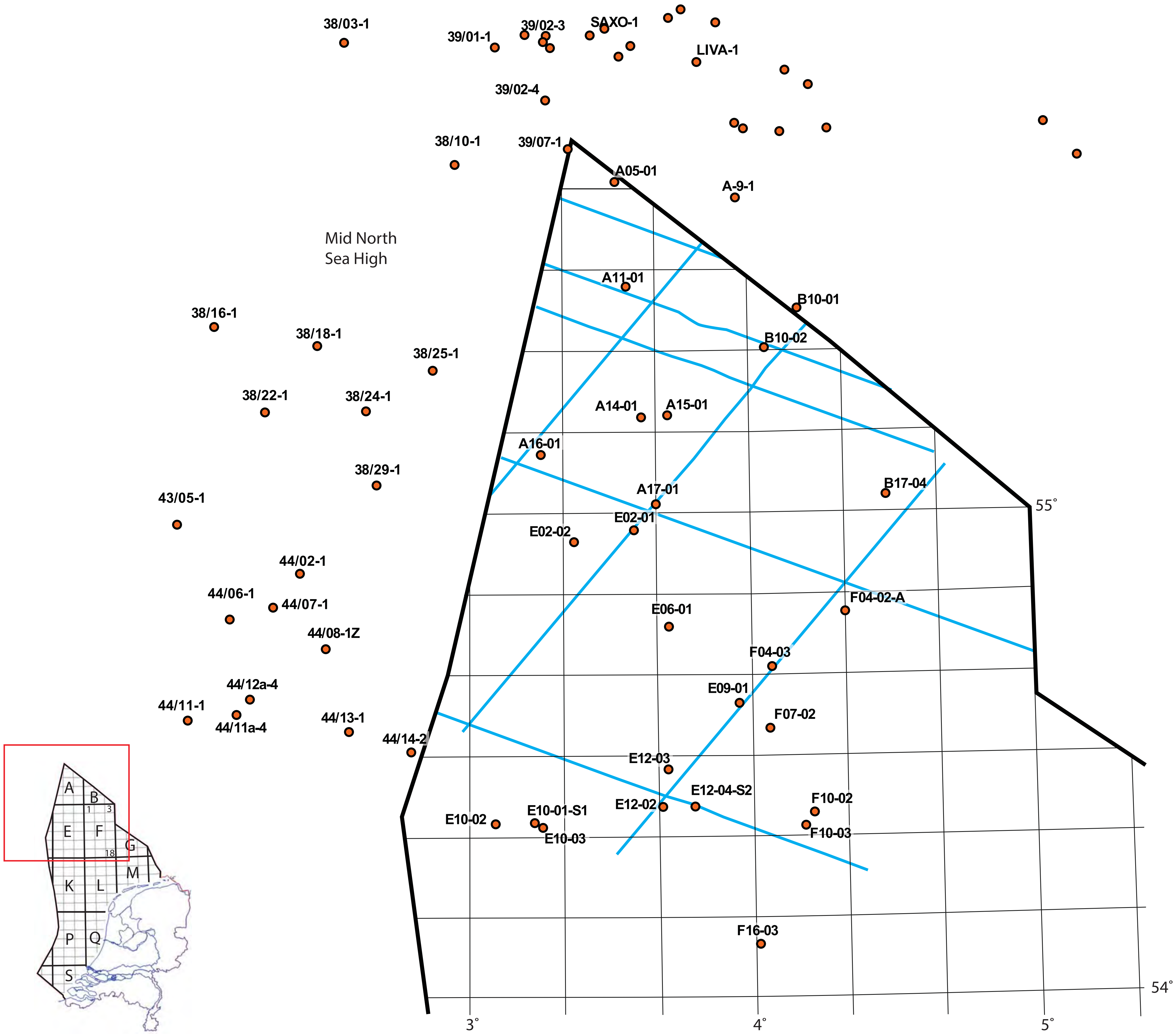
New interpretation

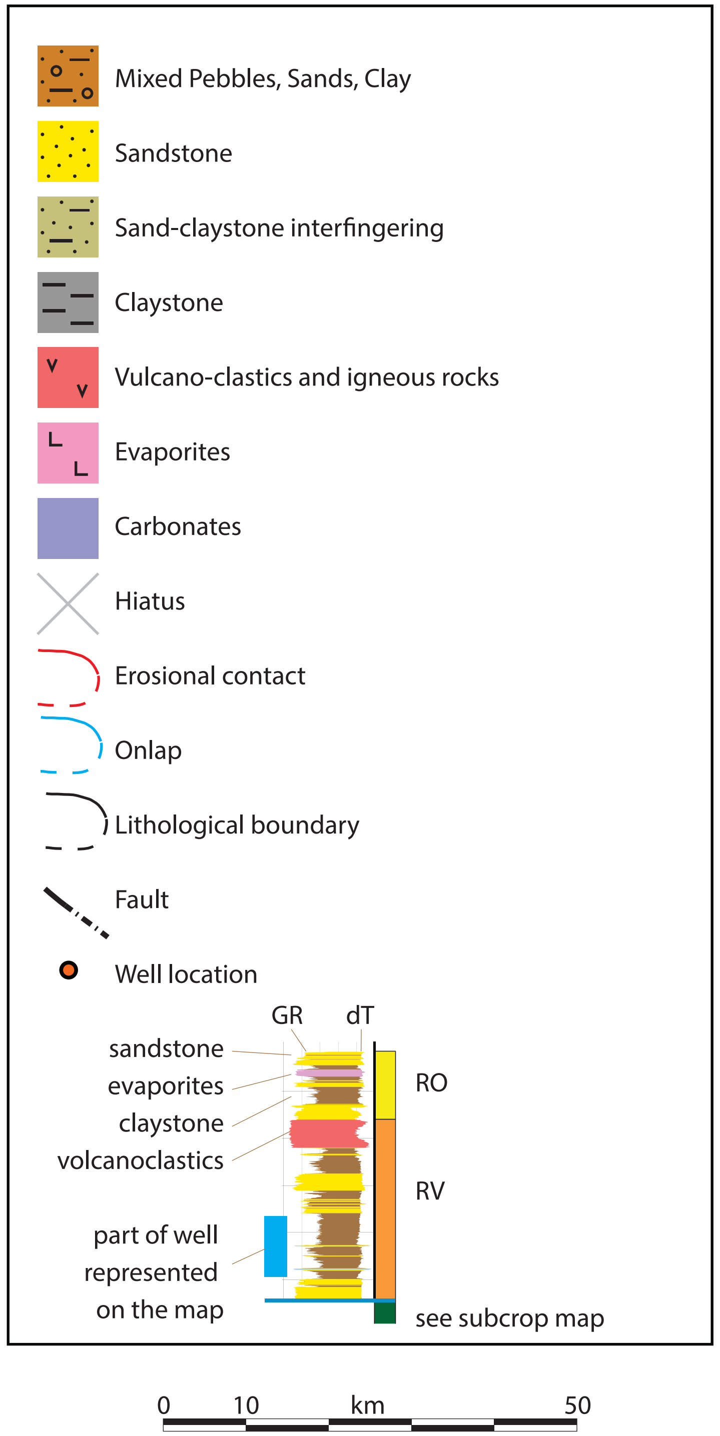
1. Minor changes in ROCLU (base 3717m shifted up to 3714m), ROCLE (base 3919m shifted down to 3924m), ROSLL (base 4155m shifted down to 4165m) and DCHP (top 4155m shifted down to 4165 m). This was all based on a comparison and correlation with neighbouring wells.

4 Seismic Mapping

List of seimic maps and cross sections:

4.01 Seismic lines NSR
4.02 Seismic interpretation Zechstein
4.03 Seismic interpretation Upper Rotliegend
4.04 Seismic interpretation Lower Rotliegend
4.05 Seismic interpretation Westphalian
4.06 Seismic interpretation Scremerston Coals
4.07 Time structure map Zechstein
4.08 Time structure map Upper Rotliegend
4.09 Time structure map Lower Rotliegend
4.10 Time structure map Westphalian
4.11 Time-thickness map Upper Rotliegend
4.12 Time-thickness map Lower Rotliegend
4.13 Time-thickness map Westphalian
4.14 Depth map Upper Rotliegend
4.15 Depth map Lower Rotliegend
4.16 Depth map Westphalian
4.17 Faults at the top Rotliegend from 3D Seismic
4.18 Interval velocities Upper Rotliegend
4.19 Interval velocities Westphalian
4.20 Survey polarities
4.21 Top Scremerston seismic character N85-2 (partial)
4.22 Unconformities in the Step Graben NSR 12288 (partial)
4.23 Bases of Westphalian, Lower Rotliegend, Upper Rotliegend, and Zechstein NSR 12288
4.24 Unconformities in the Step Graben SNST83-20 (partial)
4.25 Stratigraphic development of the Lower and Upper Rotliegend NSR 41061(flattened)
4.26 Stratigraphic development of the Lower and Upper Rotliegend NSR 12288 (flattened)





Appendix 4.01
Seismic Lines
NSR

New Petroleum plays in the Dutch Northern Offshore

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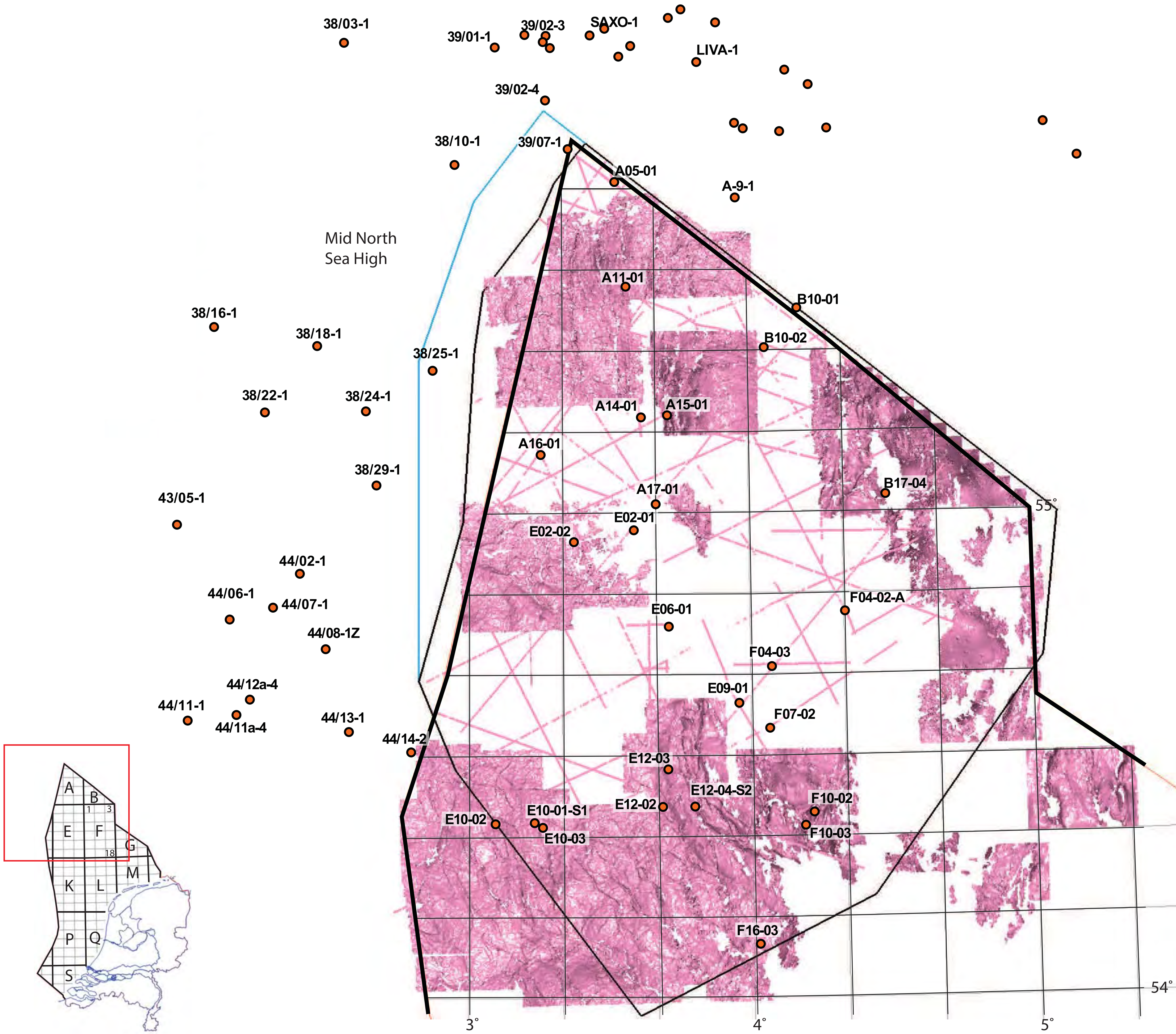

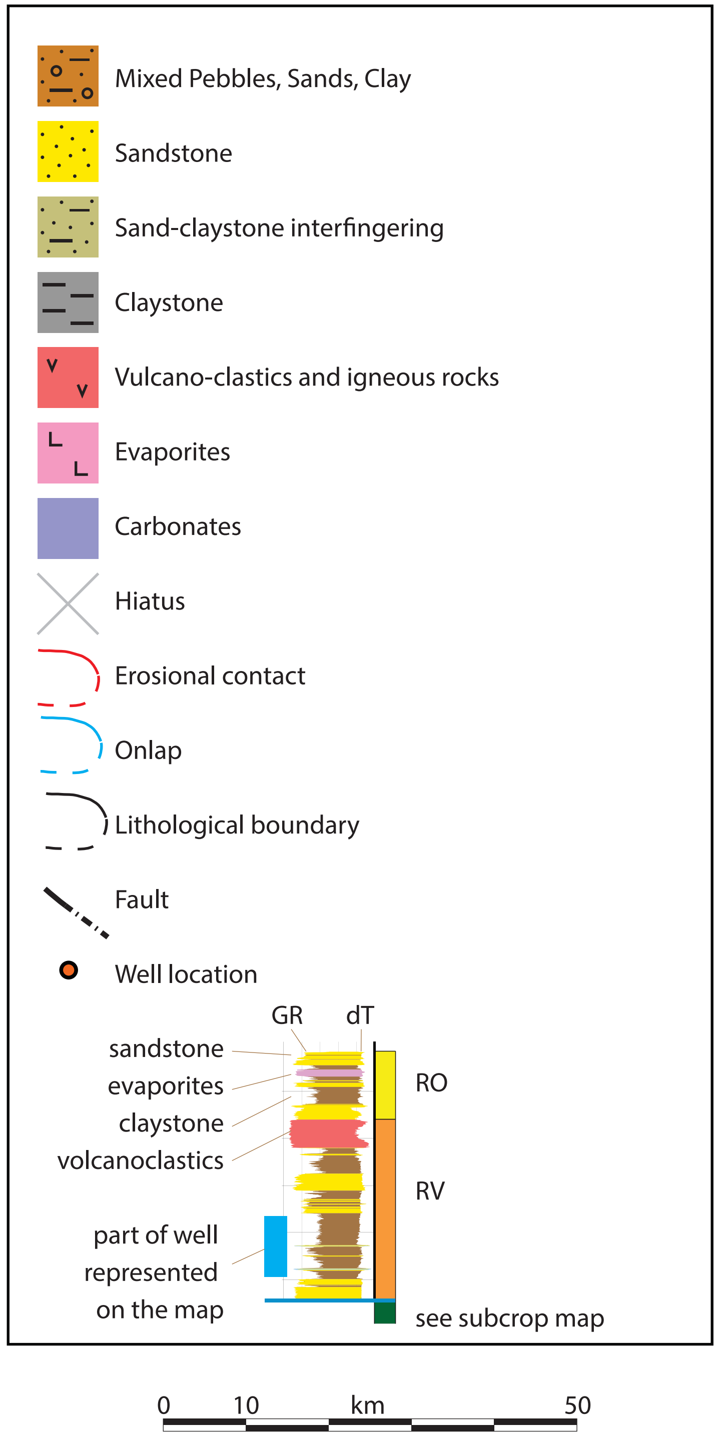

Appendix 4.02
Seismic interpretation
Base Zechstein (ZE)

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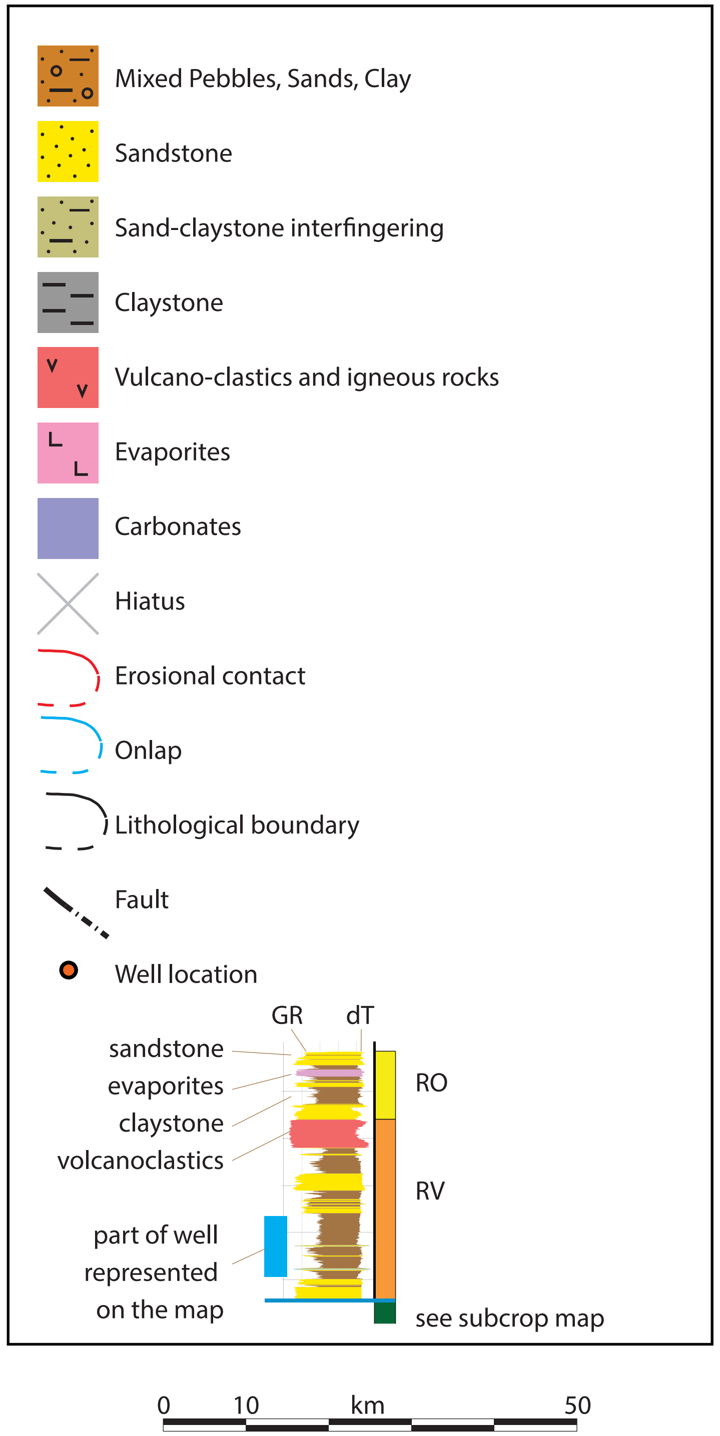

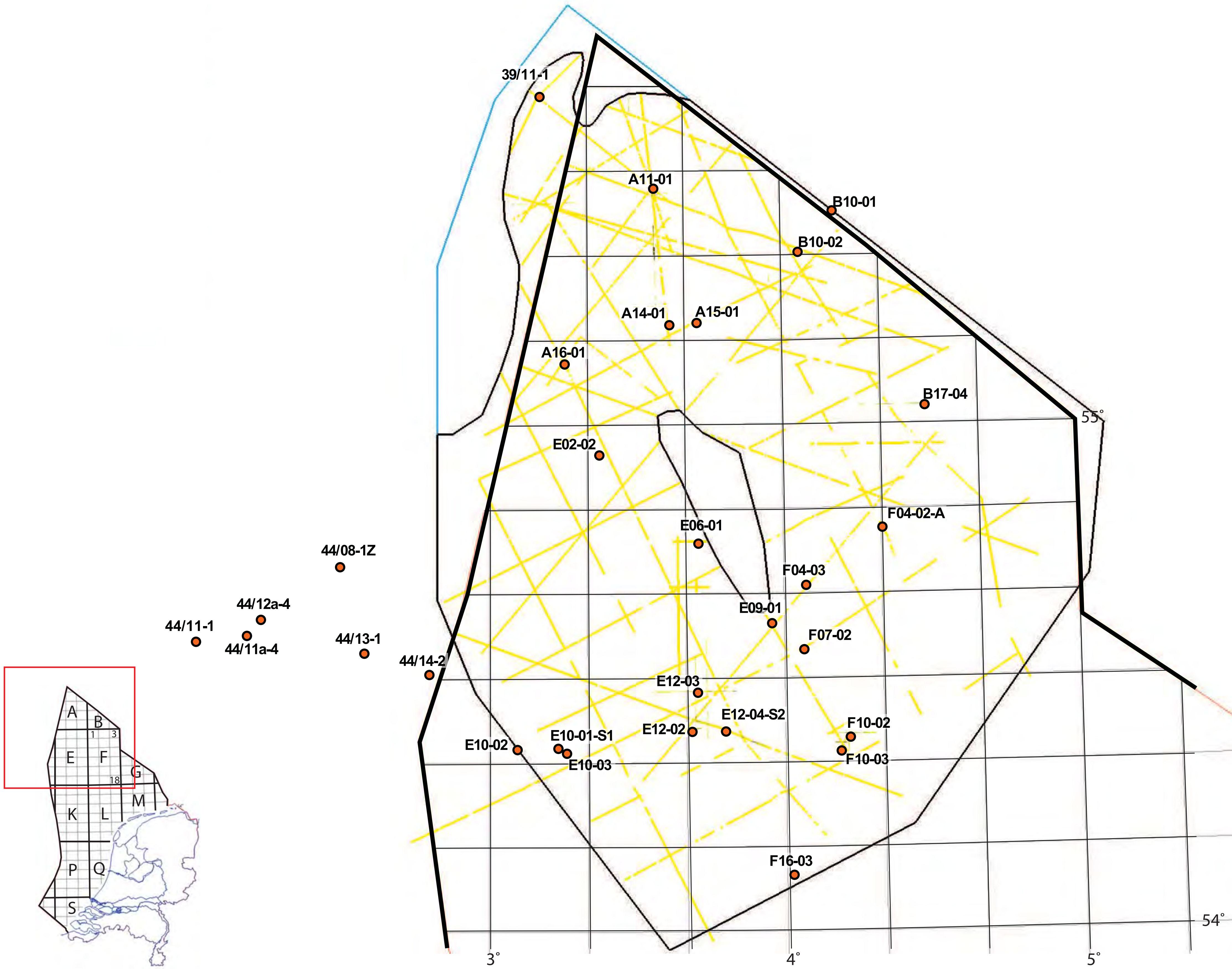

Appendix 4.03
Seismic interpretation
Base Upper Rotliegend (RO)

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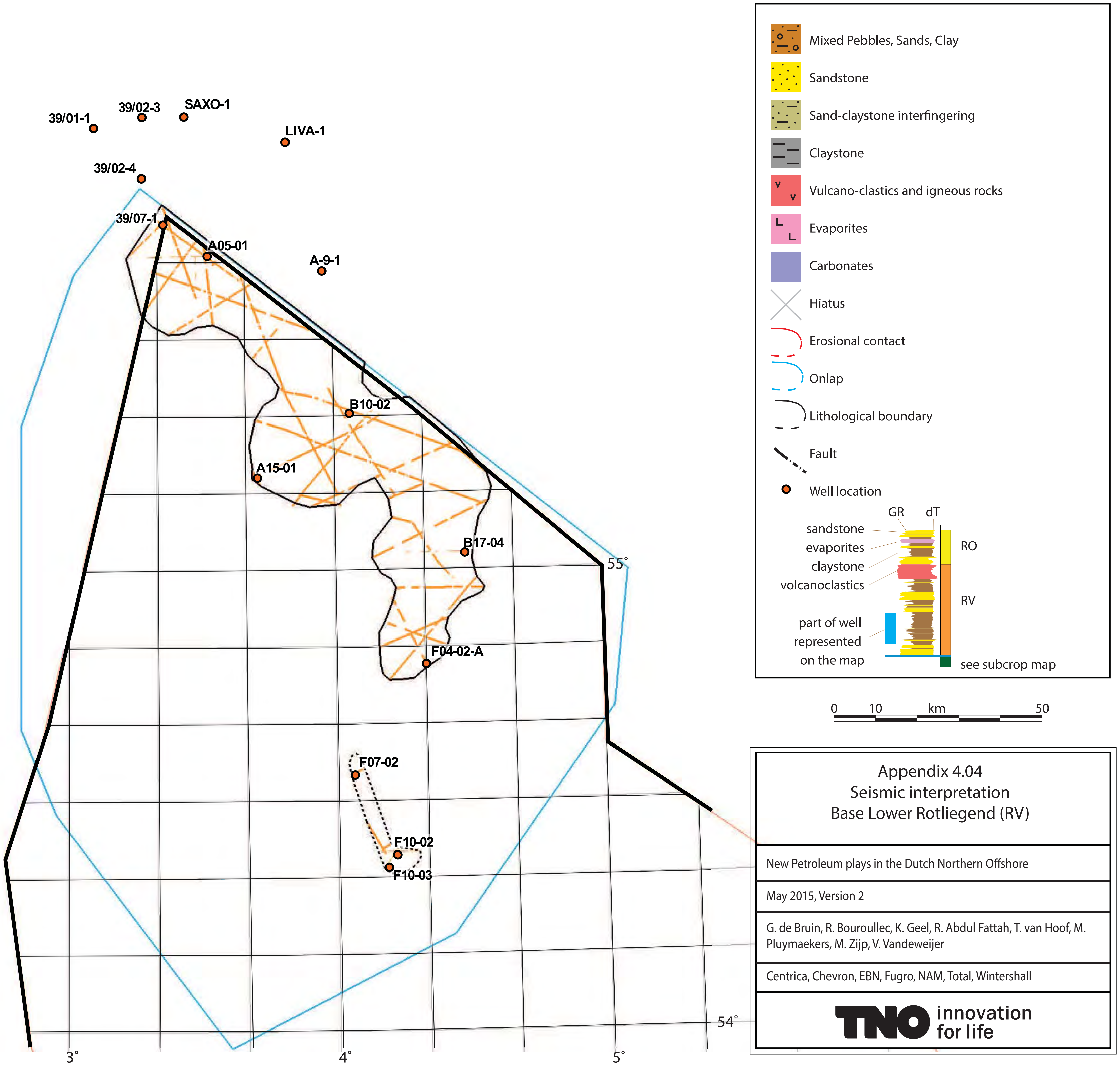

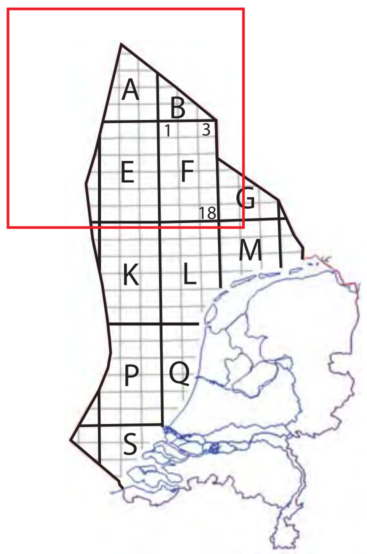

Appendix 4.04
Seismic interpretation
Base Lower Rotliegend (RV)

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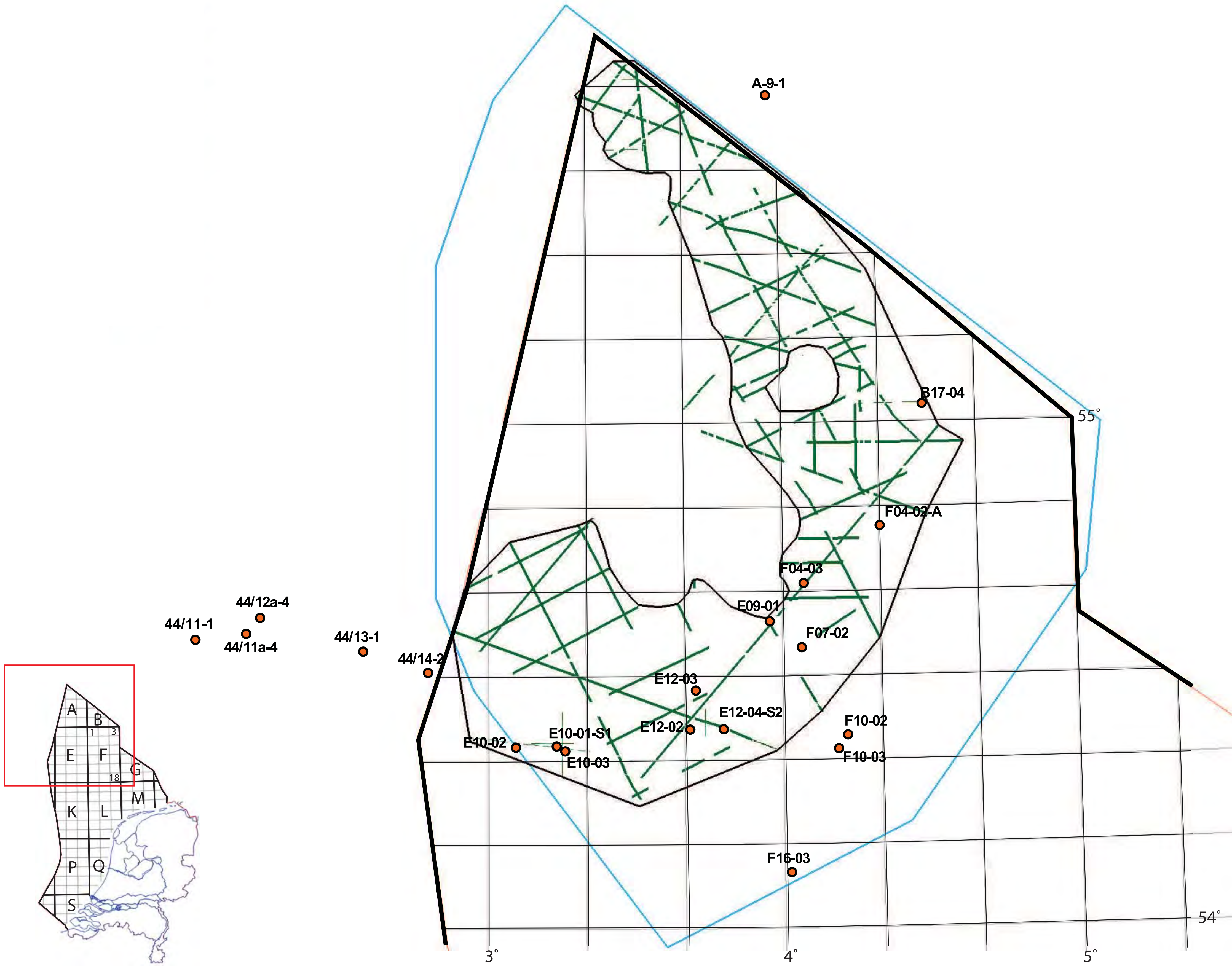
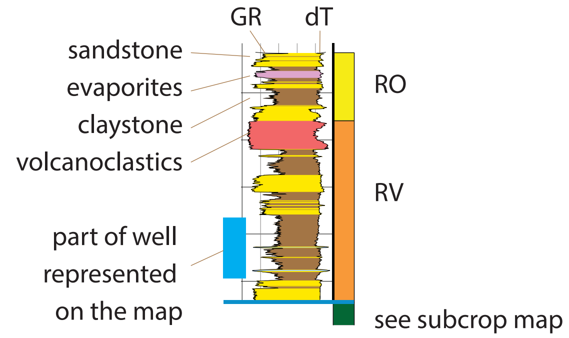


Mixed Pebbles, Sands, Clay
Sandstone
Sand-claystone interfingering
Claystone
Vulcano-clastics and igneous rocks
Evaporites
Carbonates
Hiatus
Erosional contact
Onlap
Lithological boundary
Fault
Well location



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Appendix 4.05
Seismic interpretation
Base Westphalian Unconformity (BWU)

New Petroleum plays in the Dutch Northern Offshore

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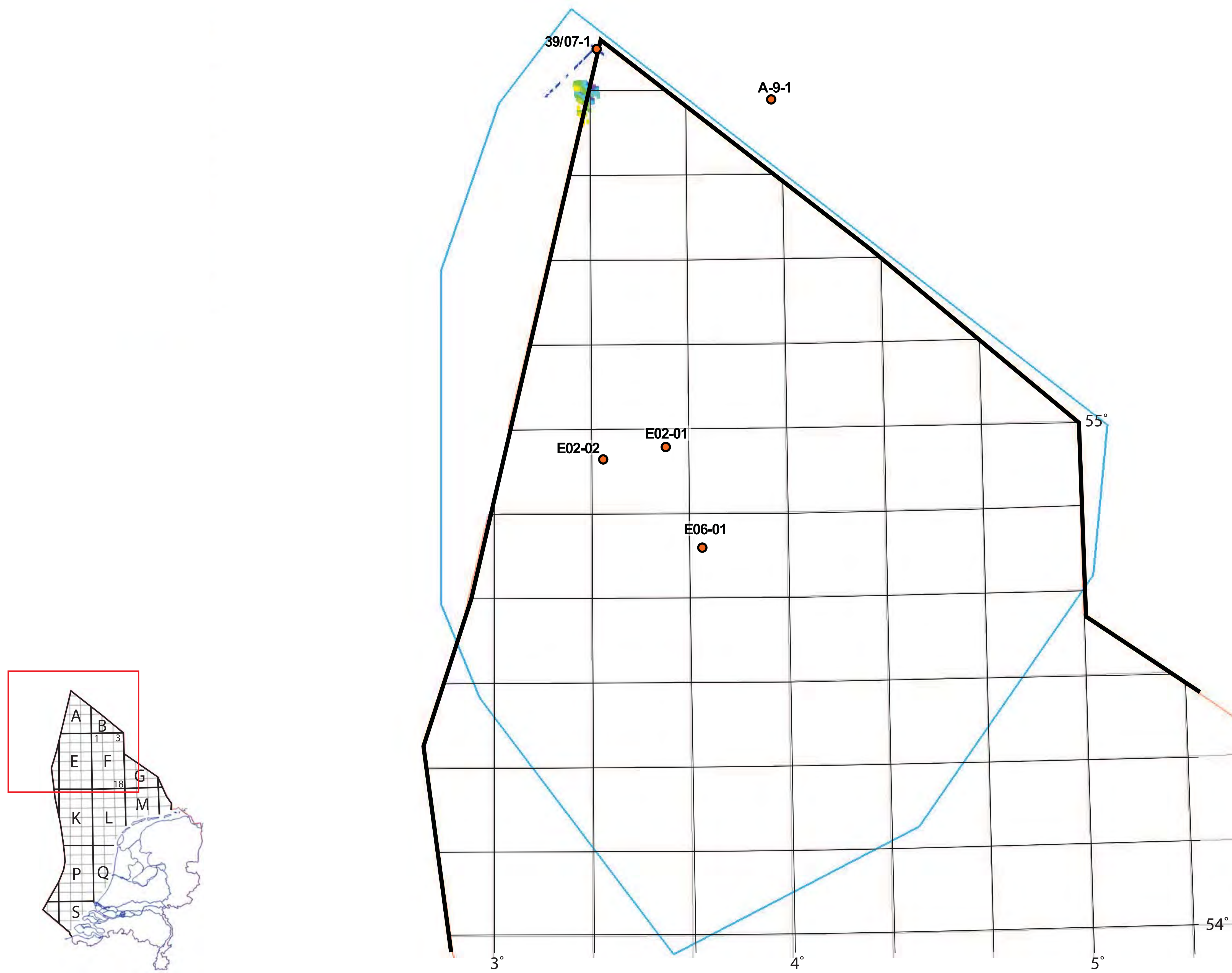

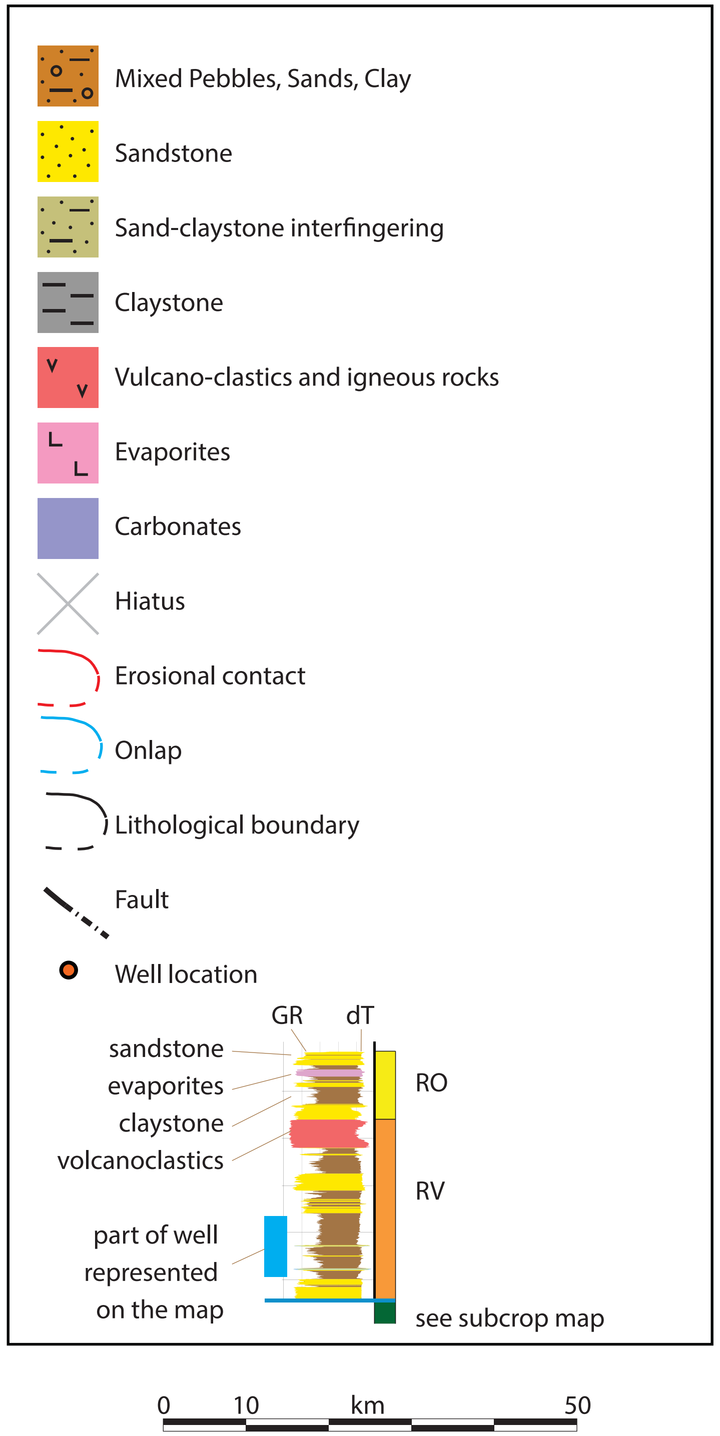

Appendix 4.06
Seismic interpretation
Top Scremerston Coal

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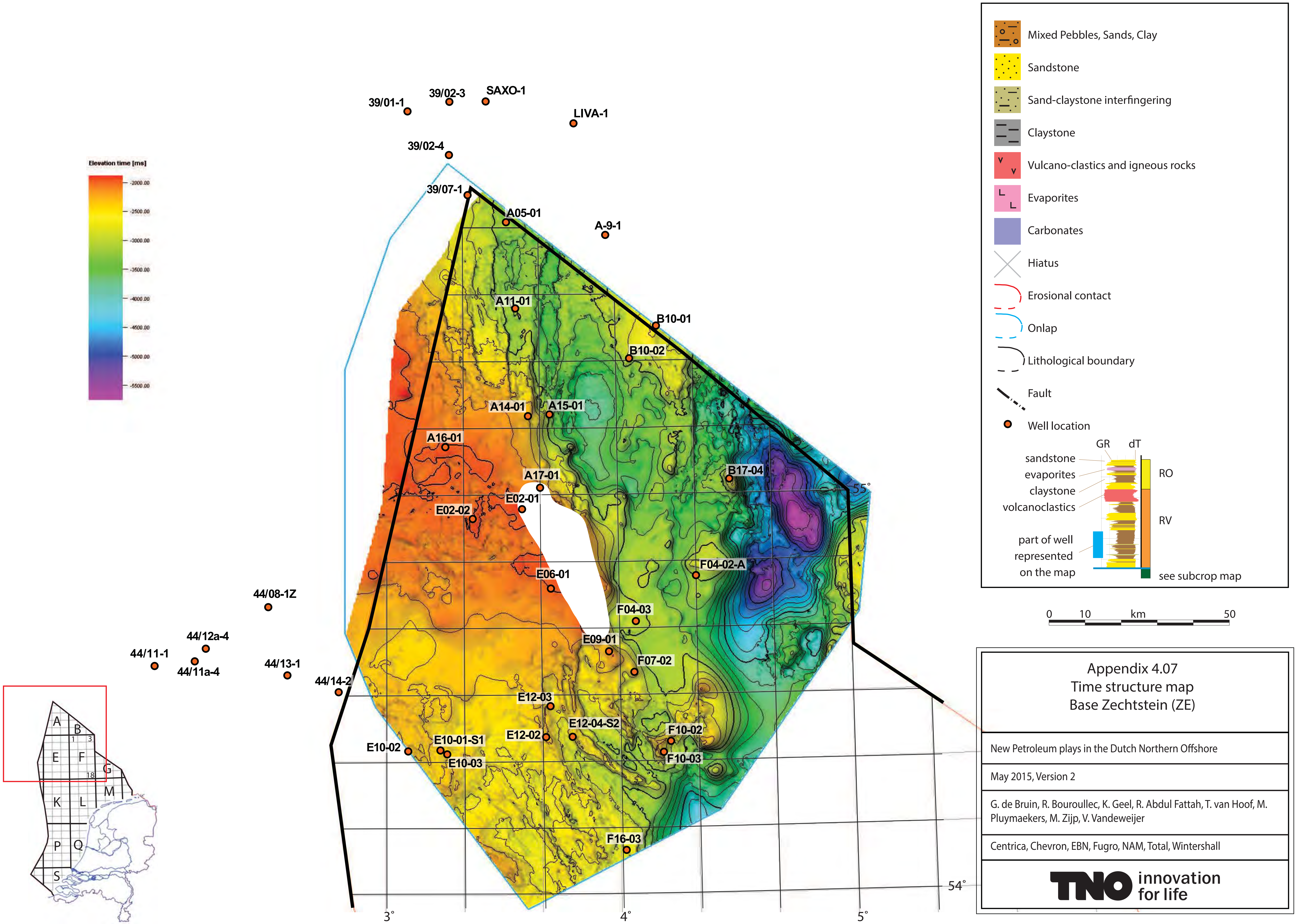

Appendix 4.07
Time structure map
Base Zechstein (ZE)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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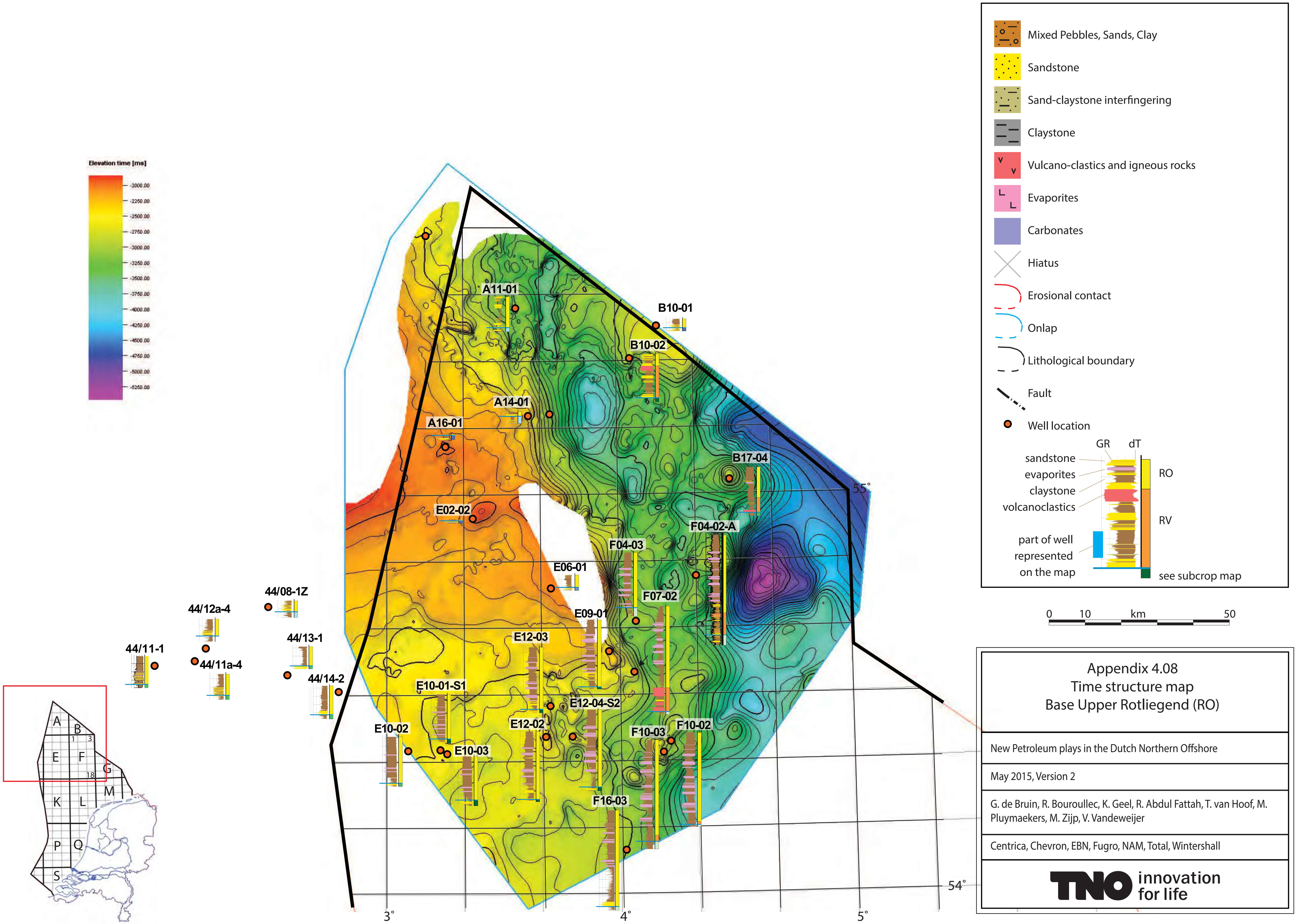

Appendix 4.08
Time structure map
Base Upper Rotliegend (RO)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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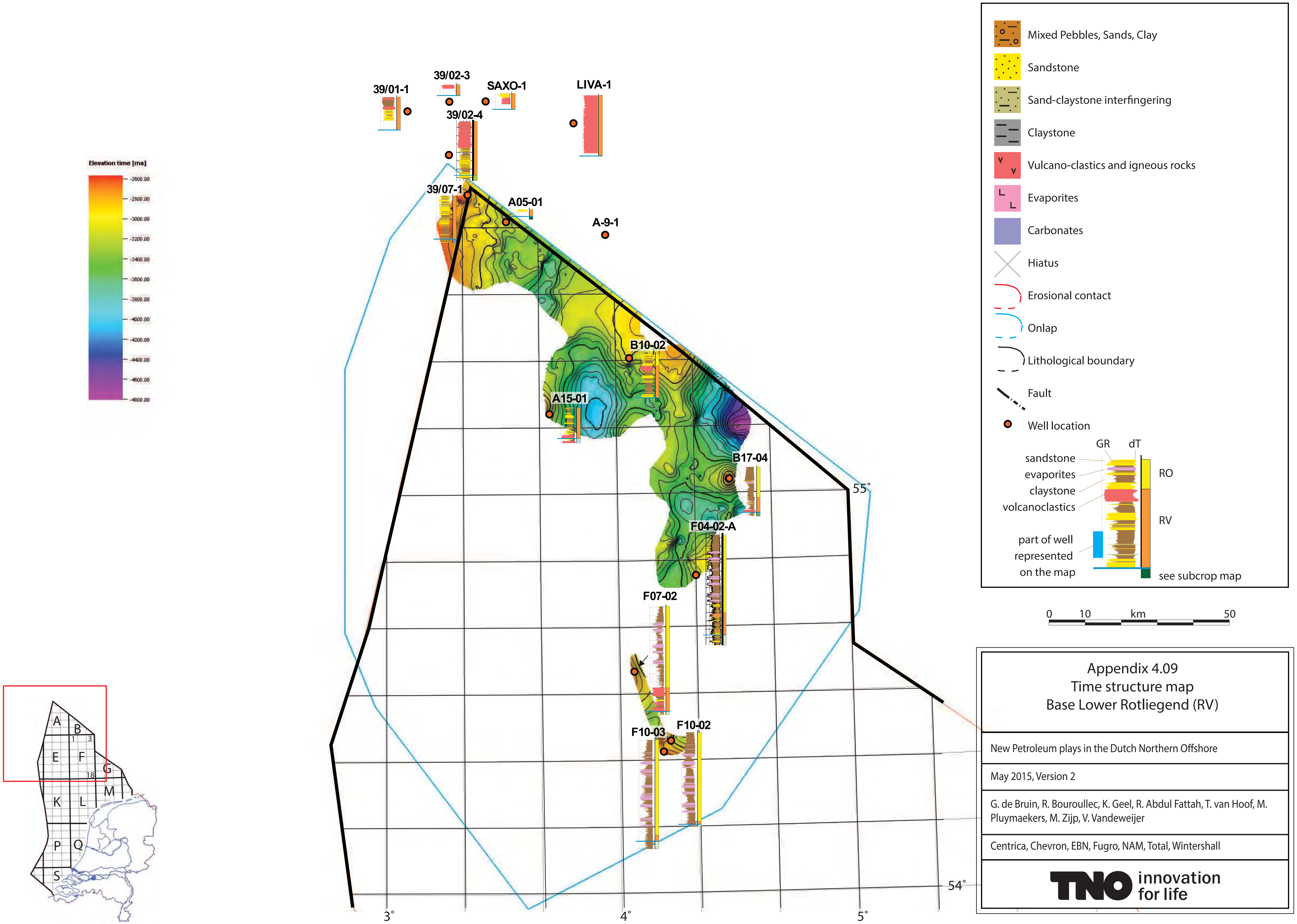

Appendix 4.09
Time structure map
Base Lower Rotliegend (RV)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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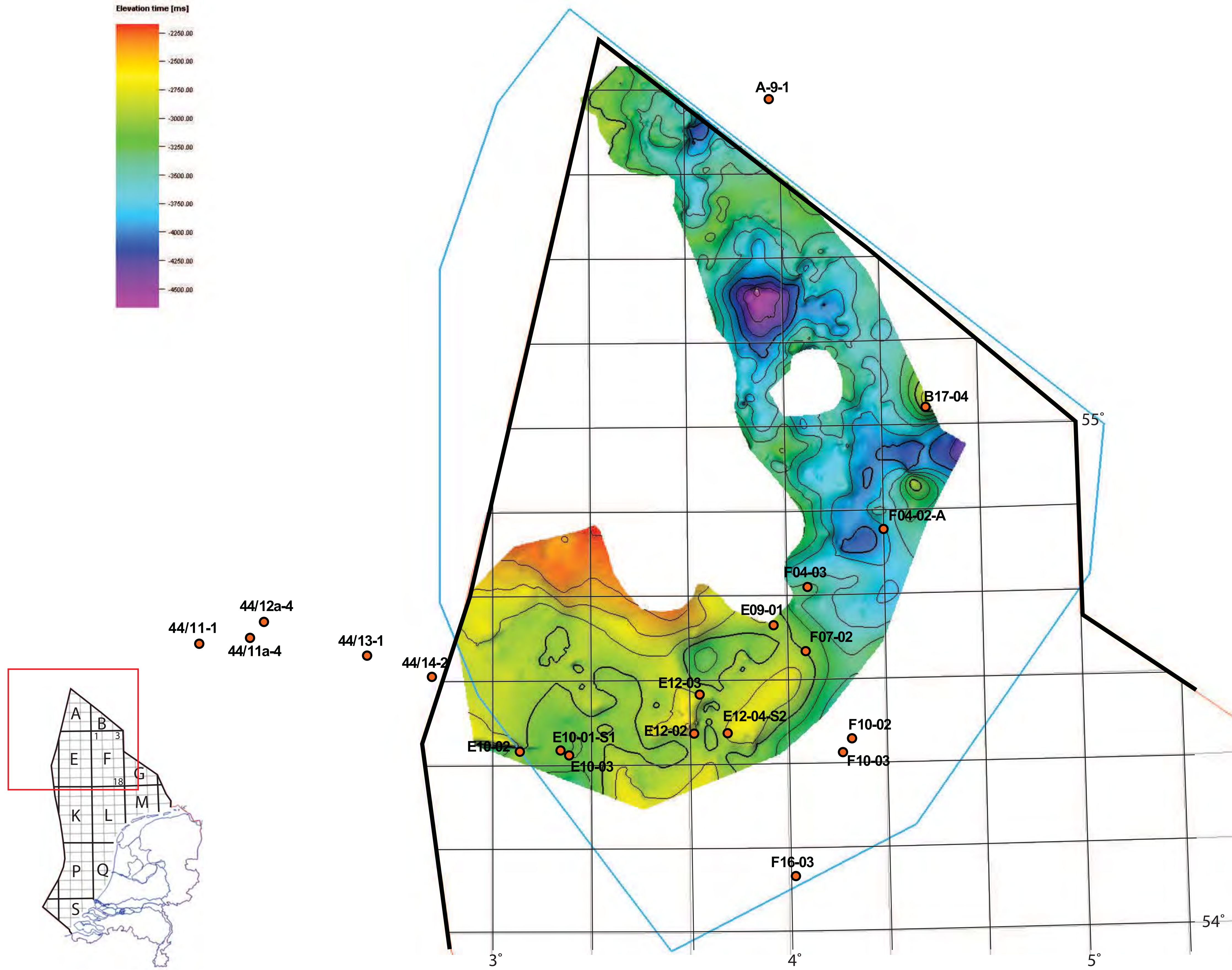

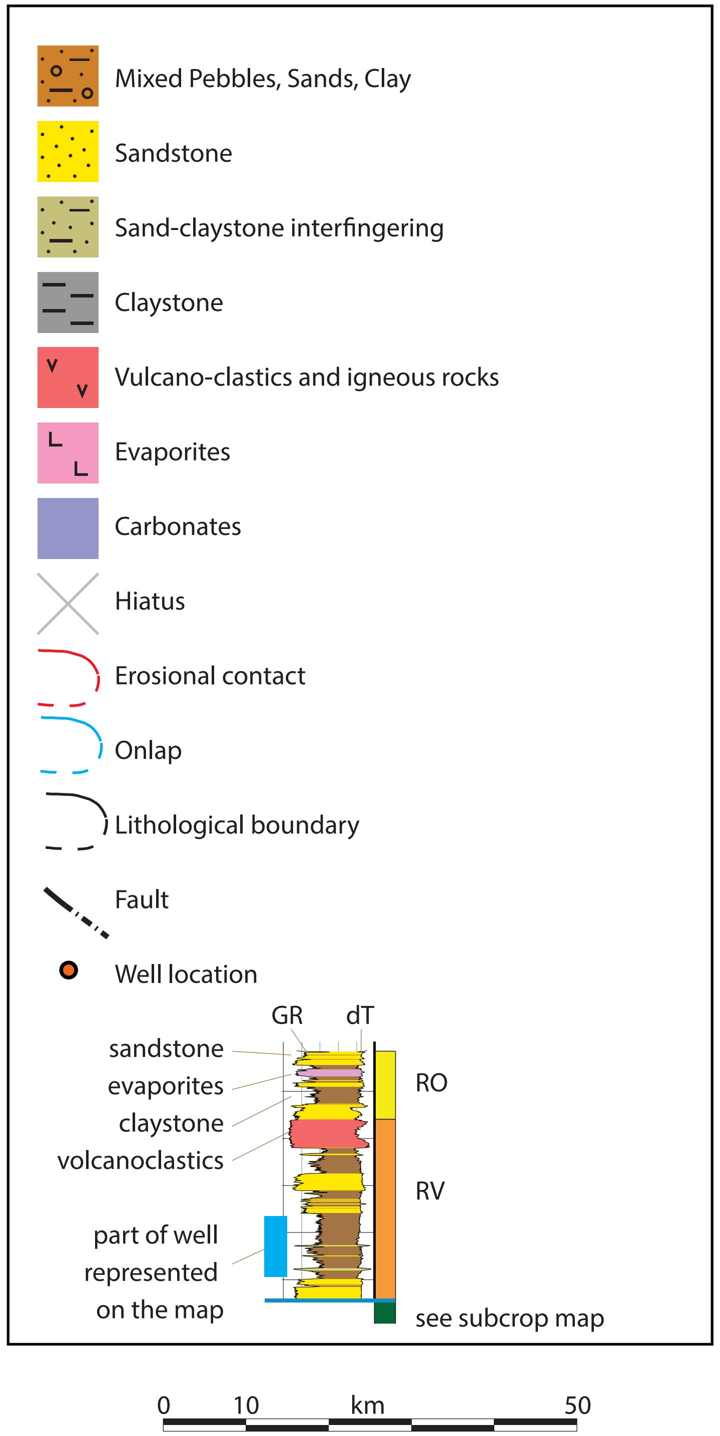

Appendix 4.10
Time structure map
Base Westphalian Unconformity (BWU)

New Petroleum plays in the Dutch Northern Offshore

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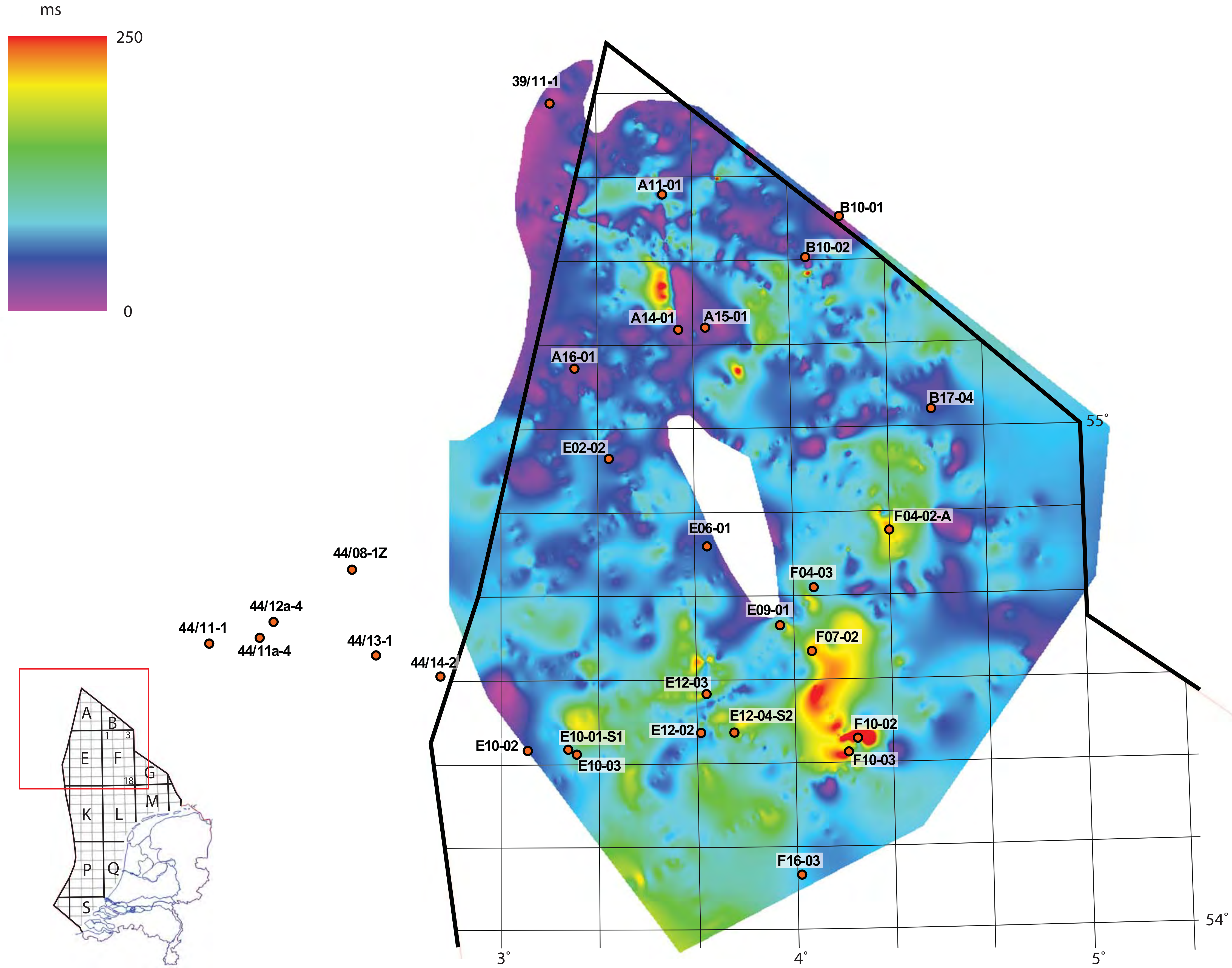

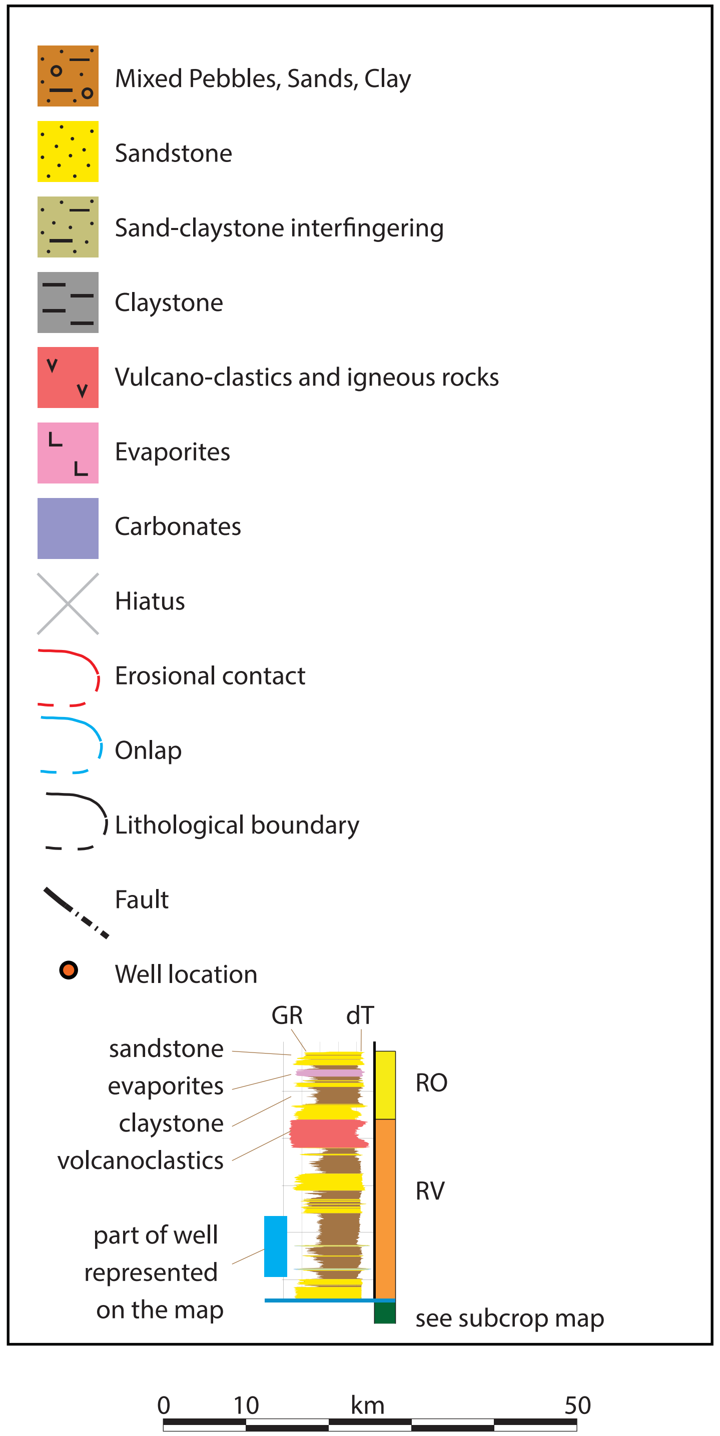

Appendix 4.11
Time thickness map
Upper Rotliegend (RO)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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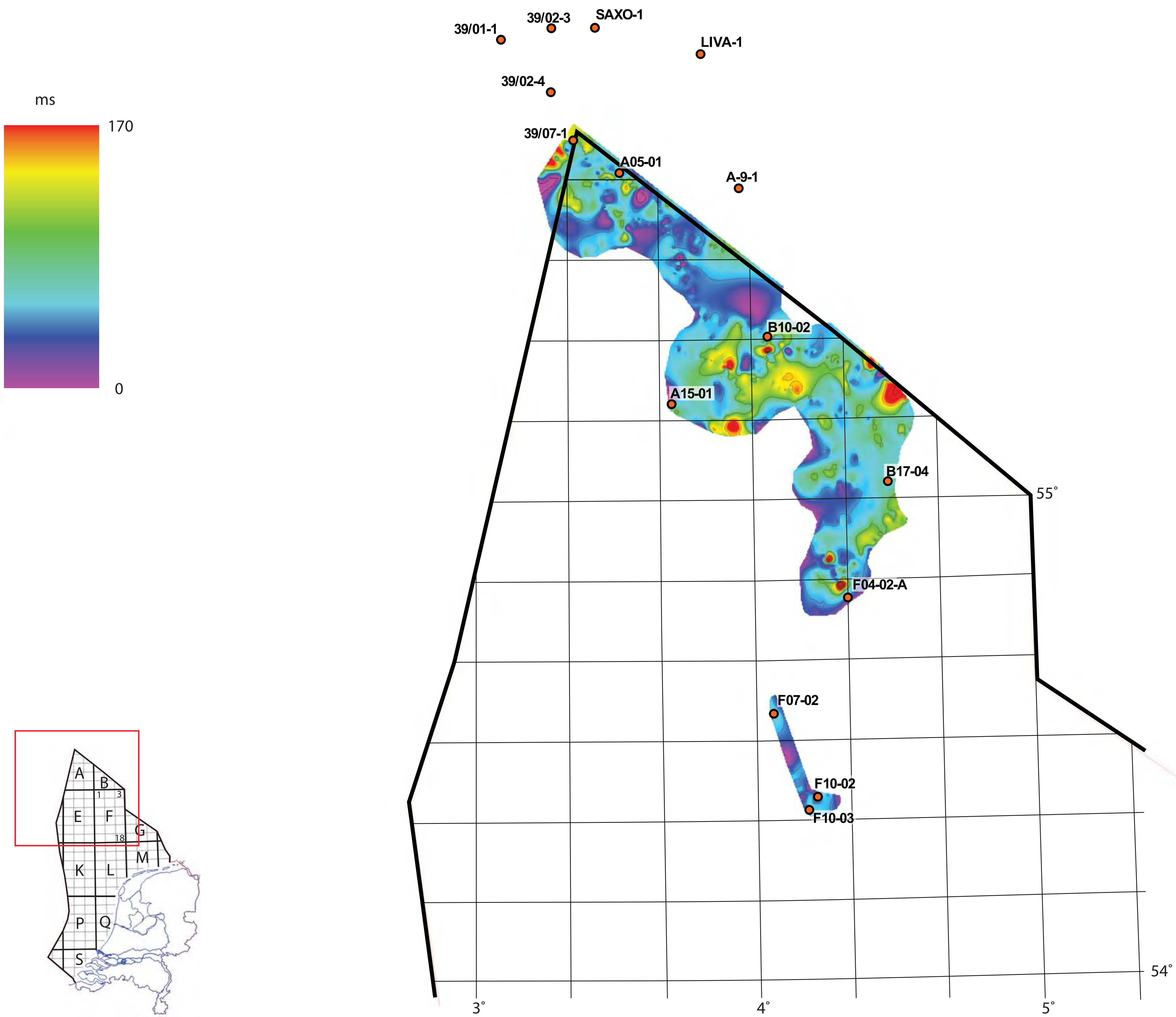

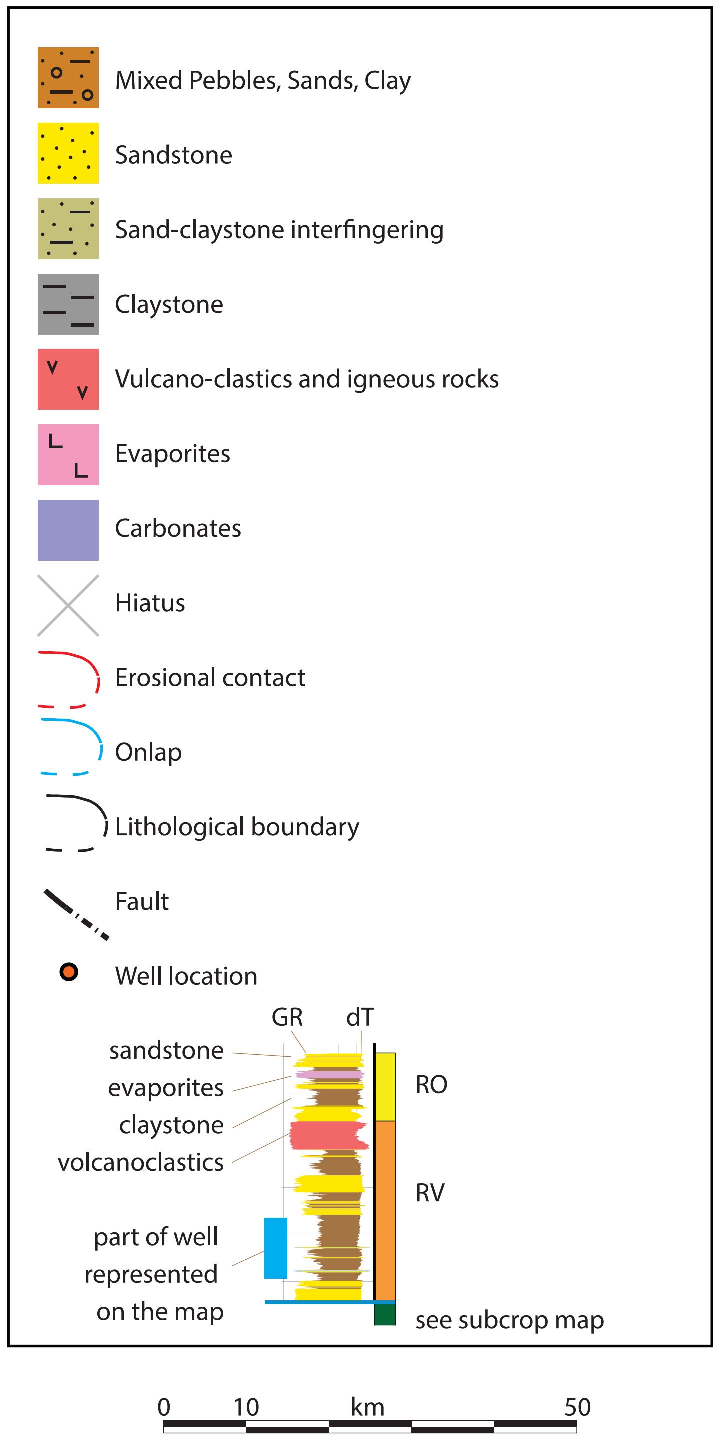

Appendix 4.12
Time-thickness map
Lower Rotliegend (RV)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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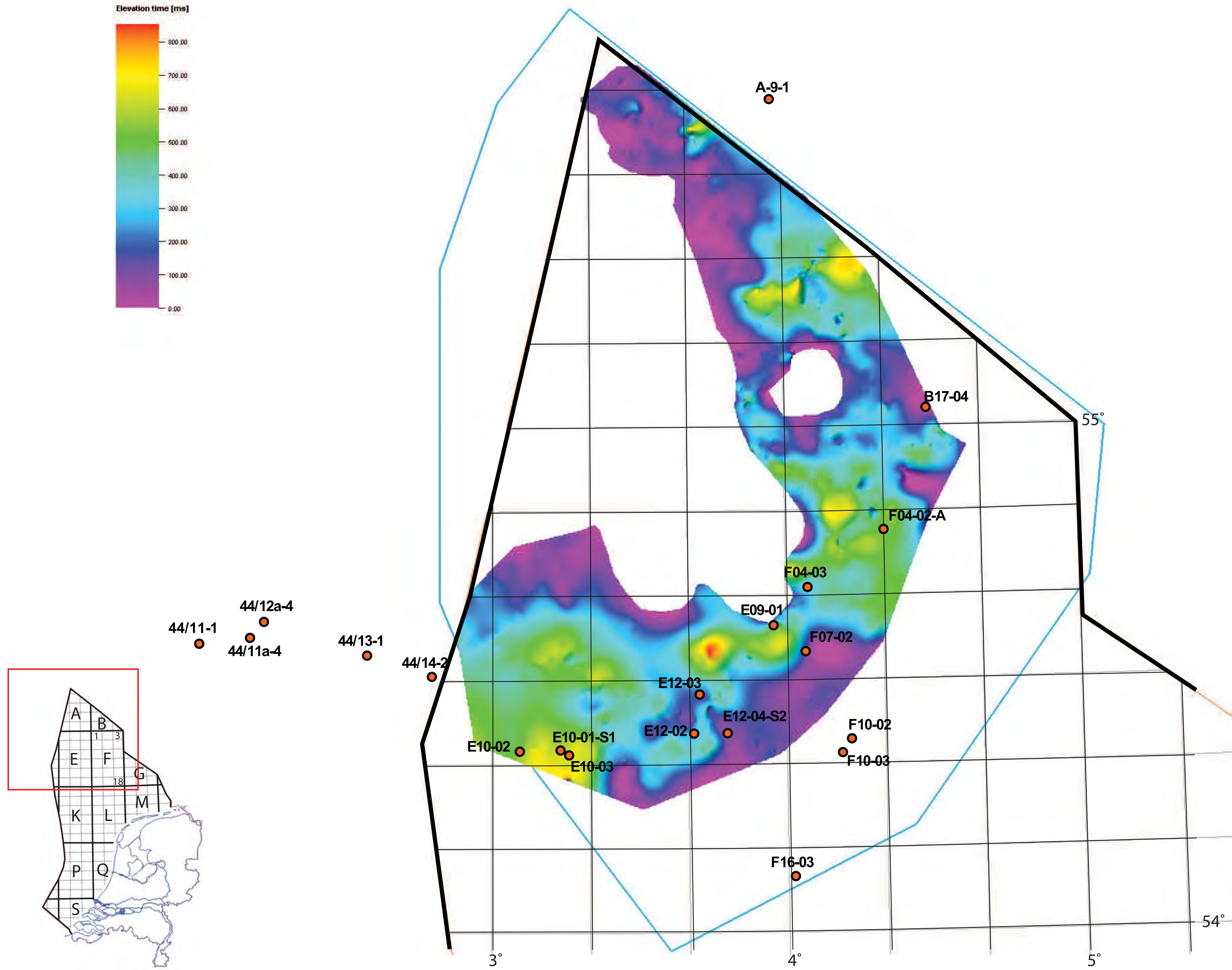

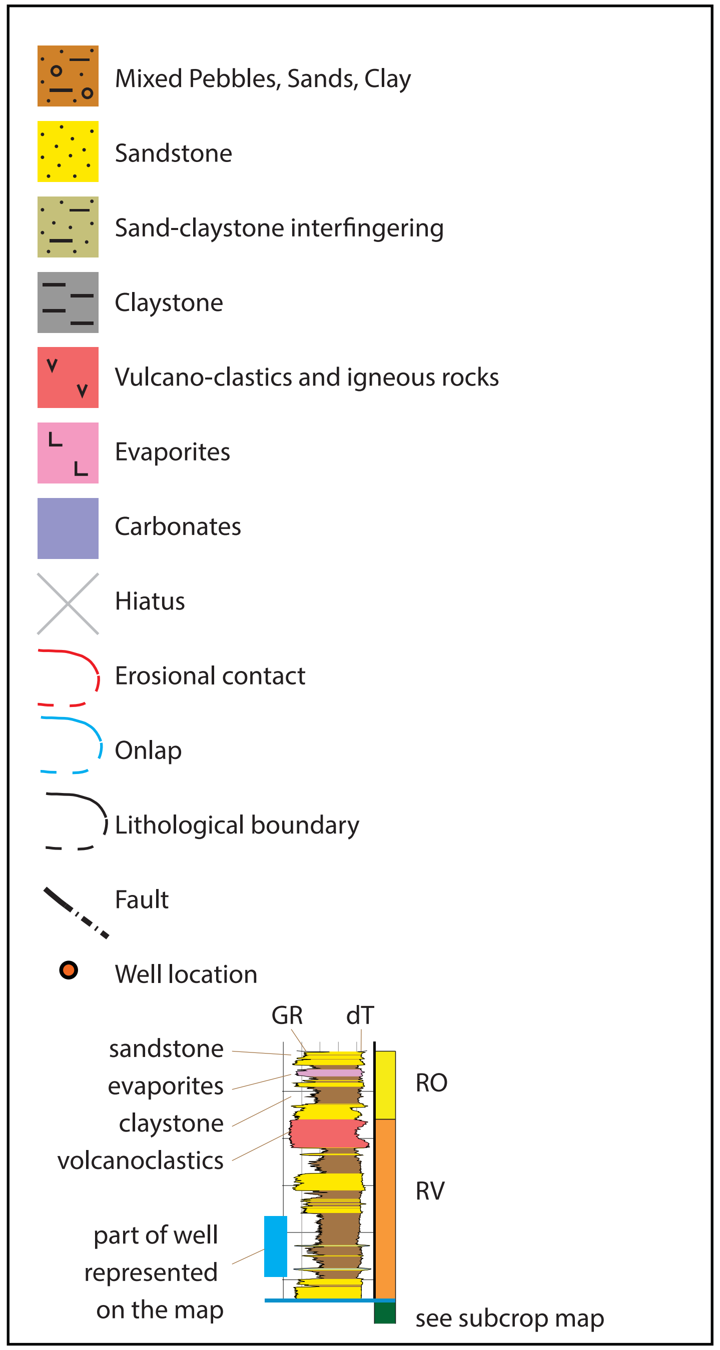

0 10 km 50

Appendix 4.13
Time-thickness map
Westphalian (BWU)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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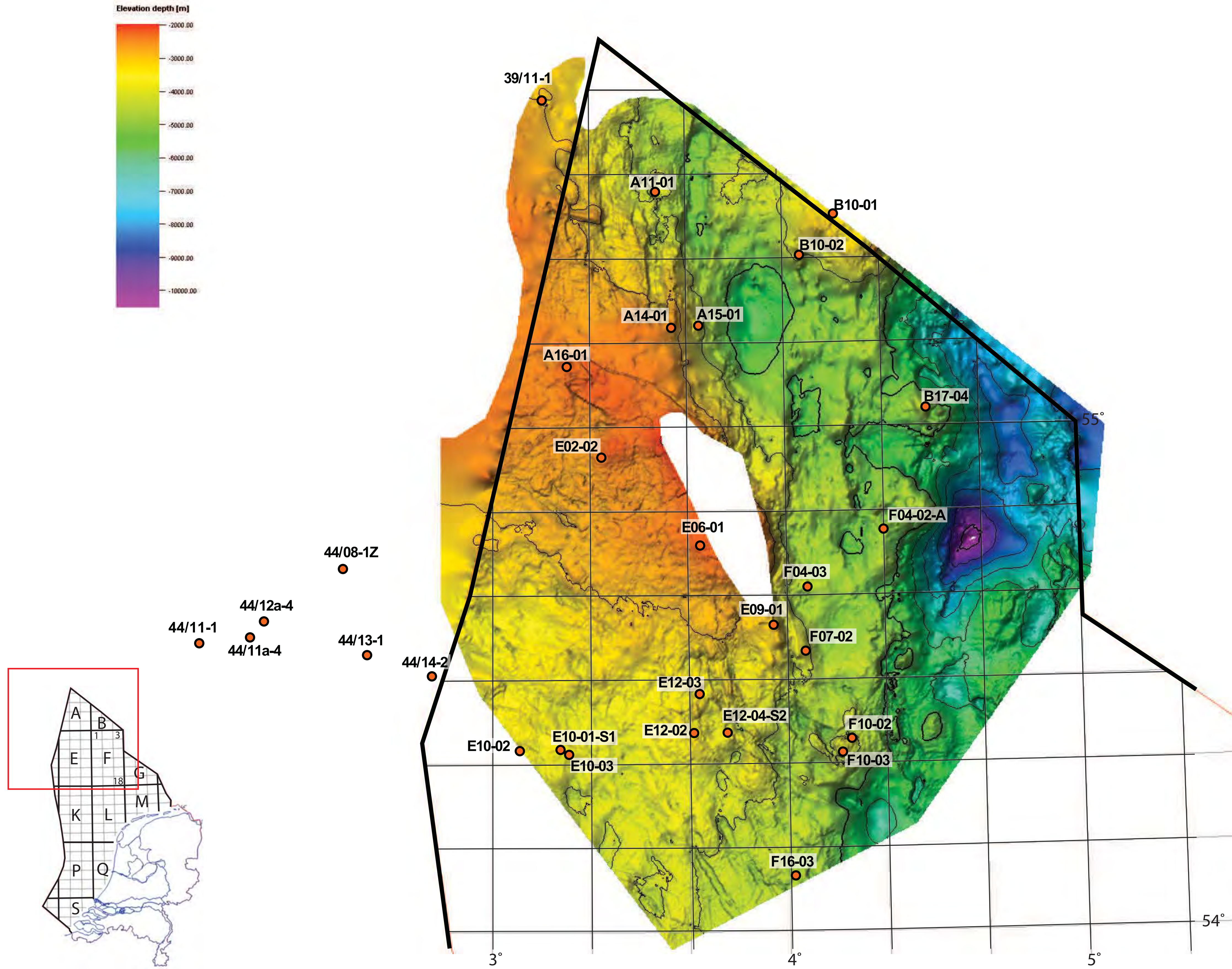

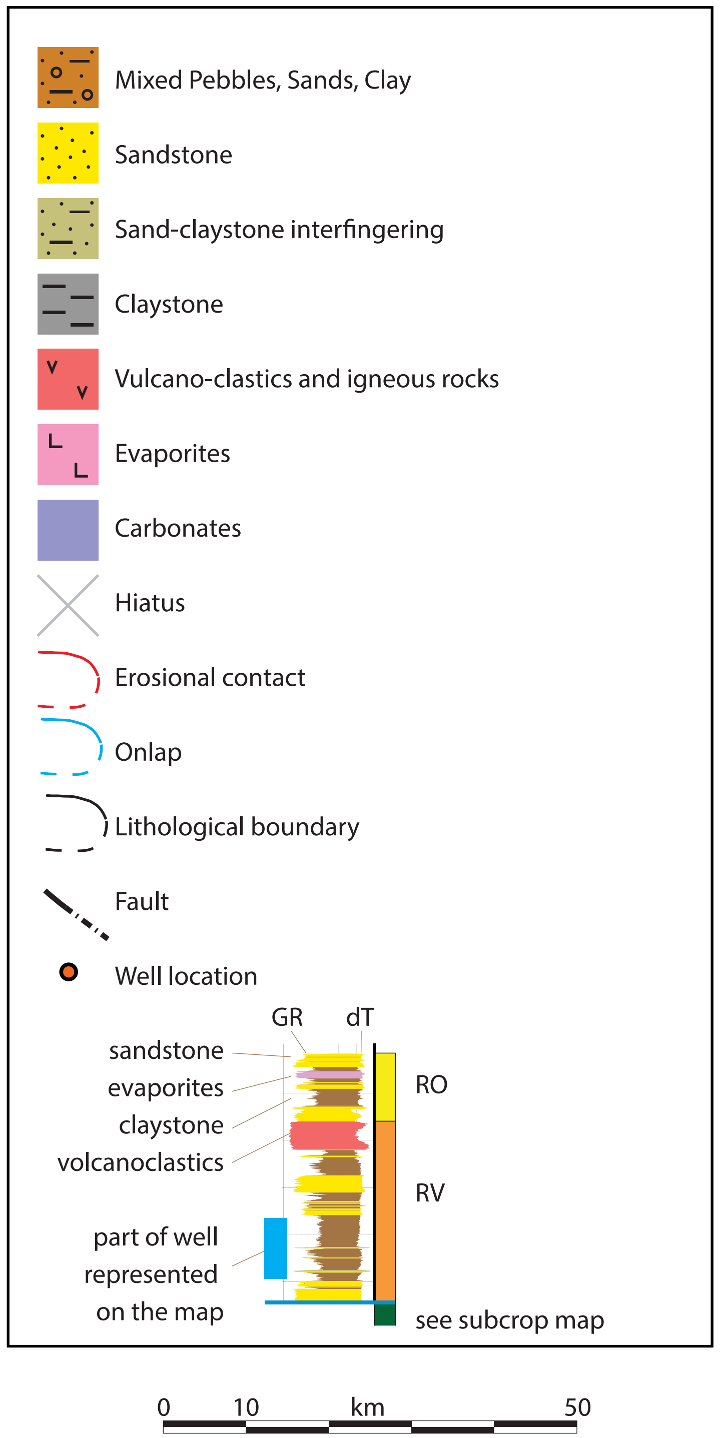

Appendix 4.14
Depth map
Base Upper Rotliegend (RO)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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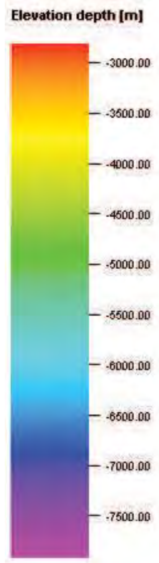

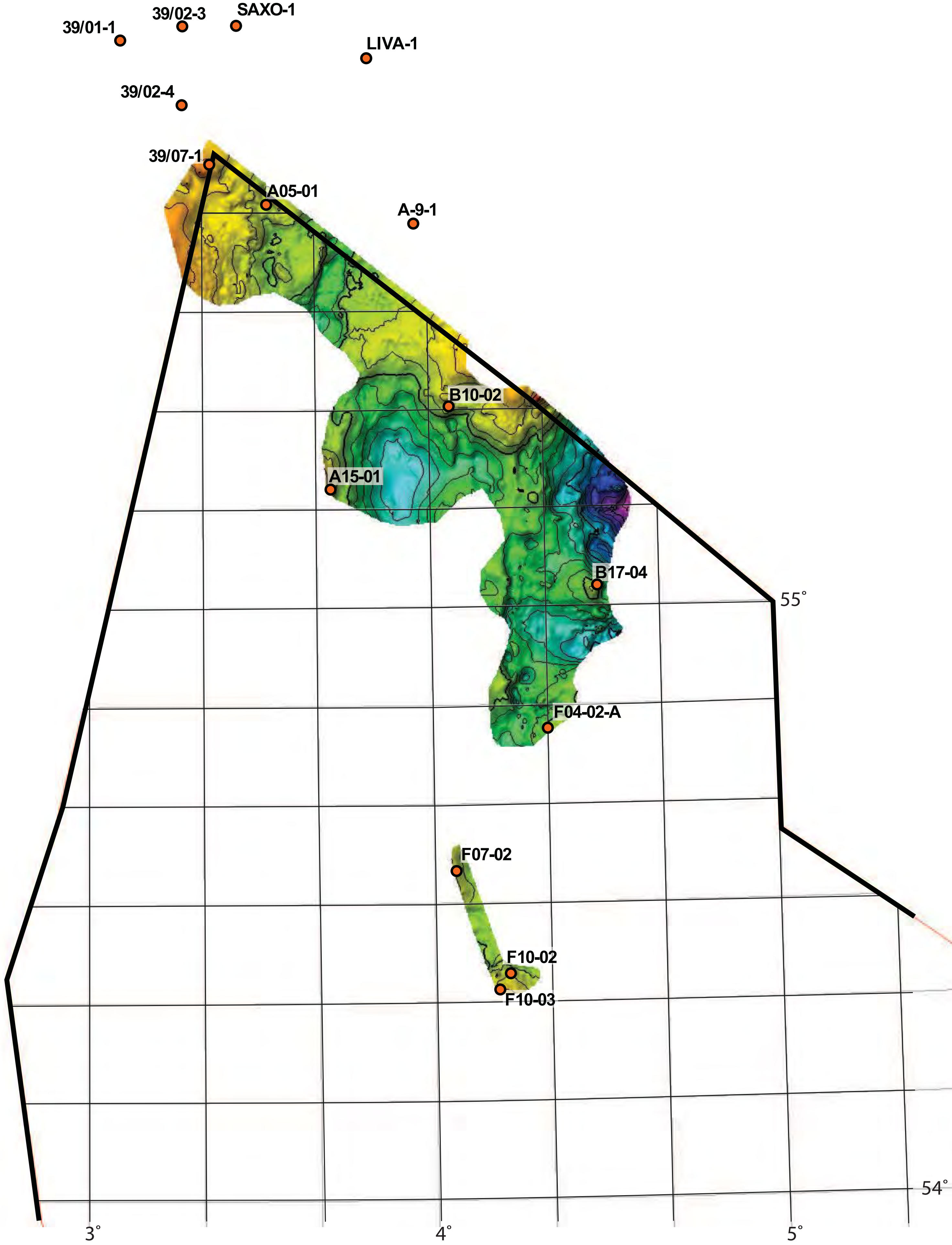

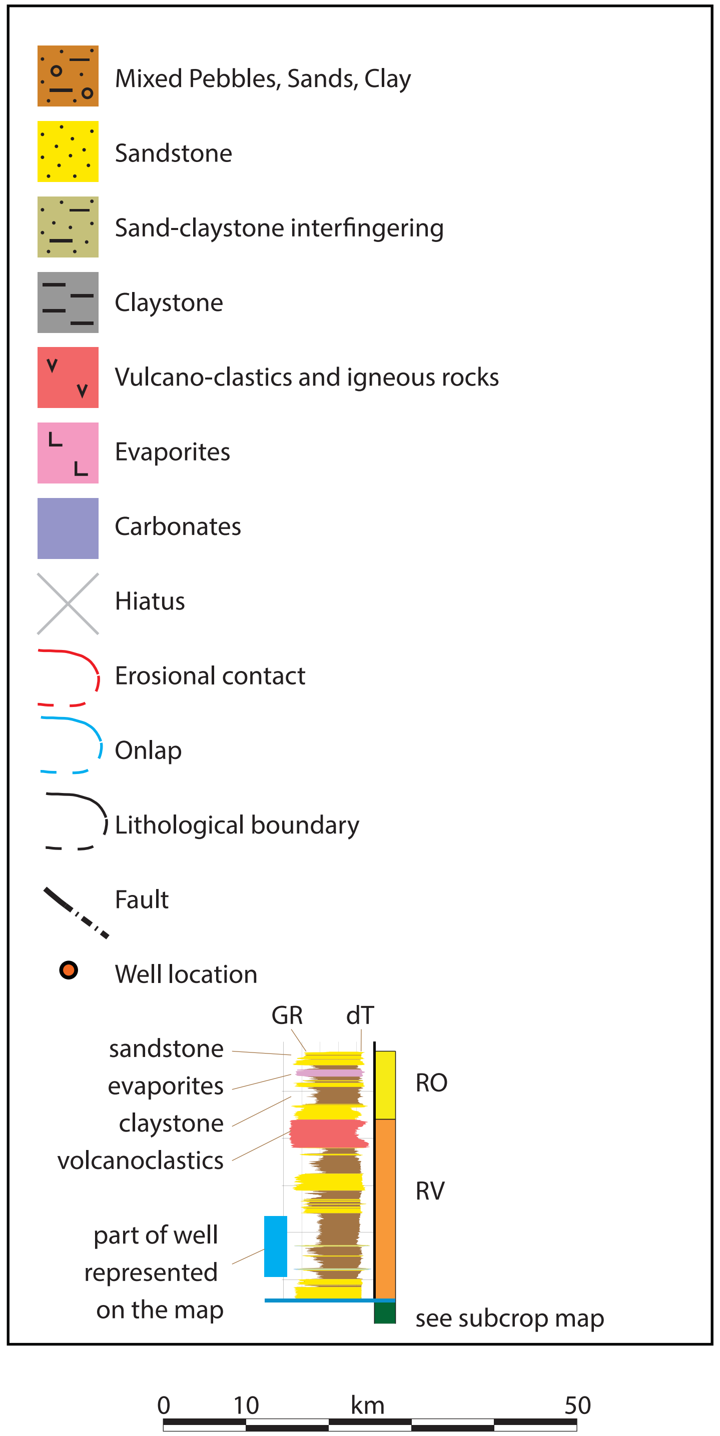

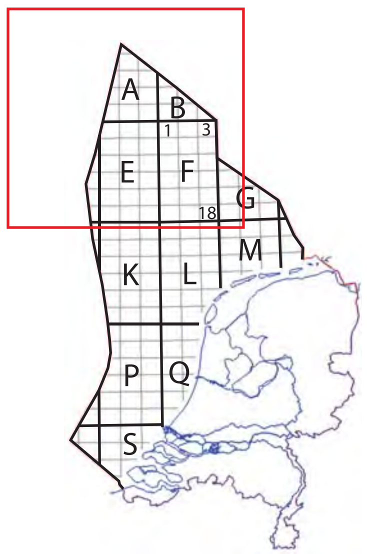

Appendix 4.15
Depth map
Base Lower Rotliegend (RV)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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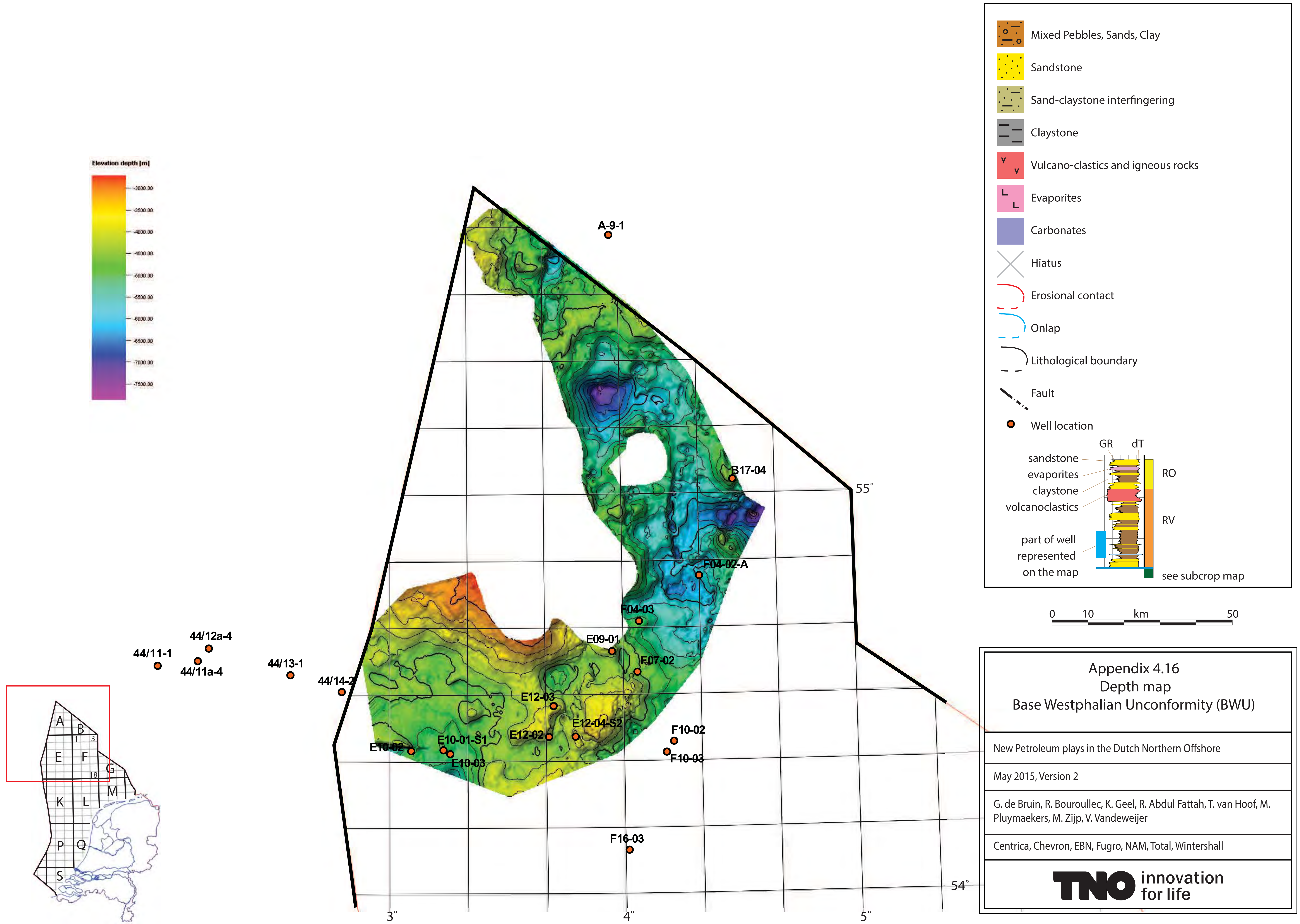

Appendix 4.16
Depth map
Base Westphalian Unconformity (BWU)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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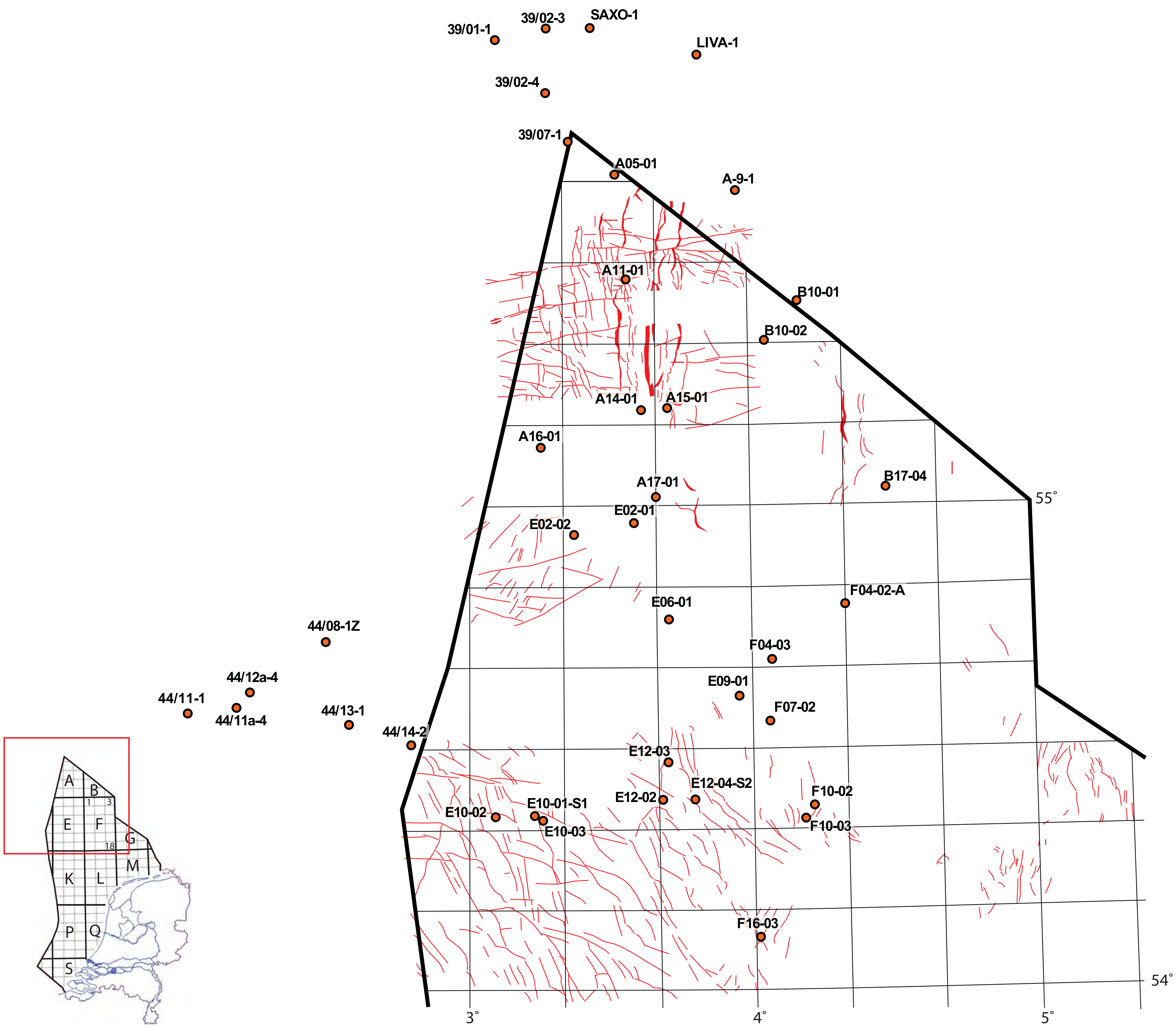

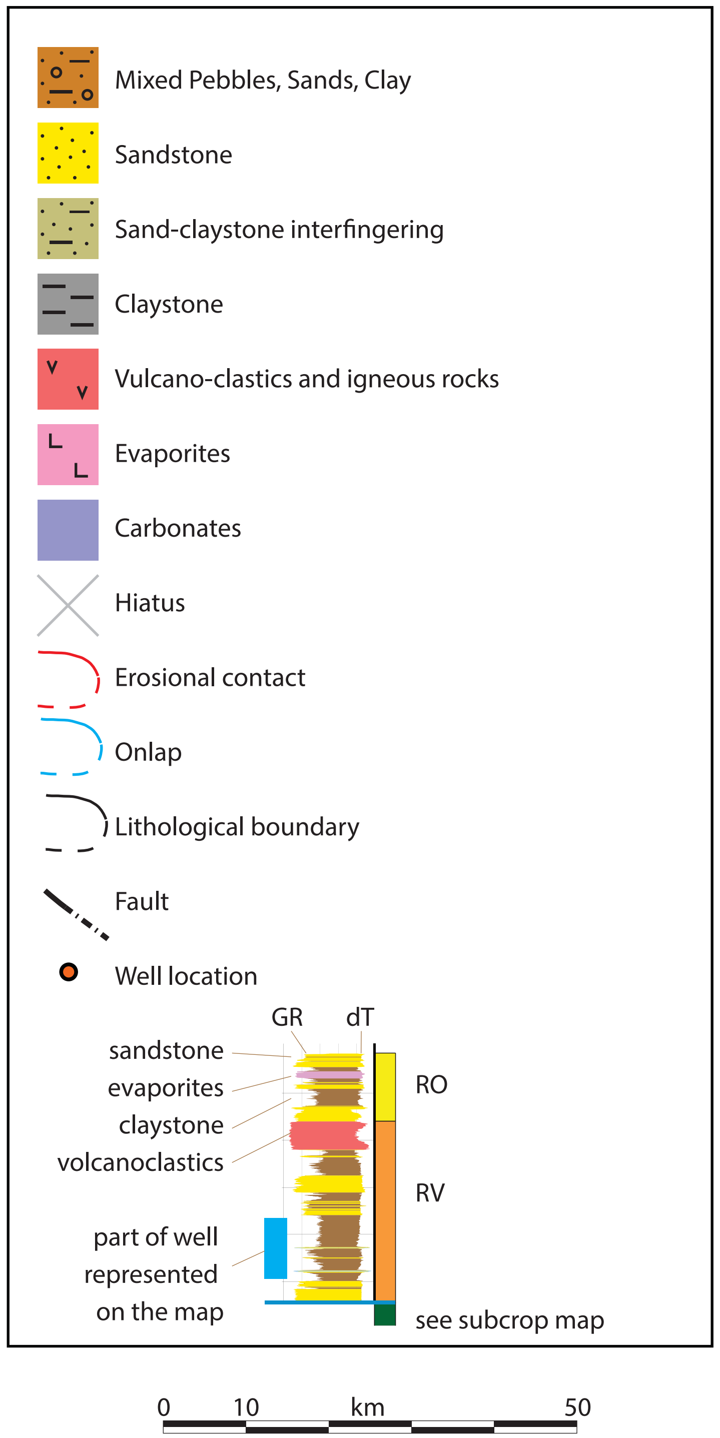

Appendix 4.17
Faults at top Rotliegend
from 3D seismic

New Petroleum plays in the Dutch Northern Offshore

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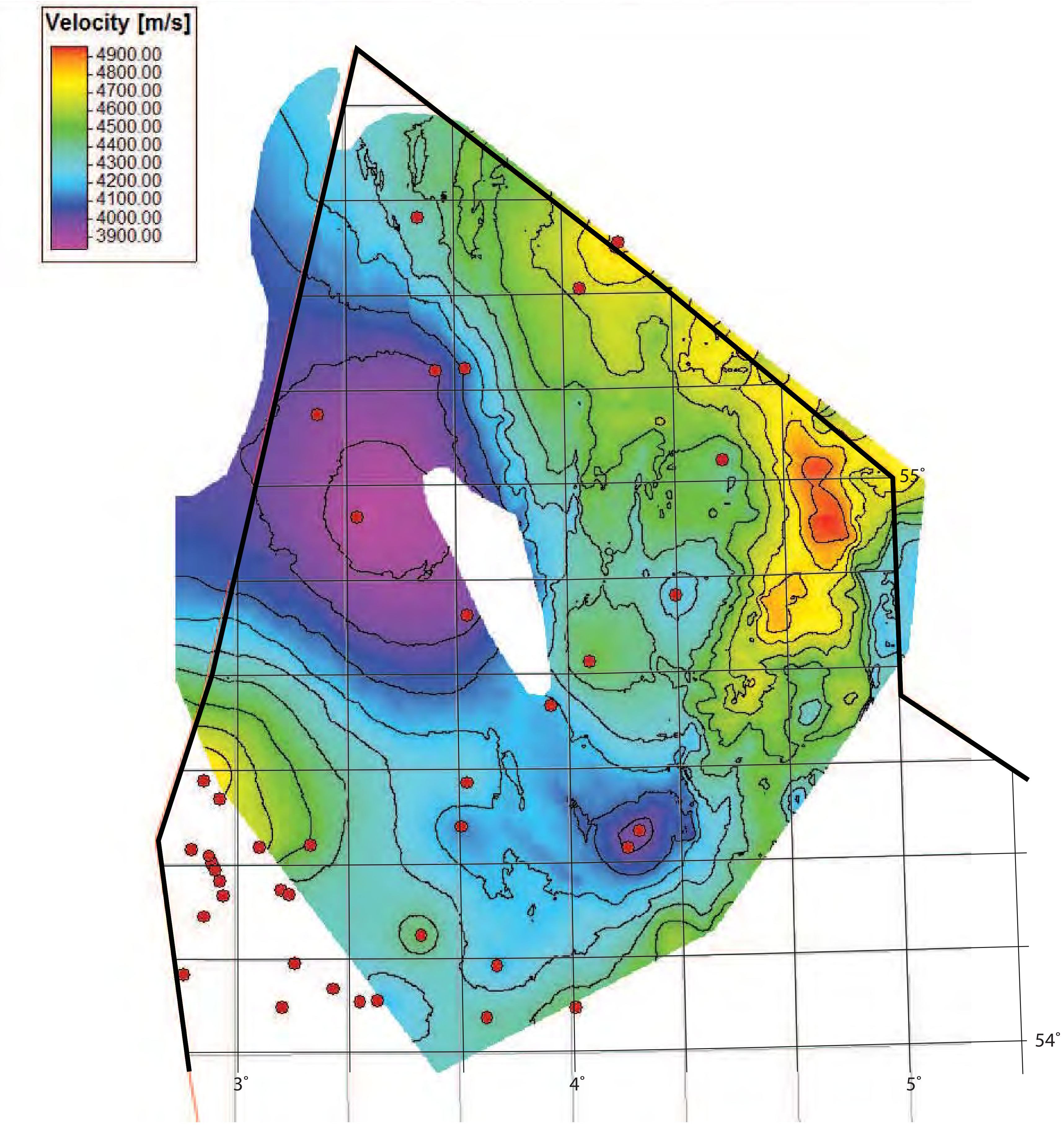

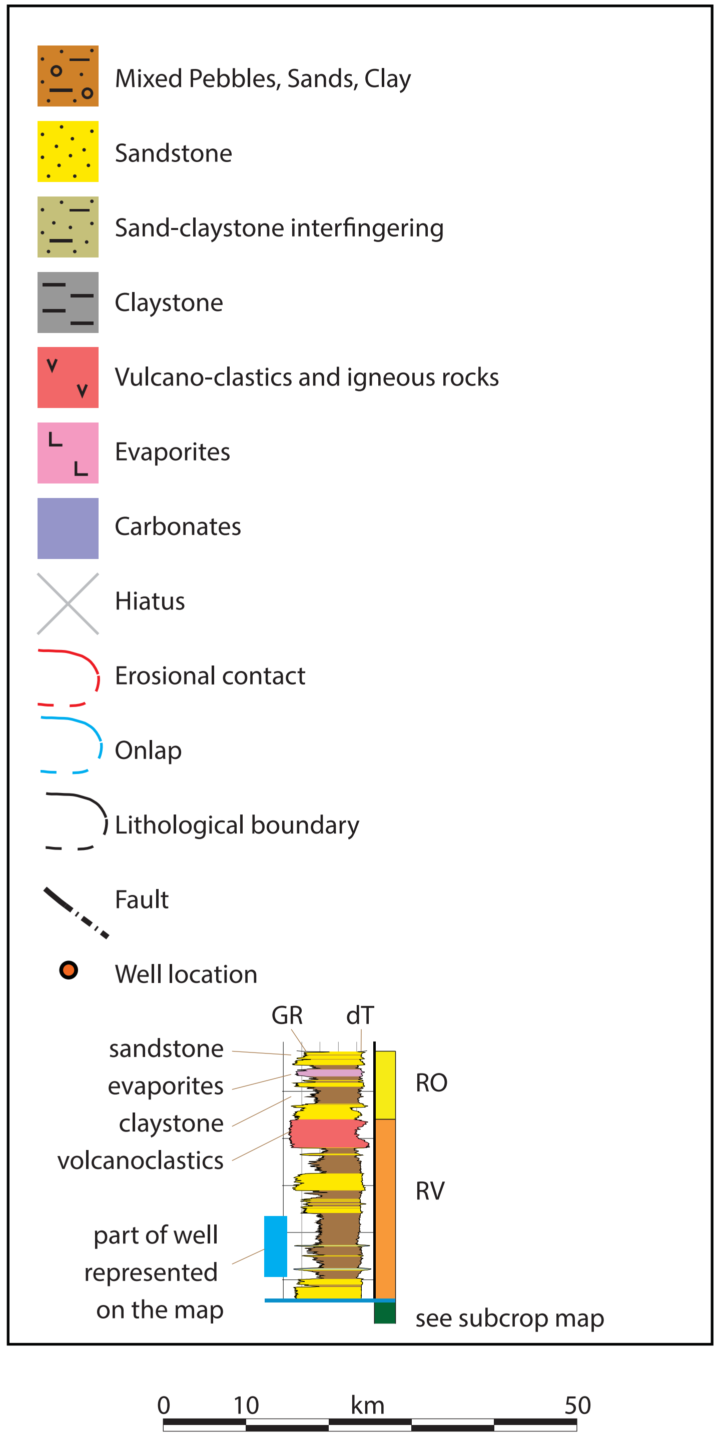

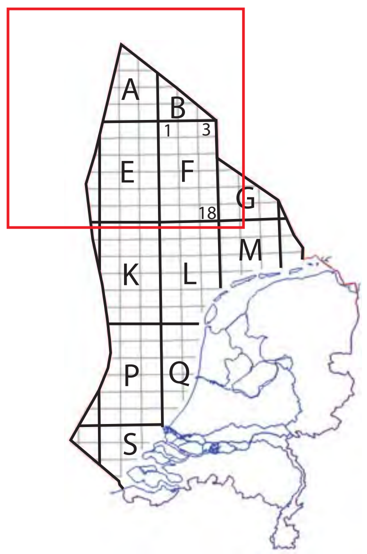

Appendix 4.18
Interval velovities of the
Upper Rotliegend

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May 2015, Version 2

G. de Bruin, R. Bouroullec, K. Geel, R. Abdul Fattah, T. van Hoof, M. Pluymaekers, M. Zijp, V. Vandeweijer

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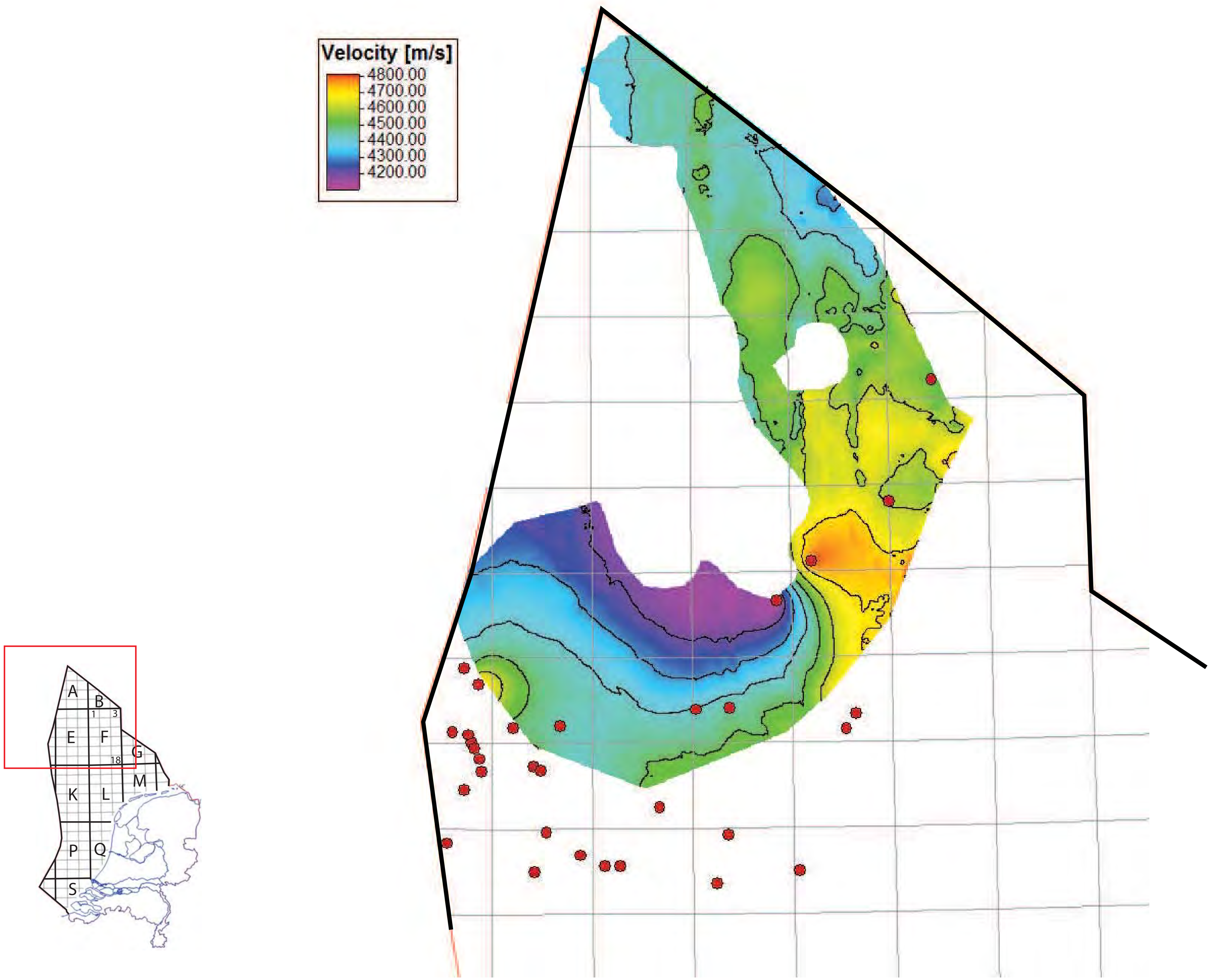

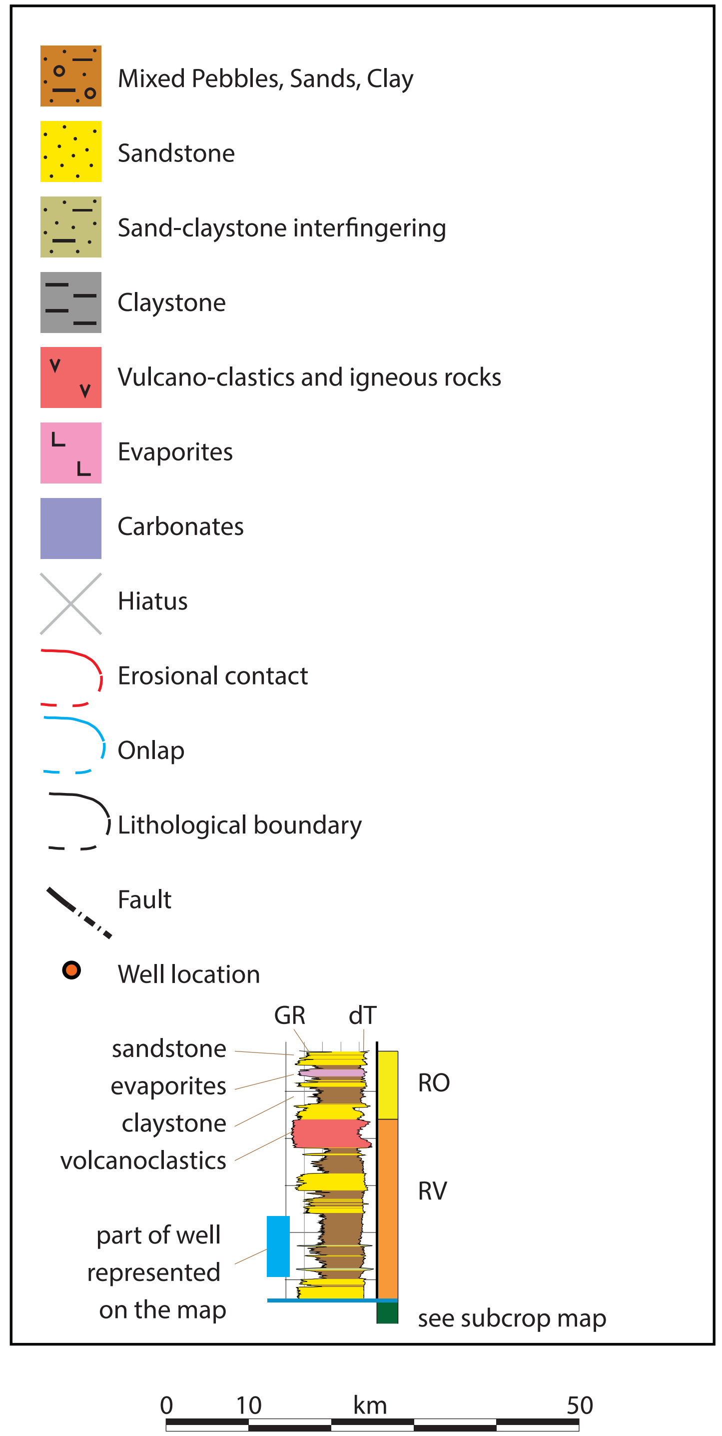

Appendix 4.19
Interval velocities of the
Westphalian

New Petroleum plays in the Dutch Northern Offshore

Januari 2015, Version 1

Geert de Bruin, Renaud Bouroullec, Kees Geel,
Rader Abdul Fattah, Tom van Hoof, Maarten Pluymaekers, Mart Zijp

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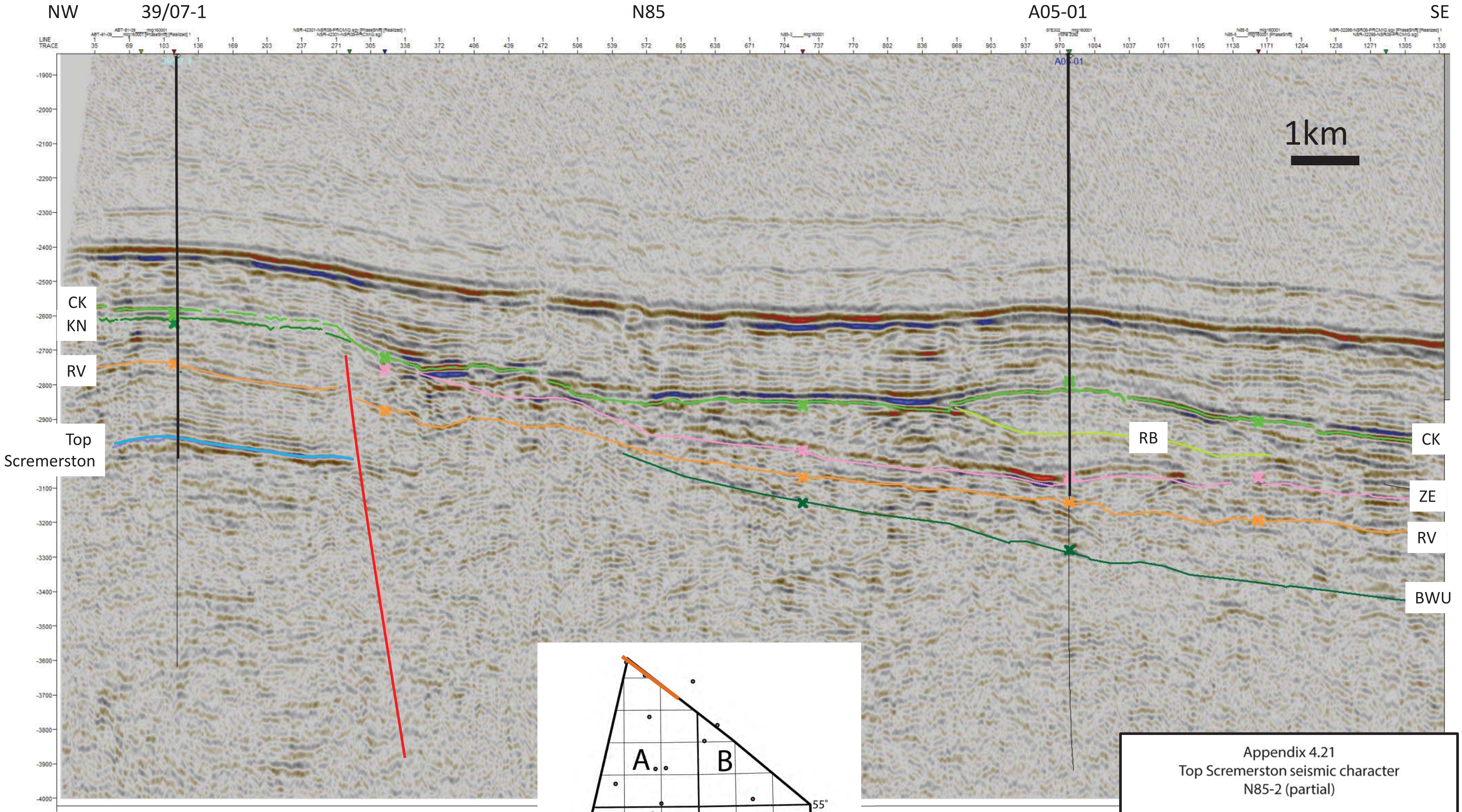
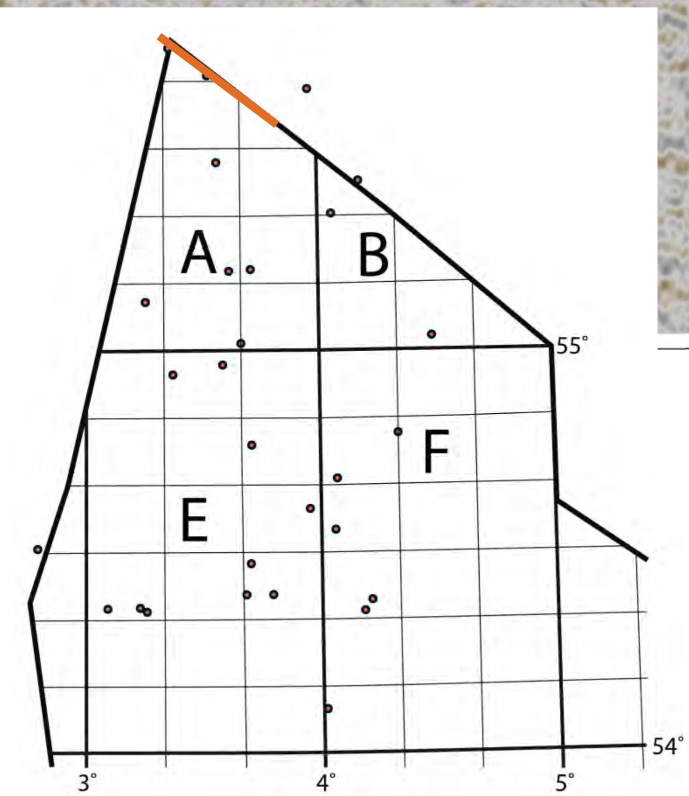
Name	Shallow Gas	Polarity	Applied phase shifts
2D Long Cable			
NSR09-21068-PRCMIG	R/B/R	+90	+270
NSR09-41049-PRCMIG	?	Zero American?	+180
NSR09-41061-PRCMIG	R/B/R	+30	+210
NSR10-42279-PRCMIG	B/R	Zero American	+180
NSR-12288-NSR08-PRCMIG	B/R	Zero American	+180
NSR-32294-NSR08-PRCMIG	B/R	Zero American	+180
NSR-41073-NSR08-PRCMIG	B/R	Zero American	+180
A08_A09_Z3NAM1993A	R/B	Zero European	0
A10_A11_A13_A14_Z3NAM1998C	R/B	Zero European	0
A15_A12_A14_A13_A18_A11_Z3WIN2000A	B/R	Zero American	+180
Z3FUG2002A	R/B	Zero European	0
F03_B18_Z3NAM1982A	R/B	Zero European	0
D06_D09_Z3PGS1999A	R/B	Zero European	0
D12_D15_D18_E13_Z3WIN1994A	R/B	Zero European	0
D09_D12_E07_E10_E08_E11_Z3GEC1997A	error while loading		
D12_D15_D18_Z3NAM1991C	R/B	Zero European	0
E01_E04_Z3NAM1995B	R/B	Zero European	0
E02_E03_Z3NAM1998B	R/B/R	+90	-90
E10_Z3WIN1997C	R/B	Zero European	0
E10B_Z3PET1995B	R/B	~ Zero European	0
E12_E09_Z3PET1993A	R/B	Zero European	0
E14_E15_Z3PGS1999B	B/R	Zero American	180
E16_E13_D18_Z3NAM1998A	R/B	Zero European	0
E16_E17_Z3NAM1993B	R/B	Zero European	0
E18_F16_Z3WIN1997A	R/B/R	+90	-90
F02_F03_Z3RWE1994A	R/B	Zero European	0
F02_F03_F05_F06_Z3NAM1989E	R/B	Zero European	0
F06_Z3PET1992F	R/B	Zero European	0
F08_F09_Z3OXY1994A	R/B	Zero European	0
F10_Z3PET1994B	R/B	Zero European	0
F13_F14_Z3PGS2001A	B/R	Zero American	180
F14_Z3STA1985A		Zero American	
F15_F18_Z3PET1994A	R/B	Zero European	0
F15_F18_Z3PET1987A	R/B	Zero European	0
F16_F17_L01_Z3WIN2003B	R/B	Zero European	0
F12_G10_Z3PET1991A	R/B	Zero European	0
Z2NAM1981G_810552	B/R	Zero American	180
Z2NAM1981G_810557	B/R	Zero American	180
SNST-83	B/R	Zero American	180
SNST-87	R/B/R	+90 & Zero Am	180 or 90
Z2ARC1988C	B/R	Zero American	180
87E	?	Min European	0
ABT-91	R/B/R	+90	-90
N85	R/B	Zero European & 90	0
A15_Z2WES1988B	R/B	Zero European	0



- Base Chalk [CK]
- Base Rijnland Group [KN]
- Base Triassic [RB]
- Base Zechstein [ZE]
- Base Upper Rotliegend [RO] (UCSA)
- Base Lower Rotliegend [RV] (BPU)
- Base Westphalian [BWU]



Appendix 4.21
Top Scremerston seismic character
N85-2 (partial)

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May 2015, Version 2

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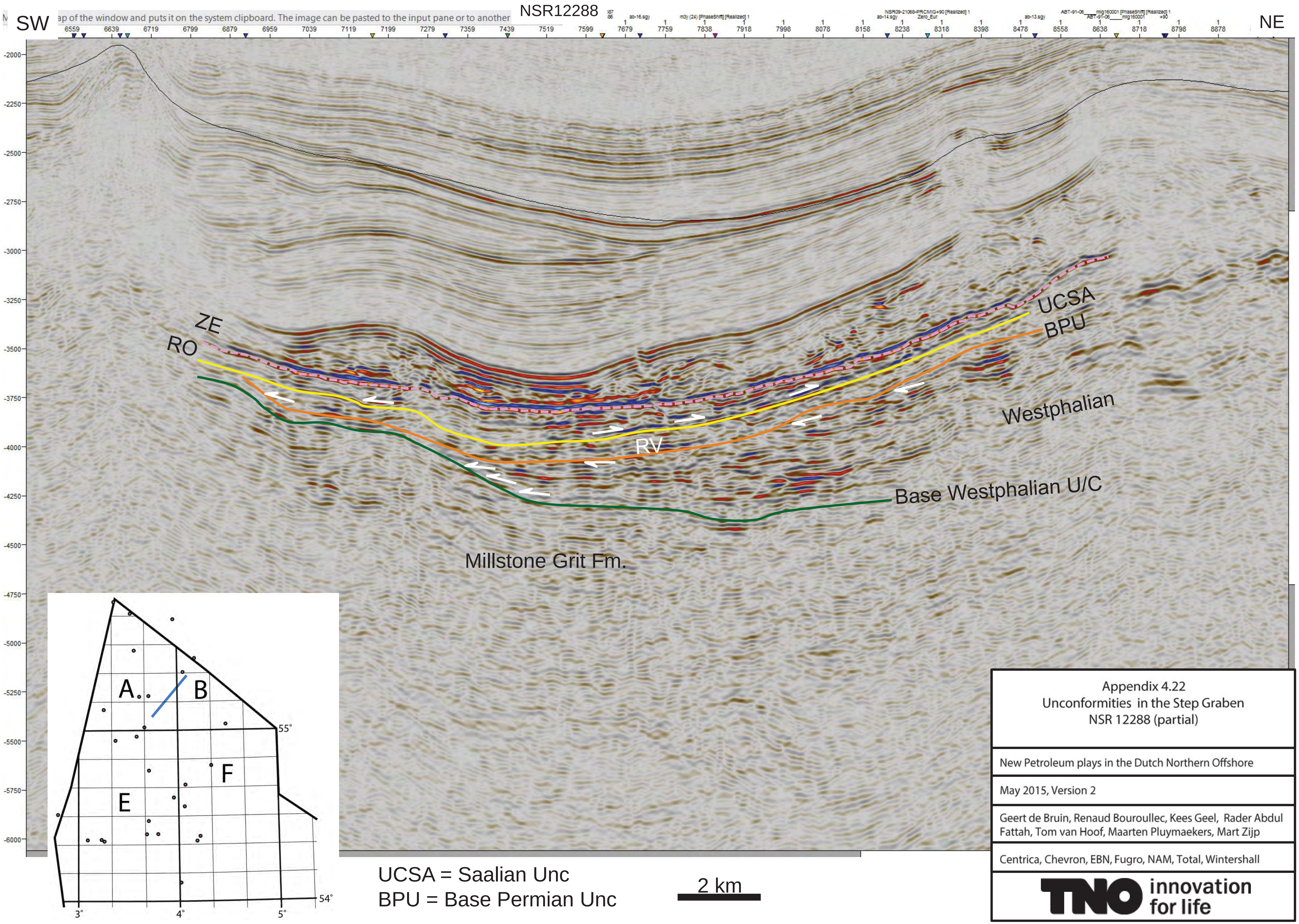

UCSA = Saalian Unc
BPU = Base Permian Unc

2 km

Appendix 4.22
Unconformities in the Step Graben
NSR 12288 (partial)

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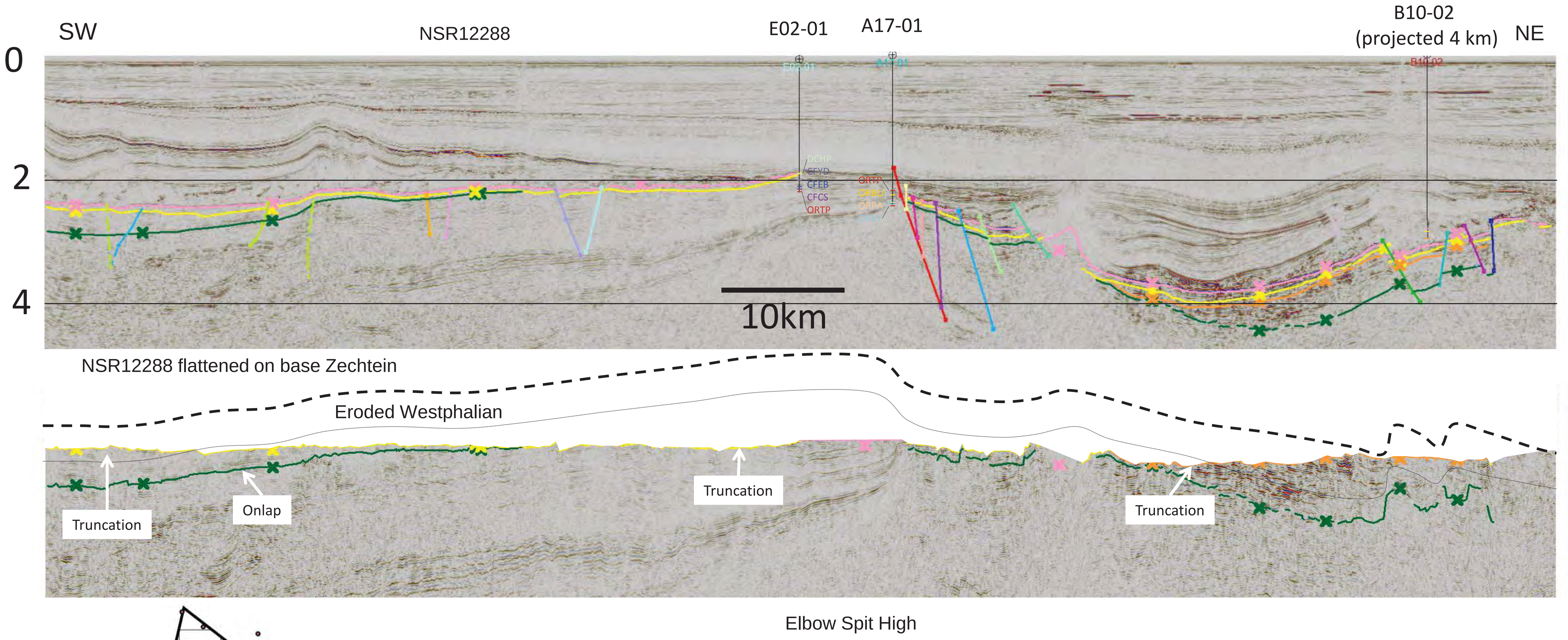

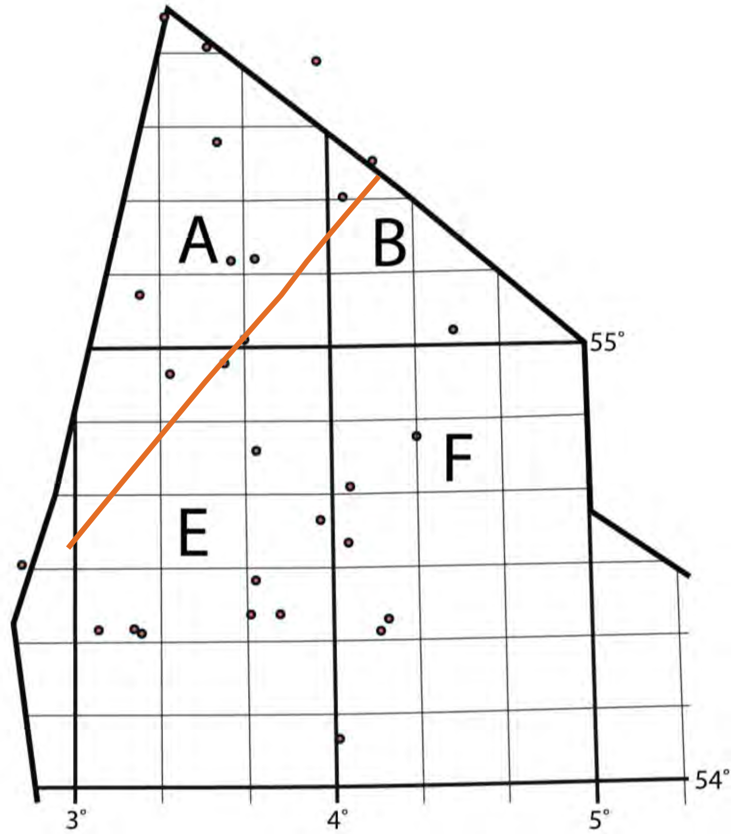

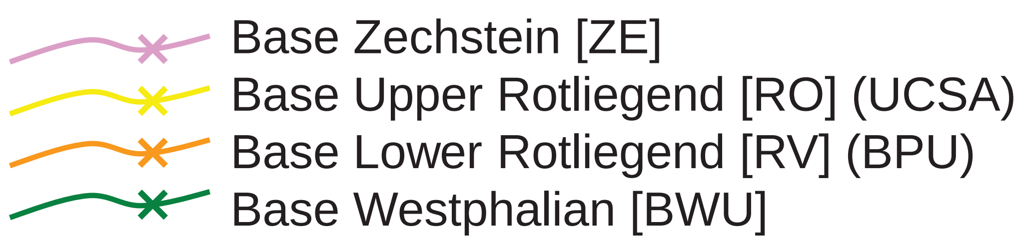

Appendix 4.23
Bases of Westphalian, Lower Rotliegend, Upper Rotliegend, and Zechstein
NSR 12288

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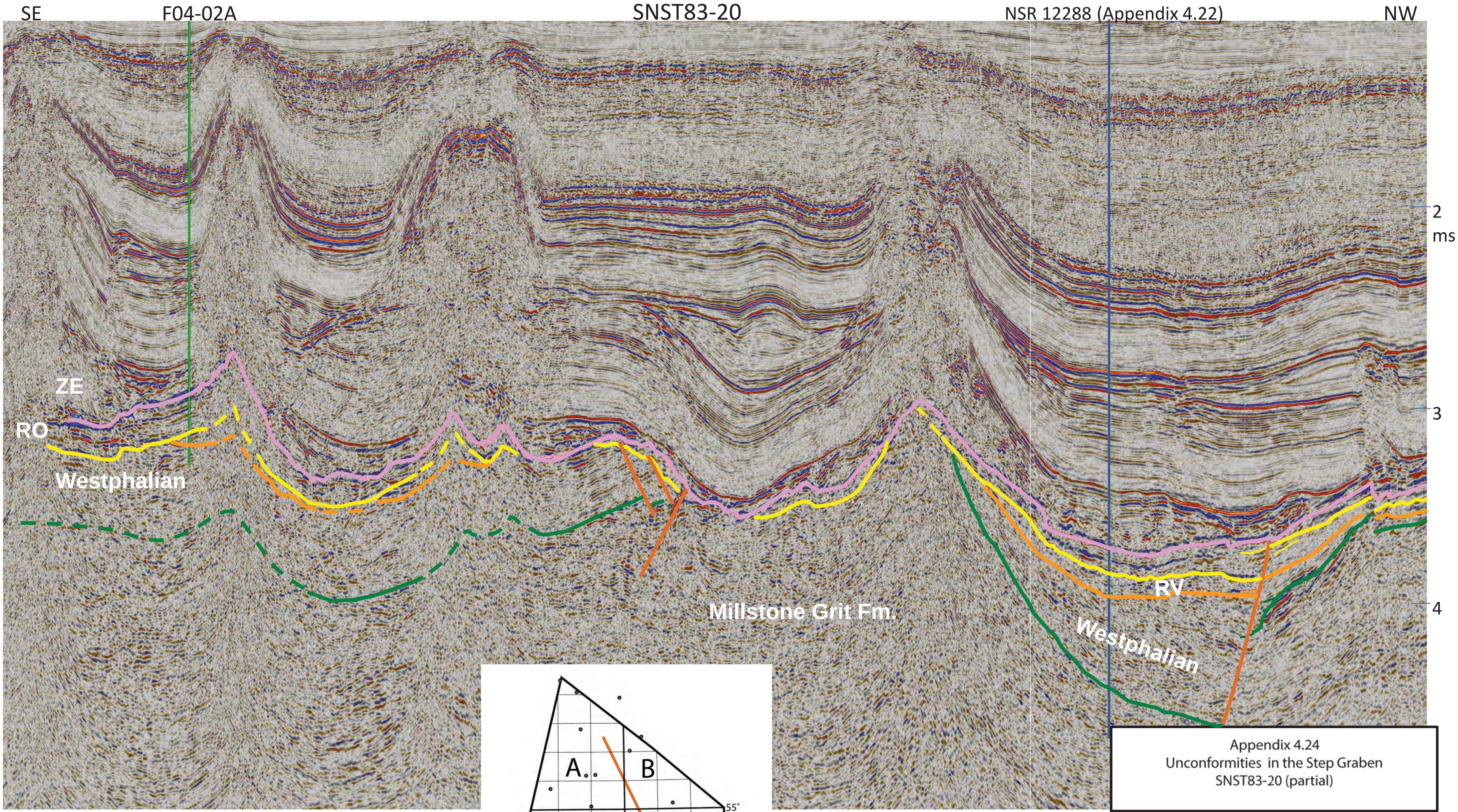

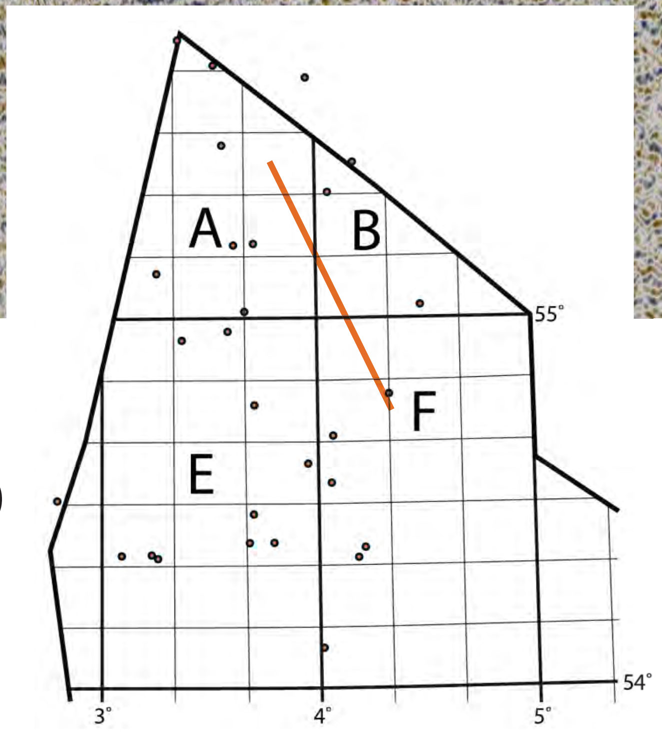

Appendix 4.24
Unconformities in the Step Graben
SNST83-20 (partial)

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May 2015, Version 2

Geert de Bruin, Renaud Bouroullec, Kees Geel, Rader Abdul Fattah, Tom van Hoof, Maarten Pluymaekers, Mart Zijp

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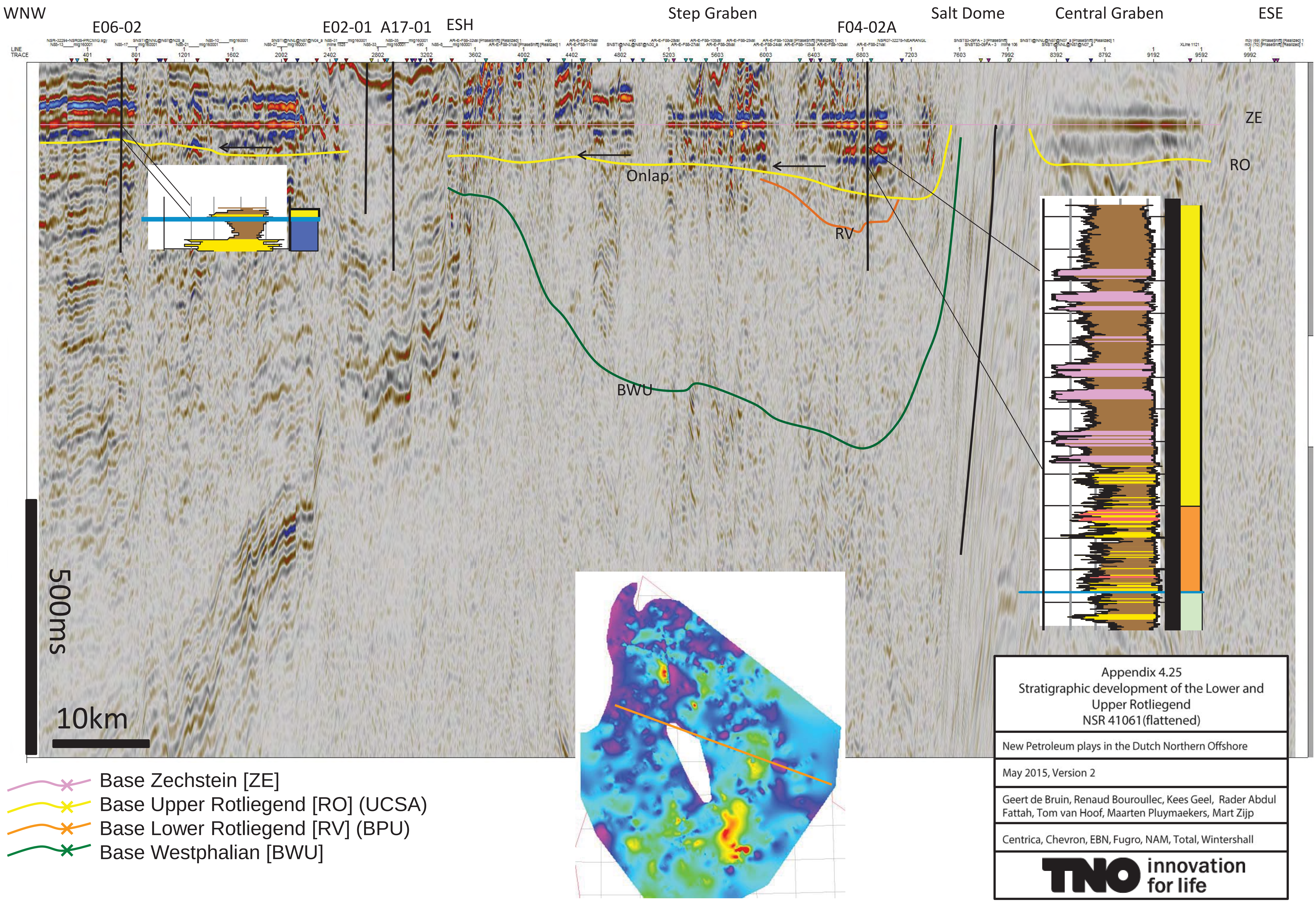

Appendix 4.25
Stratigraphic development of the Lower and Upper Rotliegend
NSR 41061(flattened)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

Geert de Bruin, Renaud Bouroullec, Kees Geel, Rader Abdul Fattah, Tom van Hoof, Maarten Pluymaekers, Mart Zijp

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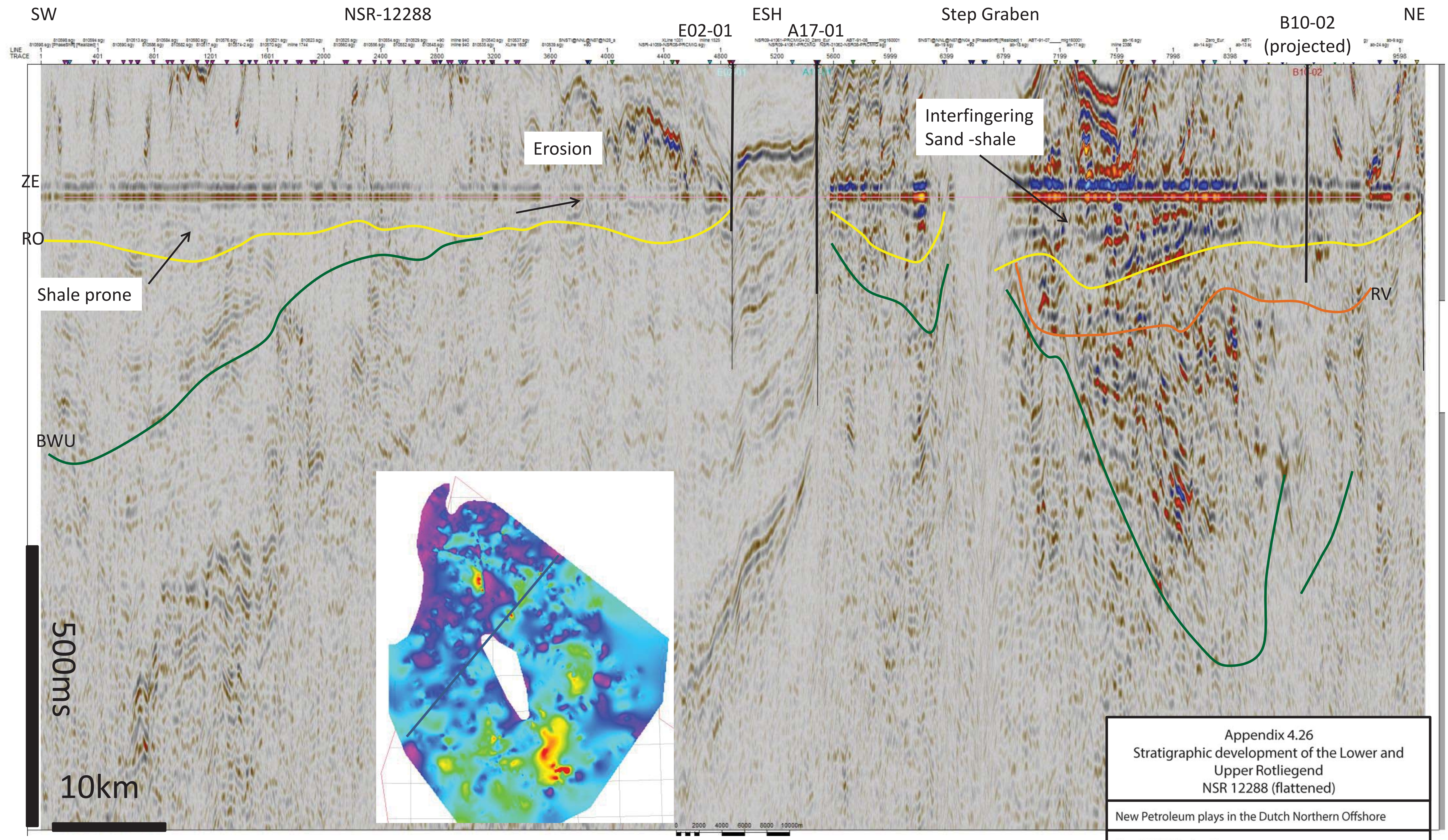

Base Zechstein [ZE]
Base Upper Rotliegend [RO] (UCSA)
Base Lower Rotliegend [RV] (BPU)
Base Westphalian [BWU]

Appendix 4.26
Stratigraphic development of the Lower and Upper Rotliegend
NSR 12288 (flattened)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

Geert de Bruin, Renaud Bouroullec, Kees Geel, Rader Abdul Fattah, Tom van Hoof, Maarten Pluymaekers, Mart Zijp

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Methodology of seismic interpretation

Below we give a more detailed description of the methodology that is used for seismic interpretation.

4.1 Well-tie and synthetic to seismic matching

Seismic interpretation start by identifying the seismic events (peak or trough) at well locations. The re-interpreted well markers have been implemented here. First, the wells are tied to the seismic by using check-shots, manual adjustments based on clear boundaries (base N, CK, ZE) and synthetic seismograms. In many cases it turned out that the seismic character of the boundary could change due to the fact that we are interpreting unconformities or due to changes in underlying strata (e.g. volcanics).

4.2 Mapped horizons and their seismic definition

The following seismic horizons are mapped within the study area
- Scremerston Coal
- Base Westphalian Unconformity (BWU)
- Base lower Rotliegend (RV)
- Base Upper Rotliegend (RO)
- Base Zechstein (ZE)

In addition the following horizons (Bases) are mapped on the selected NSR lines
- Upper North Sea Group NU
- North Sea Group N
- Chalk Group CK
- Rijnland Group KN
- Upper Germanic Trias Group RN
- Lower Germanic Trias Group RB

4.2.1 Scremerston Coal

The Scremerston coal was defined in the UK well 39/07-1 where it was drilled and were a synthetic-to-seismic match was made. Two bright reflectors indicating an low acoustic impedance layer representing the low density of the coals. The top reflector was interpreted.

4.2.2 Base Westphalian Unconformity(BWU)

Several major unconformities are observed on line NSR-12288-NSR08-PRCMIG in the Step Graben. The lower unconformity was traced back to wells B17-04, F04-02A and F04-03 were Westphalian deposits are found. This unconformity has been interpreted as the base Westphalian unconformity (BWU),

Since it is an angular unconformity it is not represented by a specific peak or through.

4.2.3 Base Lower Rotliegend (RV)

The base of the Lower Rotliegend was found in 6 wells in the Netherlands. An additional 2 wells end in the Lower Rotliegend interval. The heterogeneous nature of

this interval makes it hard to define seismically. It consists of clastics, volcanic and volcano-clastics, resulting in various amplitude characteristics (peak or through and magnitude). The base of the Lower Rotliegend is characterised by a hiatus, but often no angular relationship with the subcropping strata is clearly observed. The subcrop consists of Westphalian or older Carboniferous strata. Therefore, the base Lower Rotliegend is very often difficult to interpret. It is defined in well data and the seismic interpretation aims at connecting these results with the highest level of certainties as achievable. The Lower Rotliegend often shows a significant angular unconformity with overlying strata of the Upper Rotliegend (see below).

4.2.4 Base Upper Rotliegend (RO)

The base Upper Rotliegend was found in 22 wells in the Dutch offshore. It is a clear angular unconformity on seismic. The seismic character is mainly dictated by the underlying strata, and could be a peak when sediments are found below it, or a through when hard volcanics rocks are located underneath. Therefore, the seismic character of the base Upper Rotliegend is defined and constrained at well locations, and the angular relation observed on seismic is used whenever possible to regionally interpret this unconformity..

4.2.5 Base Zechstein

The base of the Permian Zechstein salt was encountered in 23 wells (all except 2) in the Dutch Northern Offshore. It is often a clear seismic reflector, but in areas were major salt deformation has taken place it can be very difficult to interpret. This horizon is mainly the top of the Upper Rotliegend but also locally (to the extreme north of the study area) the top of the Lower Rotliegend. The base Zechstein was often used to flatten the seismic data in order to interpret the lower horizons (RO, RV, BWU) more precisely.

4.3 Creation of surface and computations

The seismic interpretations were performed on 2D seismic lines (and individual lines from 3D surfaces) and in order to make 3D surfaces they were interpolated.

4.3.1 Surfaces True Extent

First a polygon was made to limit the interpolated surface to the depositional extent of the formation. This was done for all surfaces. Due to interpolation artefacts these horizons can cross each especially in areas where limited interpretation points are available

4.3.2 Extended Surfaces

For certain computations the surface needs to be present within the entire area of interest. Therefore, the surfaces are merged with the surface above it. First, a top horizon is constructed, the top Rotliegend, which consist of a combination of the Base Zechstein, Base Triassic or Base Chalk. Furthermore, where surfaces are crossing each other, the lower horizon is replaced by the upper horizon.

4.3.3 Thickness computations

Time thickness maps are made by subtracting two surfaces vertically. Unfortunately, due to interpolation artefacts of the surfaces, the resulting thickness results are locally not reliable. The artefacts are caused by significant depth (TWT) changes of the interpreted formations (due to faults) and the spline fitting of the interpolation process through these points. Erroneous bulges and troughs appear between the interpreted lines and should be corrected. Unfortunately, these areas make up the largest parts of the resulting 3D surface, making the thickness maps not usable without applying additional procedures. A simple trick is applied to correct this. The thickness is only kept at the interpreted seismic lines and removed where the surfaces were interpolated. Next, the thicknesses (at the interpreted seismic lines) is interpolated. Since these evaluated thickness results show less variations than the initial depth (twt) values, the interpolation is easier, and the resulting depth map are of higher quality.

4.4 Time depth Conversion

The time depth conversion was focused along the interpreted regional NSR seismic lines. A layer cake velocity model was constructed based on the main lithostratigraphical intervals, coinciding with the interpreted seismic horizons. The velocity model takes compaction into account by a linear depth dependency of velocity, except for the Zechstein. Here a constant velocity was adopted. Velocity data up to the Zechstein was extracted from TNO's Velmod-2 dataset (van Dalfsen et al., 2007).
Pre-Zechstein velocity data was extracted from the unpublished Velmod-3 dataset. Available interval velocities from wells were interpolated. The limited availability of Lower Rotliegend velocity data points did not justify interpolation, therefore a constant average was determent based on wells B17-04 and F04-02-A. Resulting interval velocity maps are enclosed as appendix 4.18 (Upper Rotliegend) A summary of used values is given in the table below.

Table 1 Summary of used Pre-Zechstein interval velocities:

Layer		Vint (m/s)
Upper Rotliegend	Surface (app 4.18)	4300 (mean)
Lower Rotliegend	Constant	4400
Westphalian	Surface (app 4.19)	4440 (mean)

The constructed velocity model was used to convert the mapped seismic horizons from time to depth domain. This results in regional depth maps for the Upper Rotliegend (appendix 4.140, Lower Rotliegend (appendix 4.15) and Base Westphalian Unconformity surfaces (appendix 4.16).

4.5 Level of confidence

The seismic interpretation is based on a large number of seismic vintages. The quality of these vintages varies greatly in the target interval. The number of high resolution lines (e.g. NSR lines) was limited to 8 lines. The variability of resolution of seismic lines hampered the quality of the seismic interpretation. Better seismic data (e.g. more NSR lines and/or the DEF survey) could improve the seismic interpretation

Due to the size of the study area, and its under explored nature, well data is sparse and distances in between can be large. For all seismic interpretations the wells were the starting points for the seismic interpretation.
Below are some comments on the quality of the seismic interpretation regarding some of the key horizons:

- The quality of the interpretation of the Scremerston is good, since it has only been mapped in a small part of the study area. There is only one well that is available for well control.
- The quality of the interpretation of the Base Westphalian Unconformity is good in the south and becomes less certain around the A11-1 area. This is due to the complexity of the geology and the large number of seismic vintages. Furthermore the well control is limited there.
- The quality of the interpretation of the Base Lower Rotliegend is moderate due to the heterogeneous character of the formation. The well control is reasonable in the north.
- The seismic interpretation of the Upper Rotliegend is considered to be of a reasonably good quality, since this formation is best visible on seismic data and the well control is good.

5 Isotopes

5.1 Methodology

Prior to analysis, sub-samples were ground to a fine powder. After grinding, the samples were placed in universal tubes, acidified with 2M hydrochloric acid, mixed and left for 24 hours allow inorganic carbon to be liberated as CO_2. The sample fractions were then isolated by centrifugation and the acid was then decanted. The samples were then washed twice using distilled water and centrifugation. After acid washing, the fractions were oven dried at 60 °C. After drying, the samples were re-ground in-situ.

The technique used for isotope analysis was Elemental Analyser - Isotope Ratio Mass Spectrometry (EA-IRMS). In this technique, samples and reference materials are weighed into tin capsules, sealed and then loaded into an automatic sampler on a Europa Scientific Roboprep-CN sample preparation module. From there they were dropped into a furnace held at 1000 °C and combusted in the presence of oxygen. The tin capsules flash combust, raising their temperature in the region of the sample to ~1700 °C. The combusted gases are swept in a helium stream over a combustion catalyst (Cr_2O_3), copper oxide wires (to oxidize hydrocarbons) and silver wool to remove sulphur and halides. The resultant gases (N_2, NO_x, H_2O, O_2, and CO_2) are swept through a reduction stage of pure copper wires held at 600 °C. This removes any oxygen and converts NO_x species to N_2. A magnesium perchlorate chemical trap removes water. Carbon dioxide is separated from nitrogen by a packed column gas chromatograph held at an isothermal temperature of 100 °C. The resultant CO_2 chromatographic peak enters the ion source of the Europa Scientific 20-20 IRMS where it is ionised and accelerated. Gas species of different mass are separated in a magnetic field then simultaneously measured using a Faraday cup collector array to measure the isotopomers of CO_2 at m/z 44, 45, and 46. Both references and samples are converted and analysed in this manner. The analysis proceeds in a batch process, whereby a reference is analysed followed by a number of samples and then another reference.

The reference material used during analysis was IA-R001 (Iso-Analytical working standard Flour, 40.2% Carbon), with a・13C value of -26.43 ‰ vs. V-PDB. IA-R001 is traceable to IAEA-CH-6 (sucrose,・13C= -10.43 ‰ vs. V-PDB). IA-R001 was chosen as a reference material as it most closely matches the organic component of your samples.
Reference standards IA-R001, IA-R005 (Iso-Analytical working standard Beet Sugar, ・13C = -26.03 ‰ vs. V-PDB, traceable to IAEA-CH-6) and IA-R006 (Iso-Analytical working standard Cane Sugar,・13C = -11.64 ‰ vs. V-PDB, traceable to IAEA-CH-6) were measured as quality control check samples during analysis. Results of the quality control samples are included in the results file.
The International Atomic Energy Agency, Vienna, distributes IAEA-CH-6 as an international isotope reference standard.

6 Basin Modelling

6.1 Model Sensitivity Source rocks in the study area

Previous studies (Schroot et al., 2006) have shown that in the Northern Dutch Offshore, including in the A, western B and the northern E blocks, a fair Carboniferous SR potential exists. Geochemical analyses of Carboniferous rock samples from the northern offshore have indicated a gas prone (Type III) source rock in what was interpreted at the time as the Dinantian sections (Yoredale Fm. equivalent) (Schroot et al., 2006). Locally the presence of Type II source rock was also anticipated near the margins of the structural highs but this was not encountered by any wells in the area. An organic rich transition between Dinantian and Namurian with Type II source rock properties has been observed in the UK offshore but not in our study area.
Analyses on Namurian shale samples from the Cleaverbank High indicate marine depositional settings. However no indications for oil prone source rocks (i.e. Type II) could be confirmed. Namurian coal seams have been identified and characterized as gas prone source rocks of Type III (Schroot et.al, 2006). The coal rich layers of the Westphalian formations (specifically the Maurits and Klaverbank formations) are known to be gas prone source rocks of Type III.

6.2 Model Sensitivity Analysis

The outcome of basin modelling is dependent on the quality and uncertainties of the input parameters.
In order to understand the sensitivity of the our models to the main input parameters, a test a number of scenarios using different assumptions related to different inputs.

6.2.1 Sensitivity to Surface Water Interface Temperature (SWIT)

Two SWIT models are selected based on which the formation temperatures and hydrocarbon generation of one selected source rock are calculated. The first SWIT model is a standardized model that is provided by the modelling package (PetroMod) and is based on Wygrala (1989). A more detailed SWIT model has also been used based on geological analysis which is provided by TNO. The simulation results using both scenarios show that using different SWIT results in different temperature history and thus different hydrocarbon generation especially in the Tertiary. TNO model is considered more reliable in this case since it is more detailed, especially in the Tertiary. For both scenarios, hydrocarbon generation declines by the end of the Miocene (Figure 12.6).

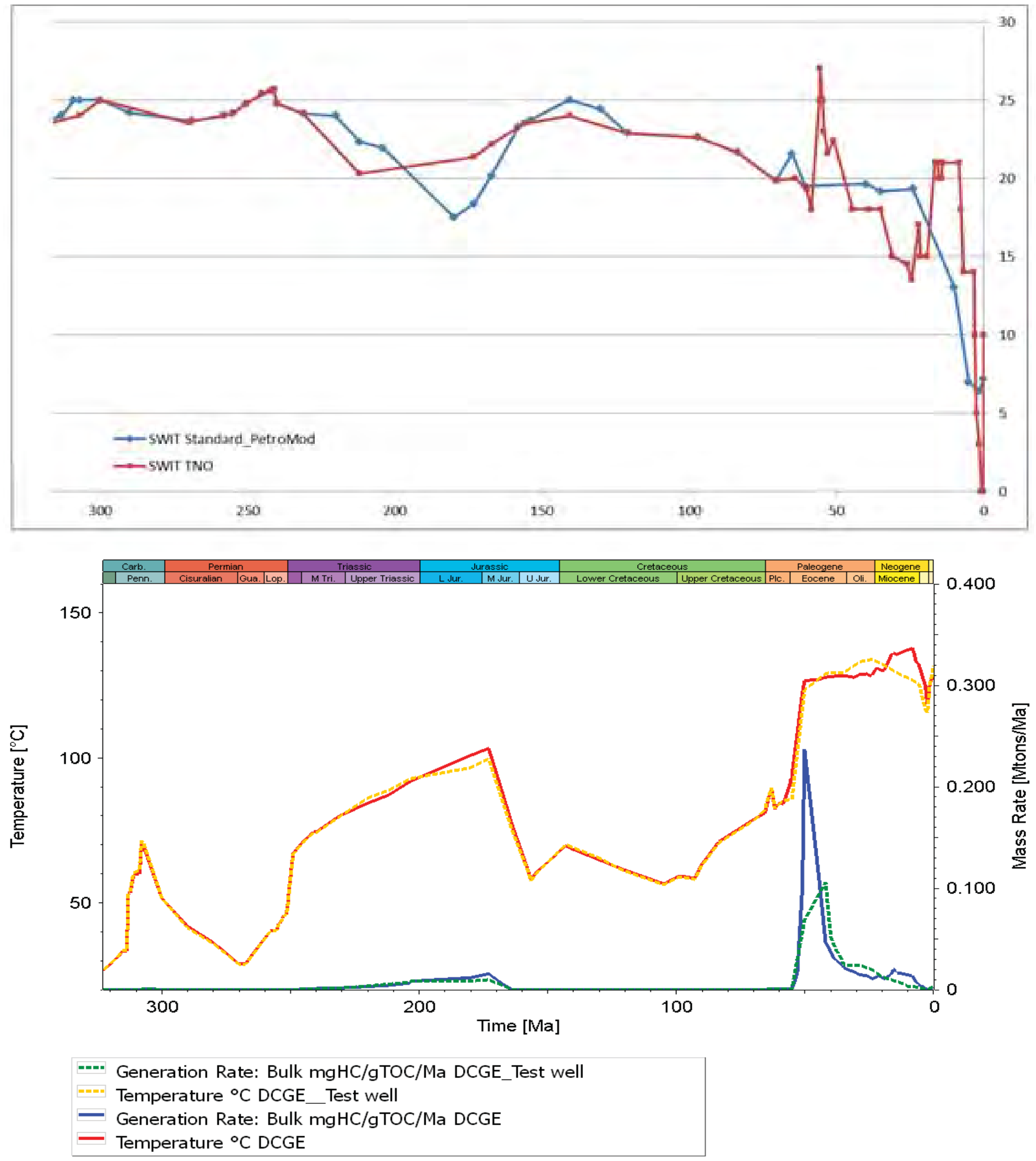


Figure 12.6: Two SWIT models used for comparison (top) and the resulted formation temperatures and hydrocarbon generation from both models (bottom).

6.2.2 *Sensitivity to basal heat flow*

Heat flow is modelled in the northern part of the Step Graben (Well A11-01). It shows a declining trend in the Miocene. In order to evaluate the impact of the heat flow trends, especially in the Tertiary, we use a modified heat flow mode where this declining trend in the Tertiary is replaced by a constant value of 55 Mw/2m.
The model comparison shows that modifying the heat flow trend in the Tertiary affects the temperature of the selected formation and thus the hydrocarbon generation. Variations in heat flow though the geological times, changes in formation temperature and hydrocarbon generation can be expected (Figure 12.7). In addition, the impact of the heat flow can be more significant when combined with other

elements such as the burial history in the Tertiary. Consequently, heat flow was modelled with details and the final results were calibrated to temperature data for each well whenever possible.

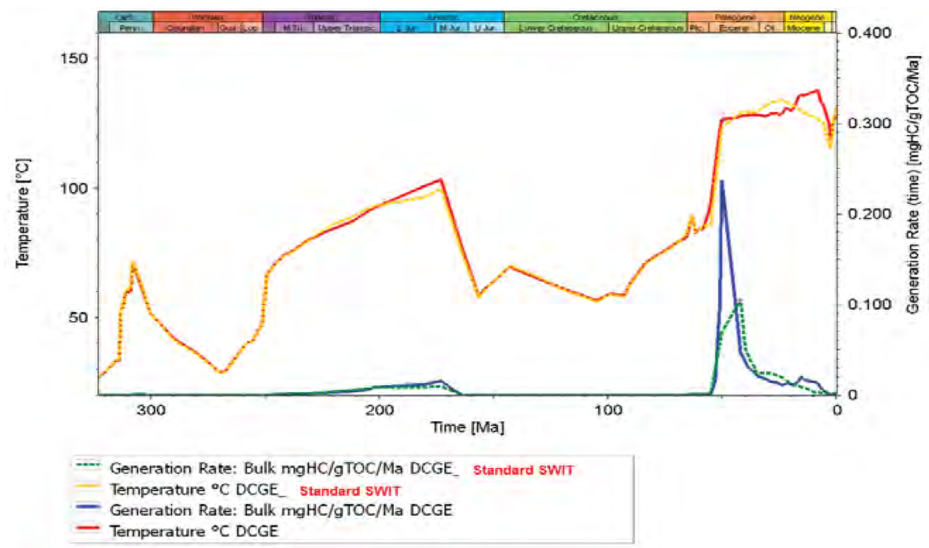


Figure 12.7: The modified heat flow models (top) and the resulting history of formation temperature and hydrocarbon generation (bottom). Modified heat flow in the tertiary does not result in large variations.

6.2.3 *Source rock kinetic models*

Kinetic models describe te transformation of organic matter to various hydrocarbon components (oil and gas generally), their masses and composition. There are many models that describe the oil and gas generation. We evaluate the effect of using different models on modelled history of hydrocarbon generation and expulsion. Two kinetic models are used for this purpose: the Pepper & Corvi (1995) and the Burnham (1989) kinetic model. The results show that using different kinetic models results in different generation rates of bulk hydrocarbon (i.e. oil and gas) under the same temperature conditions (Figure 12.8: Top).

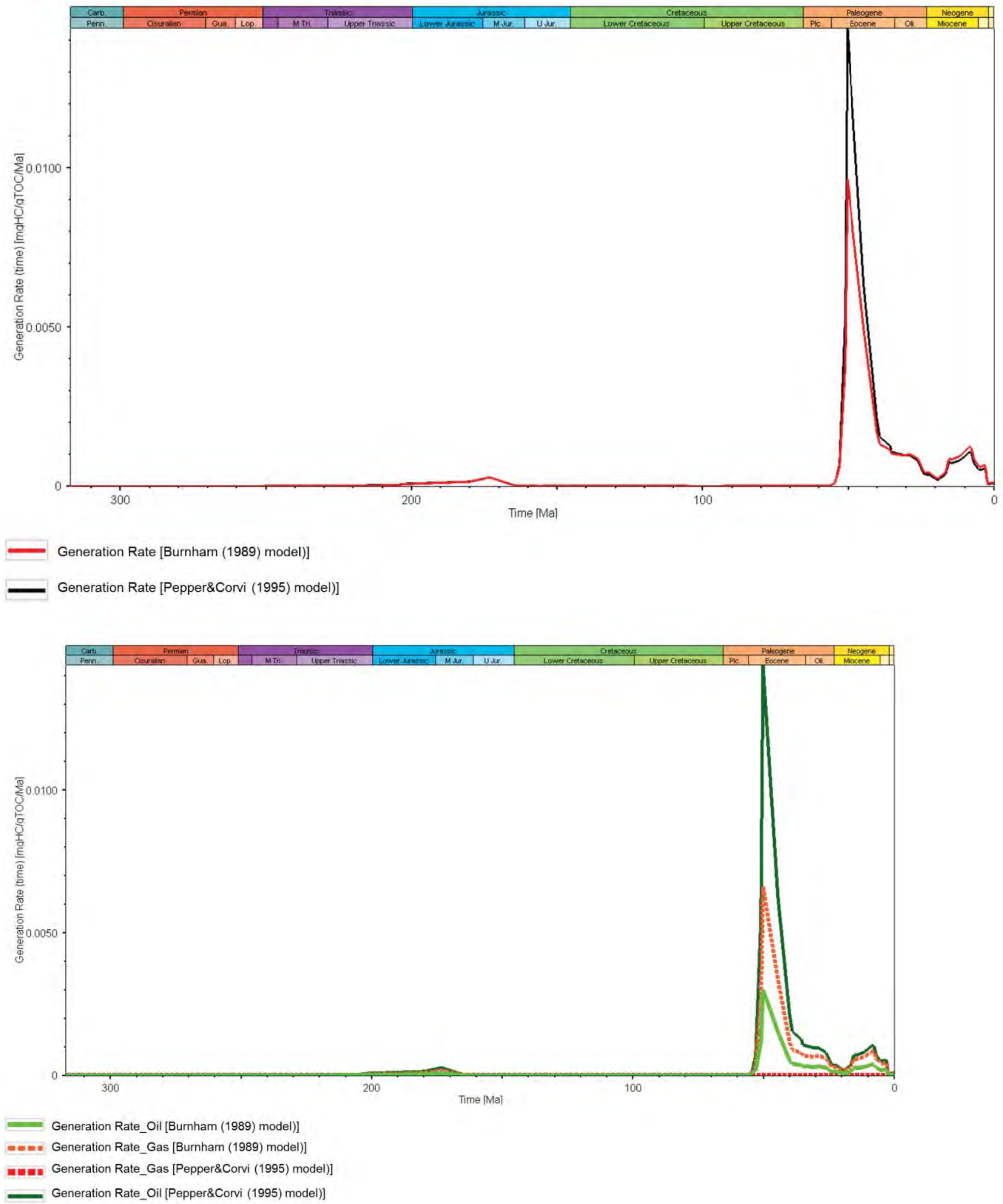


Figure 12.8: Comparison between two kinetic models, the Pepper and Corvi (1995) and Burnham (1989). Generation rates of bulk hydrocarbon (top), and modelled generation rates of oil and gas using different kinetics (Bottom).

Moreover, using different kinetics results in different oil/gas ratio in the generation hydrocarbons. In the Pepper & Corvi (1995) kinetic model, almost all of the generated hydrocarbons is oil, whereas using the Burnham (1989) kinetic model shows that both oil and gas are generated with higher percentage of gas (Figure 12.8: Bottom).

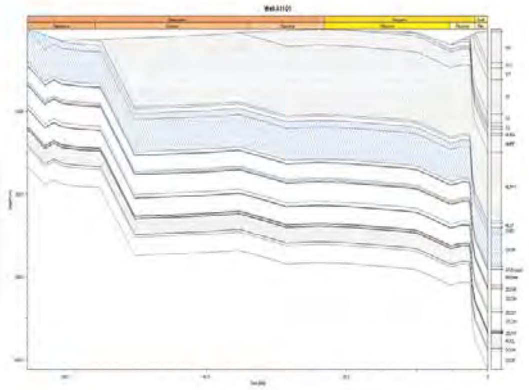
Selecting the suitable kinetic model for the modelling requires a detailed study as well as analyses. For this study, we use the Burnham (1989) kinetics since it does not exaggerate the generation of oil from the source rocks in this study which are assumed to be gas prone of Type III.

6.2.4 Effect of the stratigraphy of the Tertiary

The preliminary maturity analyses in many wells have shown that important generation and expulsion event took place in the Tertiary. It is anticipated that the stratigraphy of the Tertiary as defined in the model, and thus the burial history, can have important impact on the history of hydrocarbon generation.

To evaluate the effect of definition of the stratigraphy of the Tertiary, we model two scenarios with different stratigraphy for the Tertiary. In the first scenario, we use a general stratigraphy of the Tertiary as described in the well (i.e. Upper North Sea, Middle North Sea and Lower North Se groups). In the second scenario, a more detailed stratigraphy of the Tertiary is used, especially the Upper North Sea Group, based on previous studies at TNO (Figure 12.9).

Layer	Top [m]	Base [m]	Thick. [m]	Eroded [m]	Depo. from [Ma]	Depo. to [Ma]	Eroded from [Ma]	Eroded to [Ma]
NU	38	1303	1265		20.10	0.00		
NMRF	1303	1494	191	200	35.40	28.60	28.60	20.10
NLFFY	1494	2332	837		55.10	50.20		
NLFFT	2332	2355	23		58.00	55.10		



Layer	Top [m]	Base [m]	Thick. [m]	Eroded [m]	Depo. from [Ma]	Depo. to [Ma]	Eroded from [Ma]	Eroded to [Ma]
res	38	416	378		1.80	0.00		
S13	416	480	64		1.90	1.80		
S11	480	618	138		2.16	1.90		
S6	618	1034	416		2.44	2.16		
S5	1034	1140	106		2.58	2.44		
S4	1140	1188	48		3.60	2.58		
S3	1188	1218	30		5.20	3.60		
NU	1218	1270	52		11.80	5.20		
NUBA	1270	1301	31		20.10	11.80		
NMRF	1301	1492	191		35.40	28.60		
NLFFY	1492	2330	837		55.10	50.20		
NLFFT	2330	2353	23		58.00	55.10		

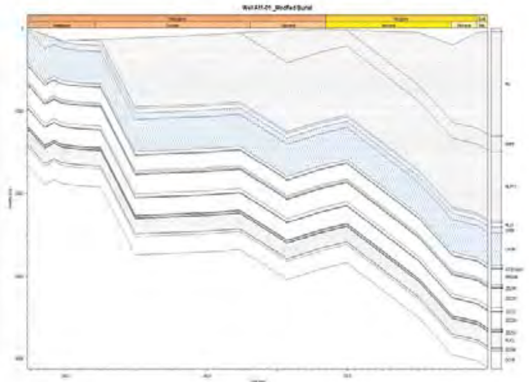


Figure 12.9: Generalized stratigraphy of the well and the related burial history(Scenario 1: Modified model: top).The detailed stratigraphy and the burial history of the modified scenario (Scenario 2: bottom).

The results show that using a more detailed and different stratigraphic subdivision of the North Sea Group influence the history of hydrocarbon generation from the source rock. The burial of the source rock during the Tertiary in different in both scenarios and this will affect the temperature evolution of the formation (Figure 12.10). It is also expected that, due to porosity and pressure changes with different burials, the modelled expulsion of hydrocarbons will be affected as well.
IT was therefore concluded that a detailed stratigraphy of the Tertiary section would be used for the modelling at the location of the wells. The detailed stratigraphy is based on the previous stratigraphic studies at TNO.

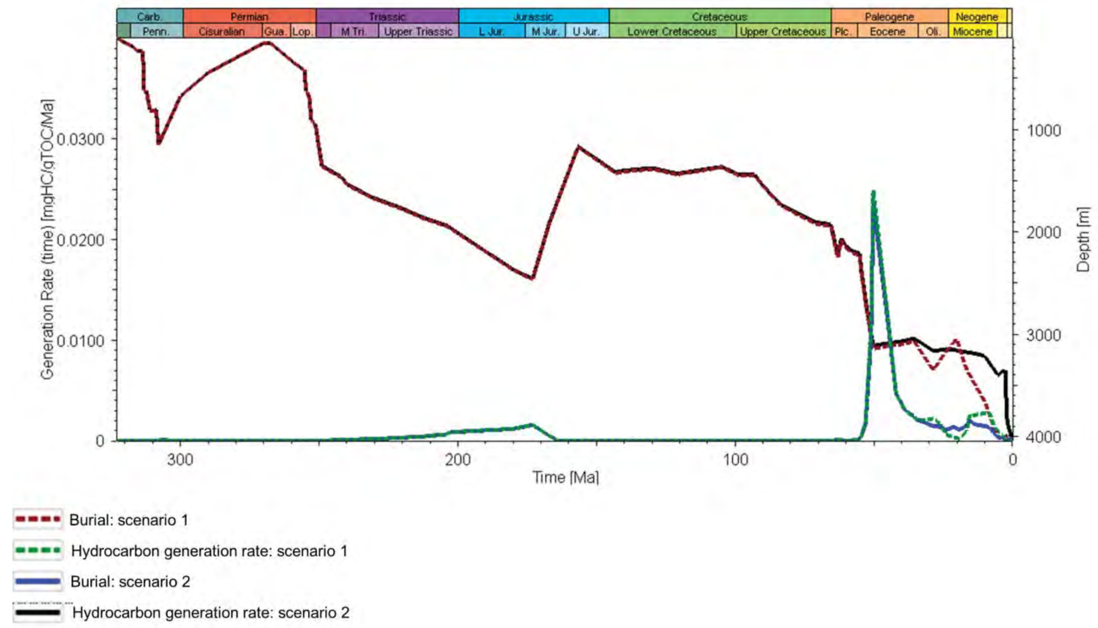
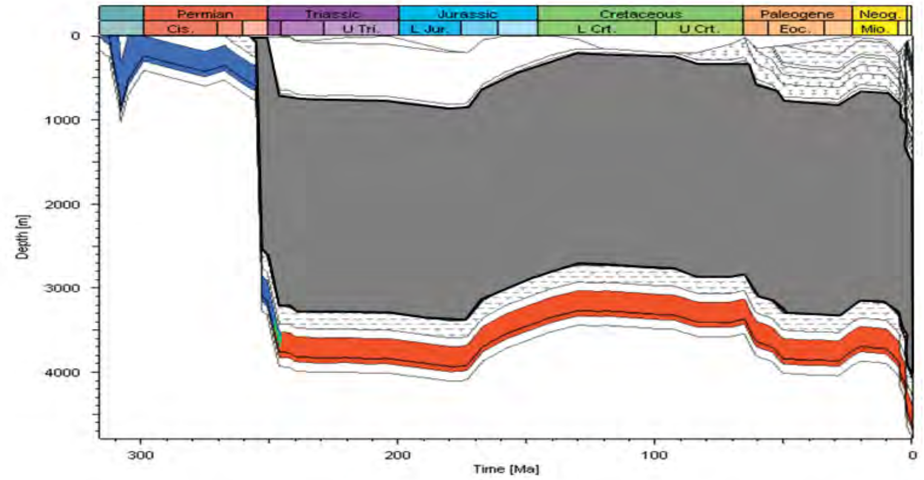


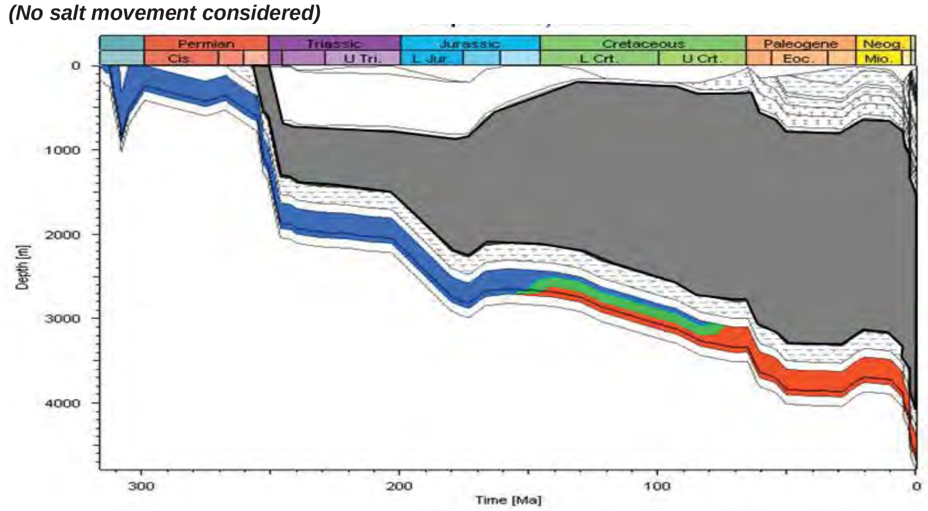
Figure 12.10: Modelled formation burial and history of hydrocarbon generation from the source rock using different stratigraphy of the Tertiary. Dashed lines represent the modified scenario (coarse stratigraphy of the Tertiary).

6.2.5   *Effect of Salt movement*

Many salt domes and slat structures exist in the northern offshore area. The effect taking salt movement into account while conduction the basin modelling was evaluated using two different scenarios. In the first scenario, no salt movement was considered and salt was treated like a regular formation. In the second scenario, the evolution of the salt structure was considered in the modelling though geological.
The sensitivity analyses indicated that salt movement during geological times have affected the burial history of the formations and therefore the history of temperature and source rock maturity (Figure 12.11). When the evolution of the salt structure is not taken into account, the source rocks go through deeper burial earlier in the history and thus early generation and expulsion is modelled. The thermal effect of salt domes can also have an impact on the temperature around the salt structure.
Salt movement and salt deformation at different geologic times was therefore taken into account in the modelling at the well locations where anomalous salt structures exist.



(No salt movement considered)



(Salt movement considered)

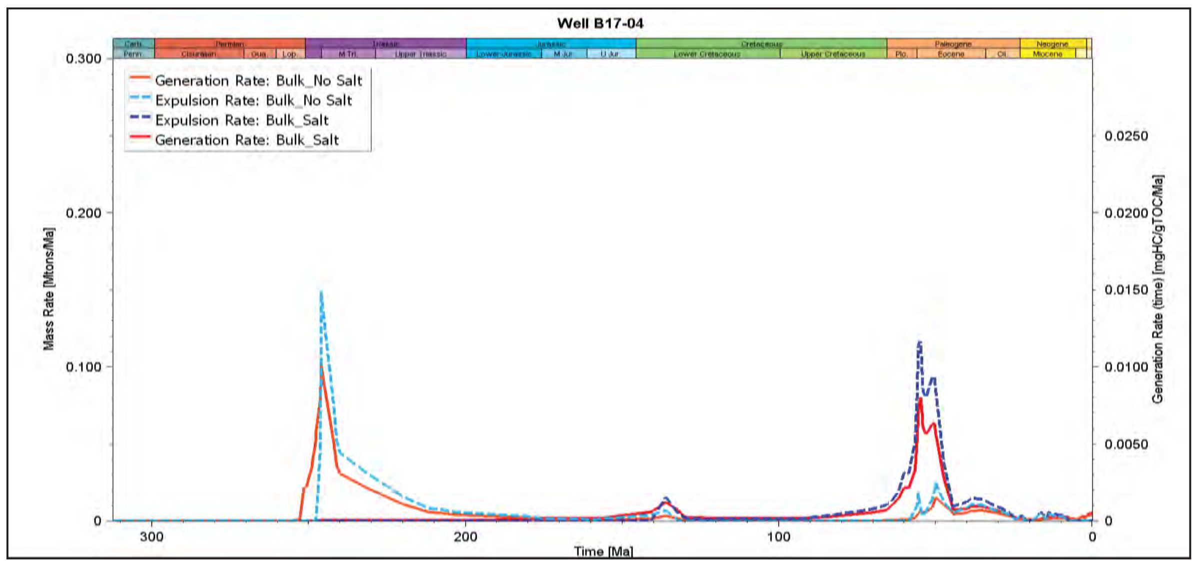
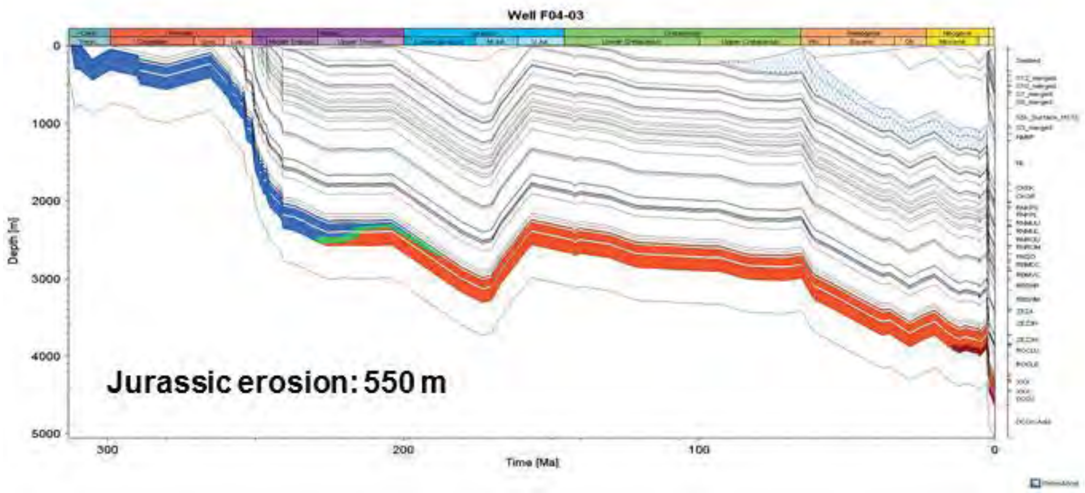


Figure 12.11: Modelled burial history of the well with different scenarios considered for salt movement (Top). Modelled history of hydrocarbon generation and expulsion for the two differ salt-movement scenarios (Bottom).

6.2.6 Post- Carboniferous erosion (Jurassic)

Different erosion scenarios will result in different burial histories and thus maturity histories. However, since in most of the cases the deepest burial is at present day, it is difficult to constrain the amount of erosion though calibration procedures with parameters such as vitrinite reflectance. Therefore, it is very important to evaluate the sensitivity of our models to the erosion thicknesses.
Several scenarios representing various amounts of erosion thicknesses for the Jurassic event (i.e. Mid-late Kimmerian event) were assumed. Well F04-03 was selected for the analysis where an initial erosion thickness of 250 m was assigned to the model. First, an erosion thickness of 550 m was assigned the maturity and history of hydrocarbon generation and expulsion were compared to the initial scenario (Figure 12.12). The results showed that deeper burial the Upper Jurassic, due to larger erosion amounts, resulted in a peak of hydrocarbon generation and expulsion in the Jurassic. This was followed by another peak in the Tertiary. In the second case, an amount of 1250 m erosion was assumed for the Jurassic resulting in a deeper burial. The model indicated that larger peak of generation and expulsion took place in the Jurassic and much less was generated in the Tertiary (Figure 12.13).

The analyses have shown that although the deepest burial is generally at present day, Jurassic erosion can influences the history of hydrocarbon generation and expulsion from Carboniferous source rocks. Consequently, the erosion amounts in the different wells were carefully determined based on regional stratigraphic correlations with surrounding areas including adjacent wells.



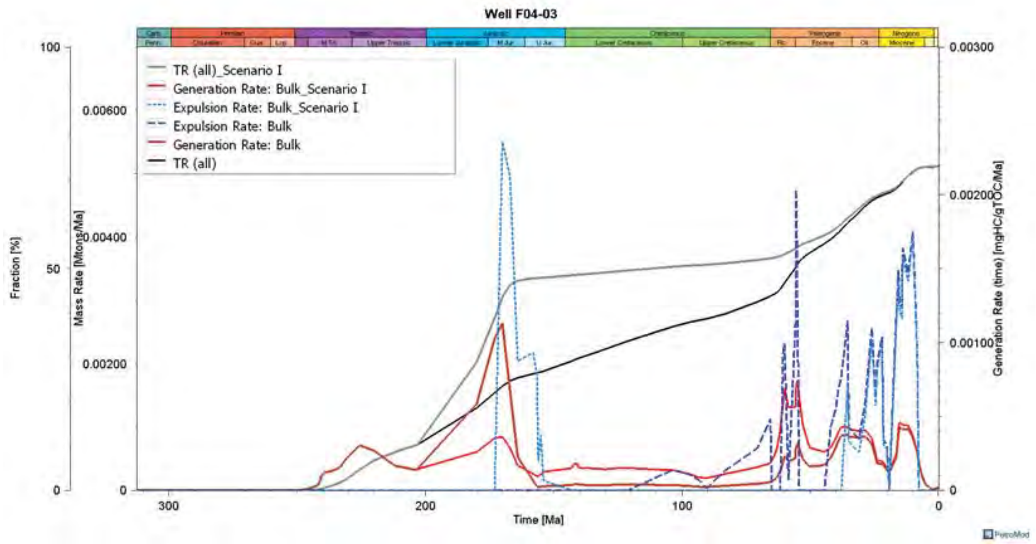
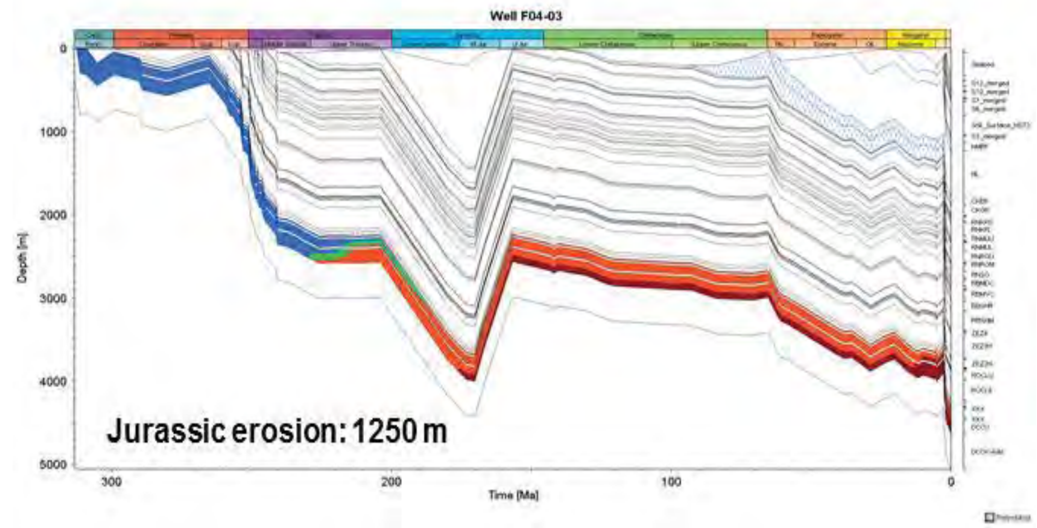


Figure 12.12: The burial history of well F04-03 with 550 m erosion assigned to the Kimmerian erosion event (Top). The resulting histories of hydrocarbon generation, expulsion and transformation ratio compared to the initial model (where 250 m erosion is used) (Bottom). Higher erosion resulted in earlier generation.



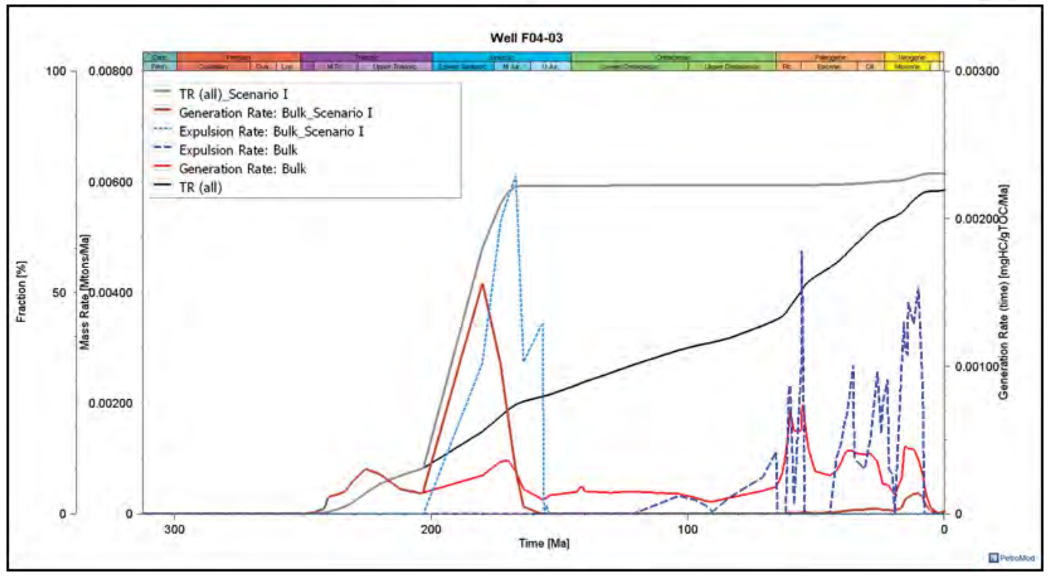
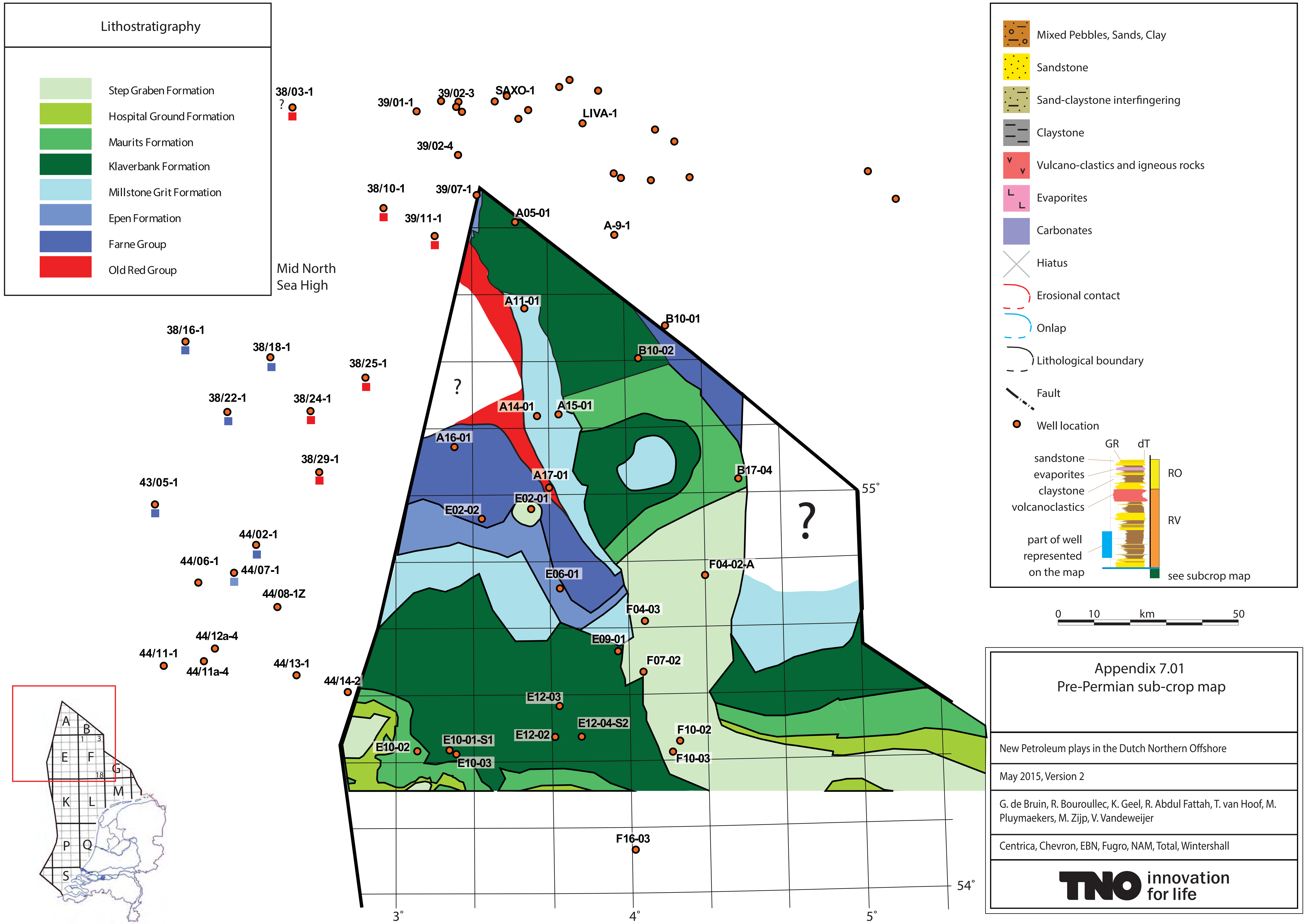


Figure 12.13: The burial history of well F04-03 with 1250 m erosion assigned to the Kimmerian erosion event (Top). The resulting histories of hydrocarbon generation, expulsion and transformation ratio compared to the initial model (where 250 m erosion is used) (Bottom). Higher erosion resulted in earlier generation peak and and almost no later generation..

7 Geological Maps

7.01 Pre-Permian Subcrop map
7.02 Lower Rotliegend (RV) Lithological map 1 of 3
7.03 Lower Rotliegend (RV) Lithological map 2 of 3
7.04 Lower Rotliegend (RV) Lithological map 3 of 3
7.05 Upper Rotliegend (RO) Lithological map 1 of 5
7.06 Upper Rotliegend (RO) Lithological map 2 of 5
7.07 Upper Rotliegend (RO) Lithological map 3 of 5
7.08 Upper Rotliegend (RO) Lithological map 4 of 5
7.09 Upper Rotliegend (RO) Lithological map 5 of 5
7.10 Sand map. Combination of all sand occurrences of appendices 7.02 to 7.09
7.11 Maturity map of the Westphalian
7.12 Map of prospective regions. Combination of sand map and maturity map
7.13 Net sand map of the Rotliegend



Appendix 7.01
Pre-Permian sub-crop map

New Petroleum plays in the Dutch Northern Offshore

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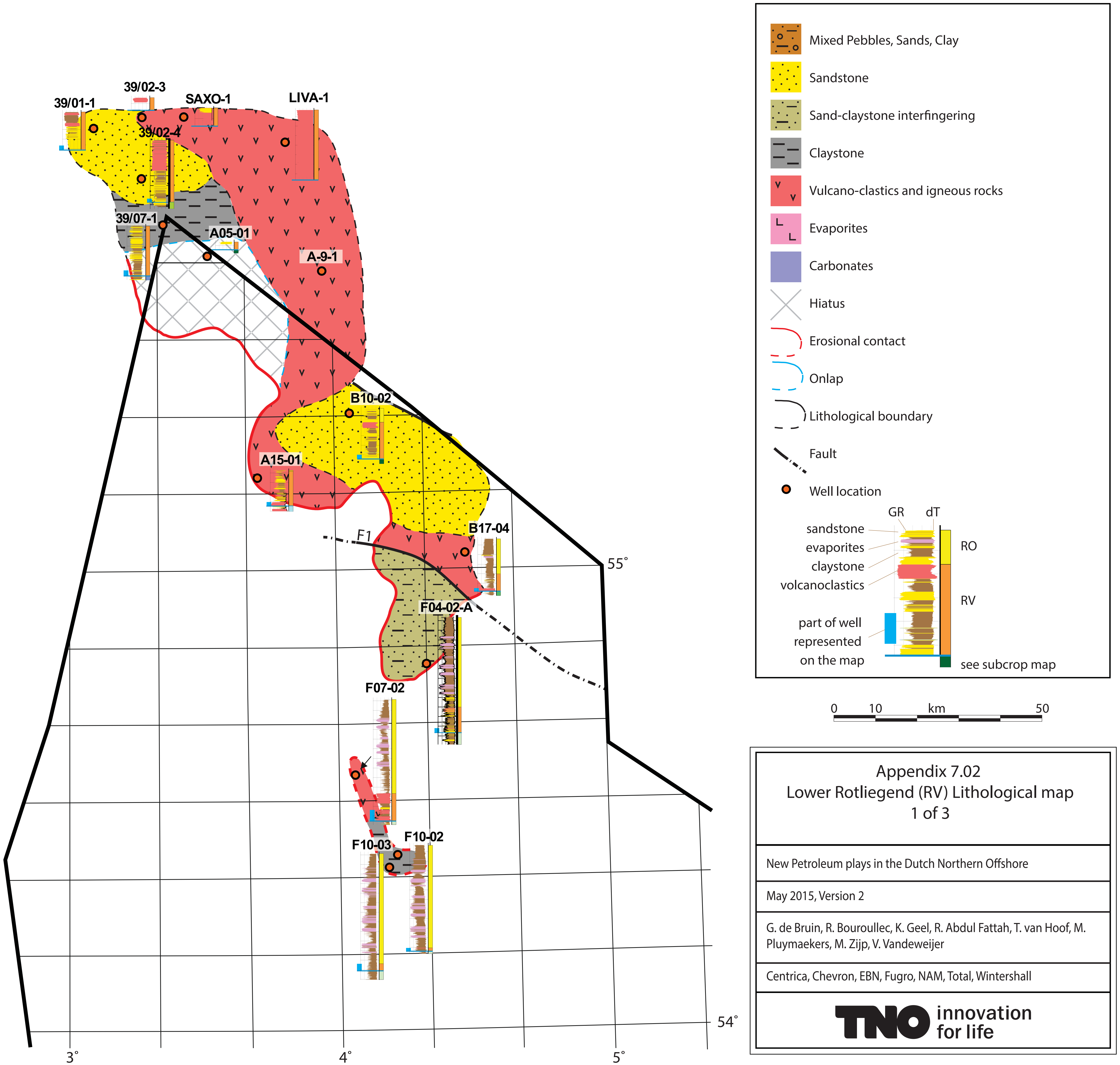

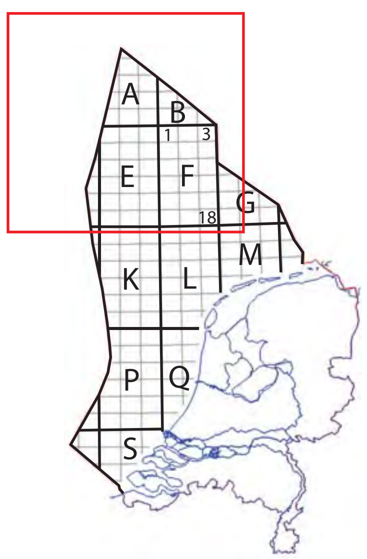

Appendix 7.02
Lower Rotliegend (RV) Lithological map
1 of 3

New Petroleum plays in the Dutch Northern Offshore

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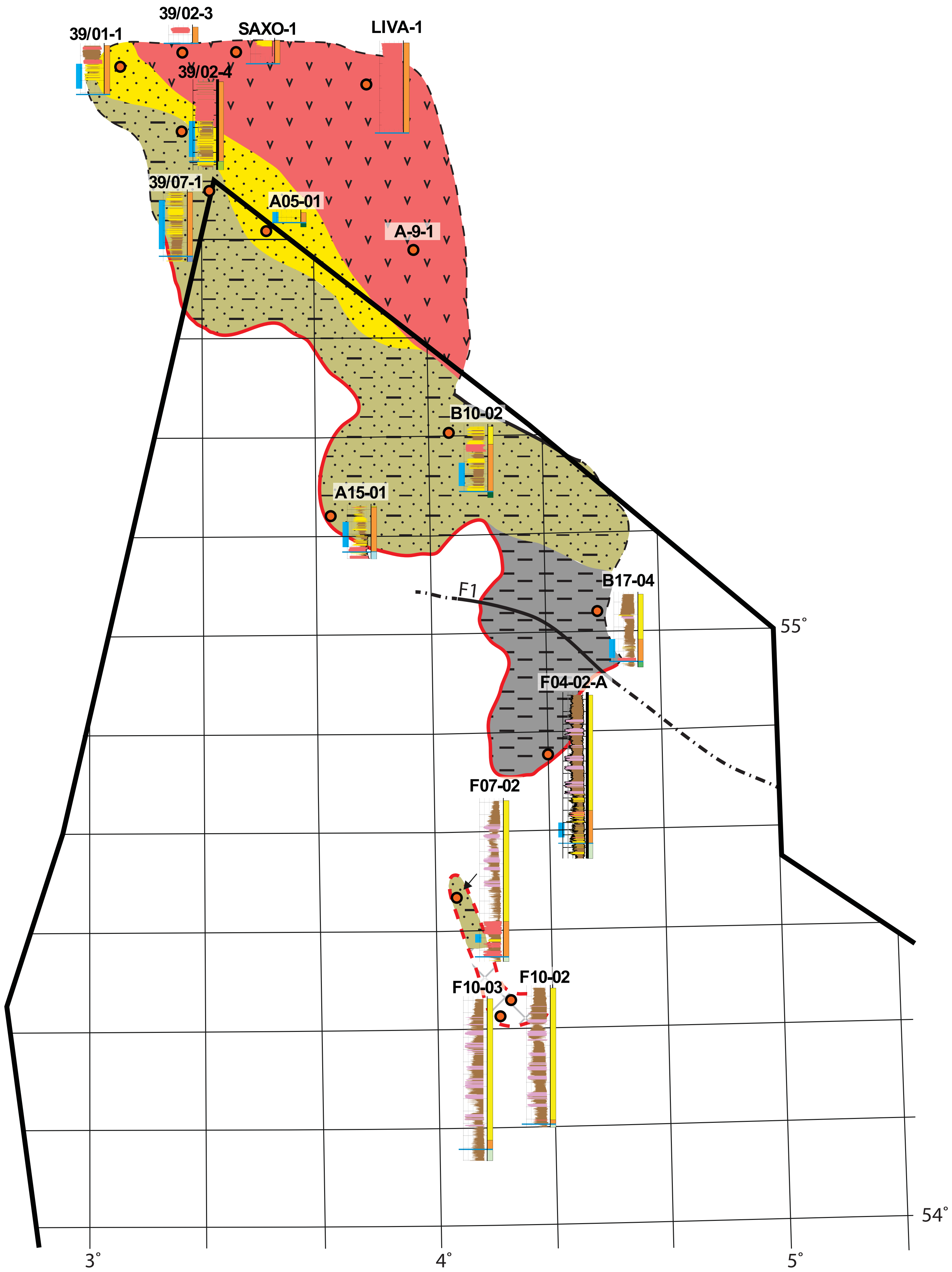

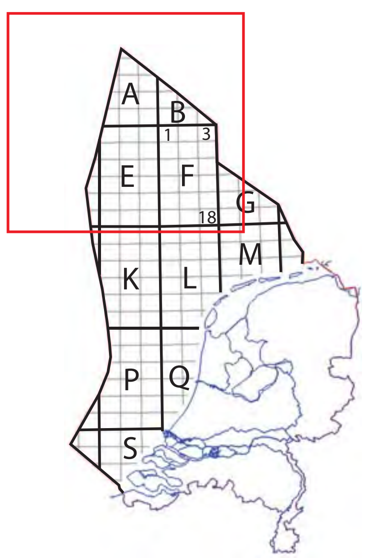

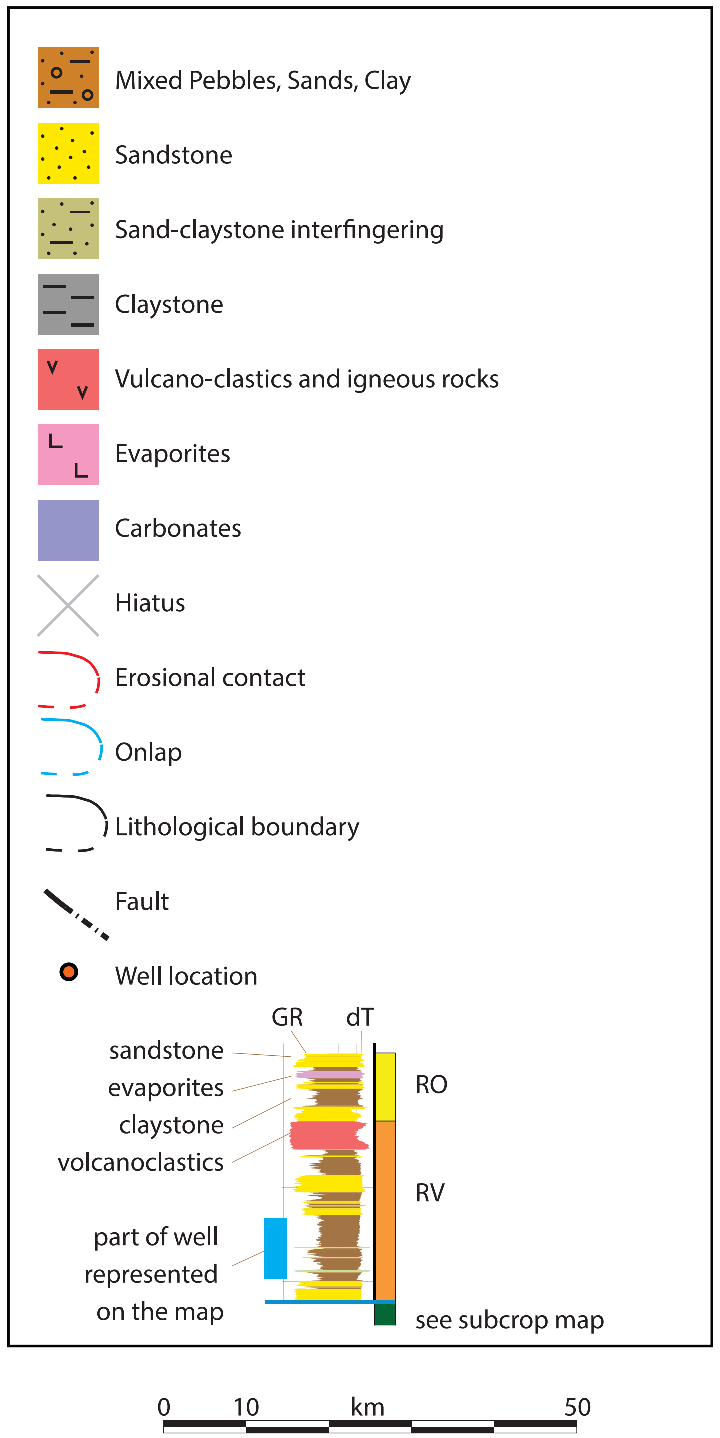

Appendix 7.03
Lower Rotliegend (RV) Lithological map
2 of 3

New Petroleum plays in the Dutch Northern Offshore

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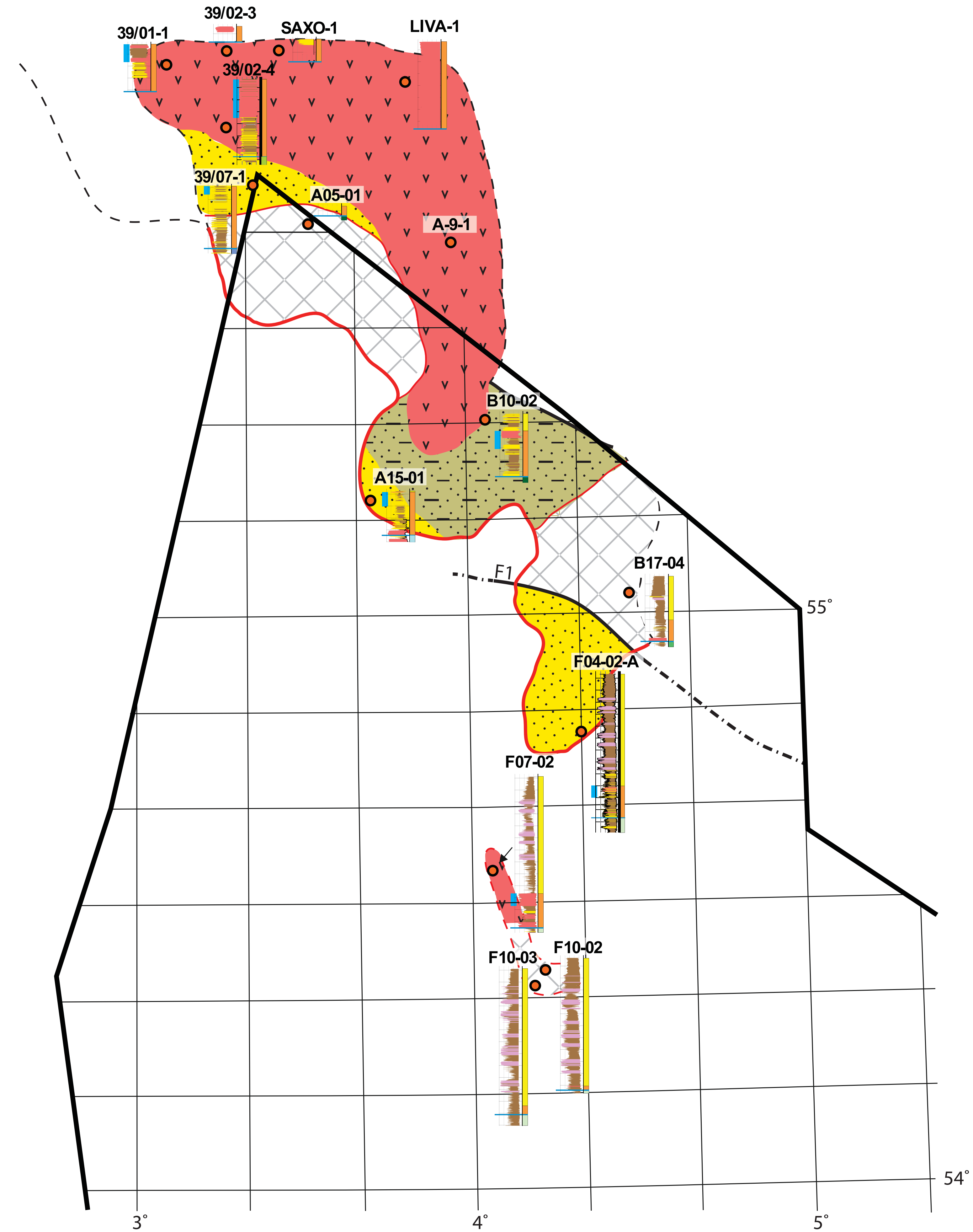

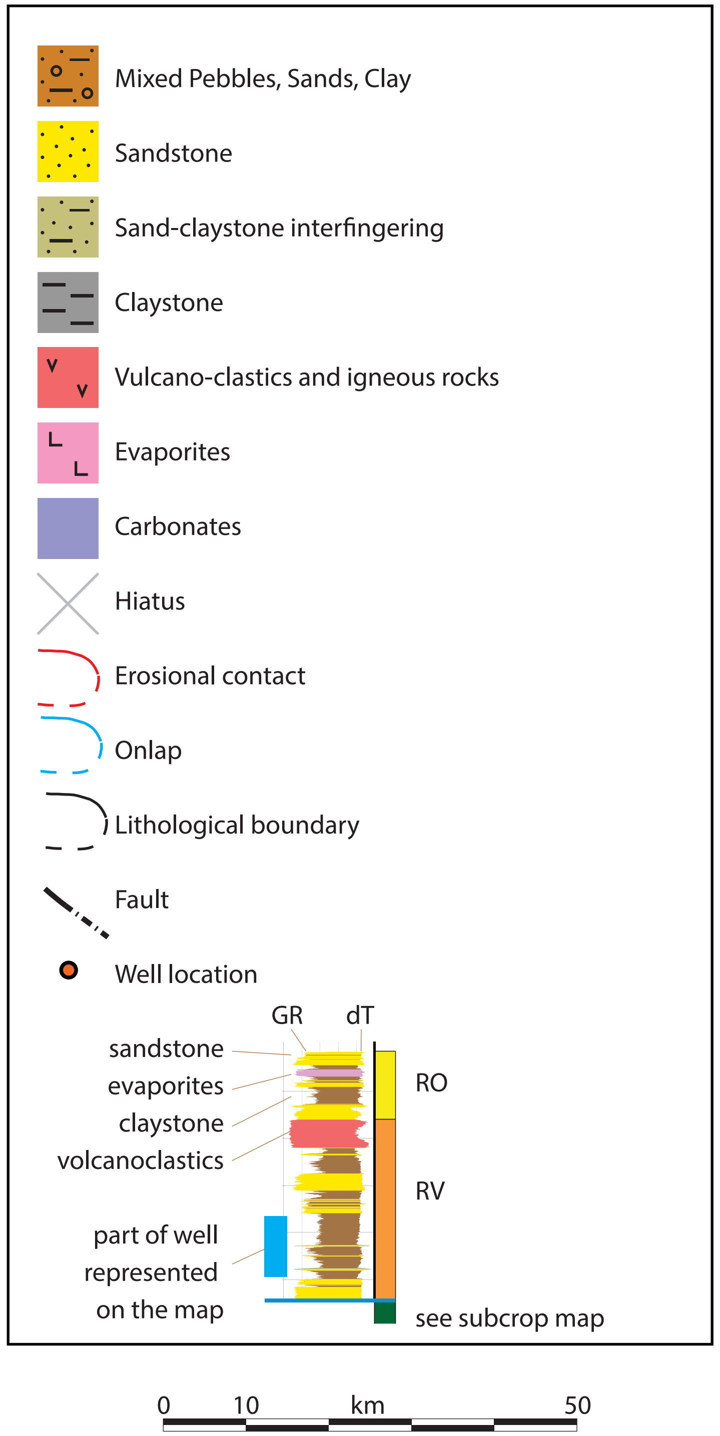

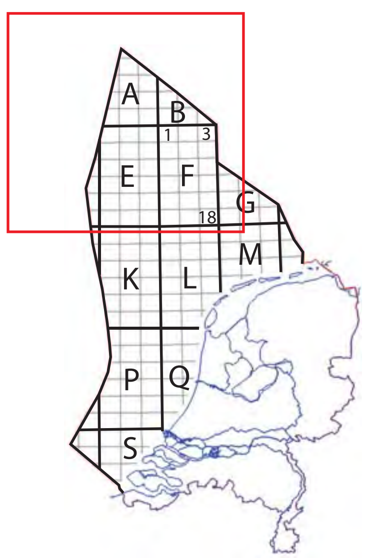

Appendix 7.04
Lower Rotliegend (RV) Lithological map
3 of 3

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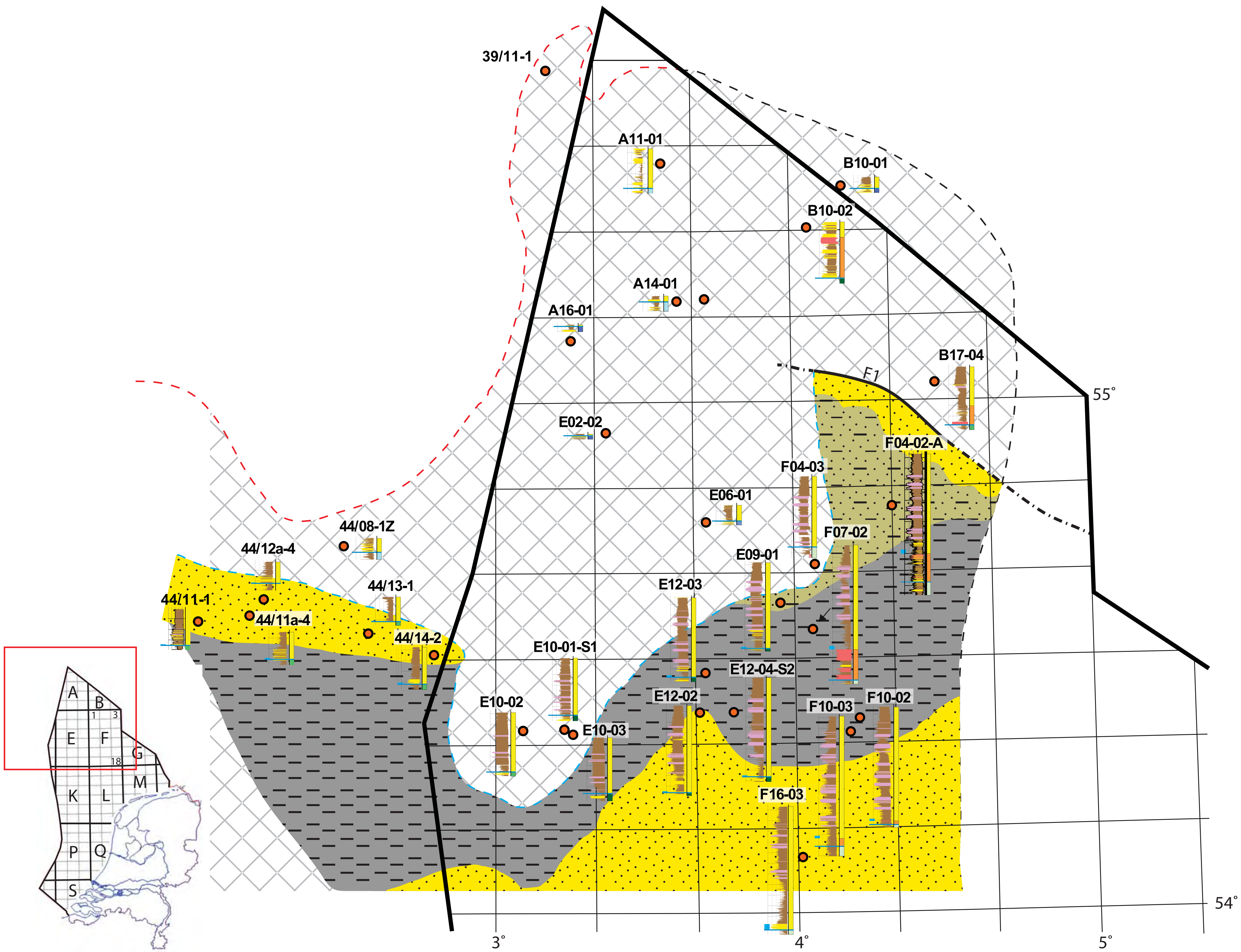

Mixed Pebbles, Sands, Clay
Sandstone
Sand-claystone interfingering
Claystone
Vulcano-clastics and igneous rocks
Evaporites
Carbonates
Hiatus
Erosional contact
Onlap
Lithological boundary
Fault
Well location

GR dT
sandstone
evaporites
claystone
volcanoclastics
RO
RV
part of well represented on the map
see subcrop map

0 10 km 50

Appendix 7.05
Upper Rotliegend (RO) Lithological map
1 of 5

New Petroleum plays in the Dutch Northern Offshore

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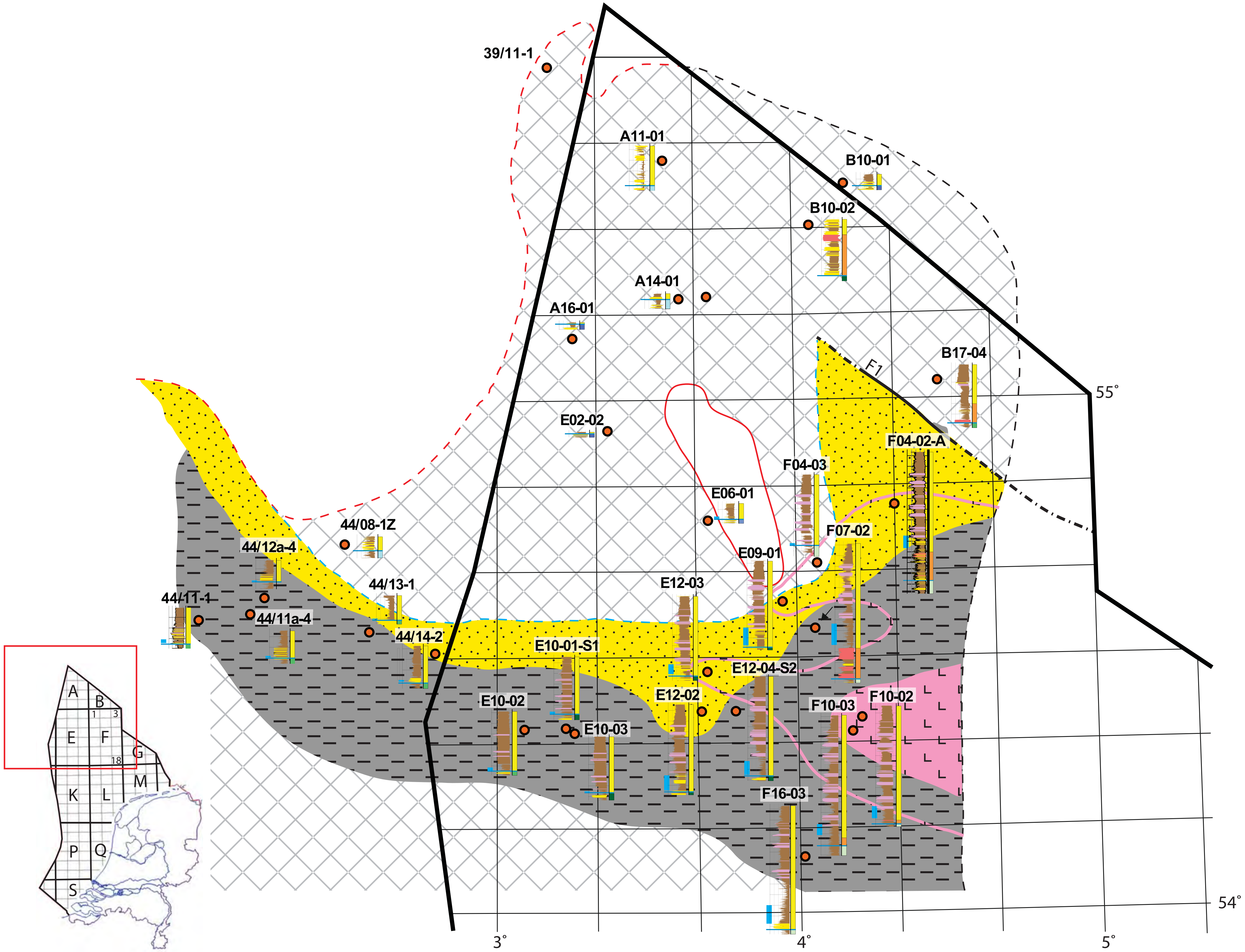

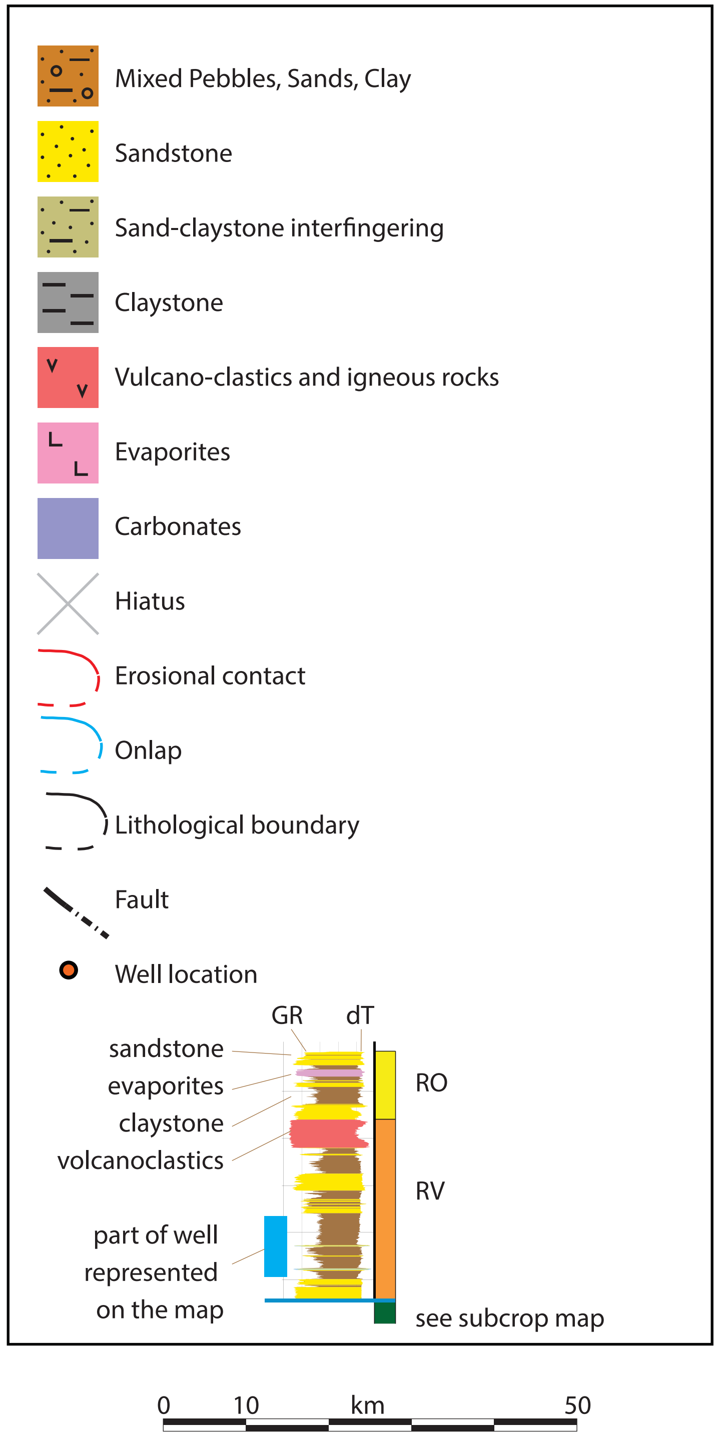

Appendix 7.06
Upper Rotliegend (RO) Lithological map
2 of 5

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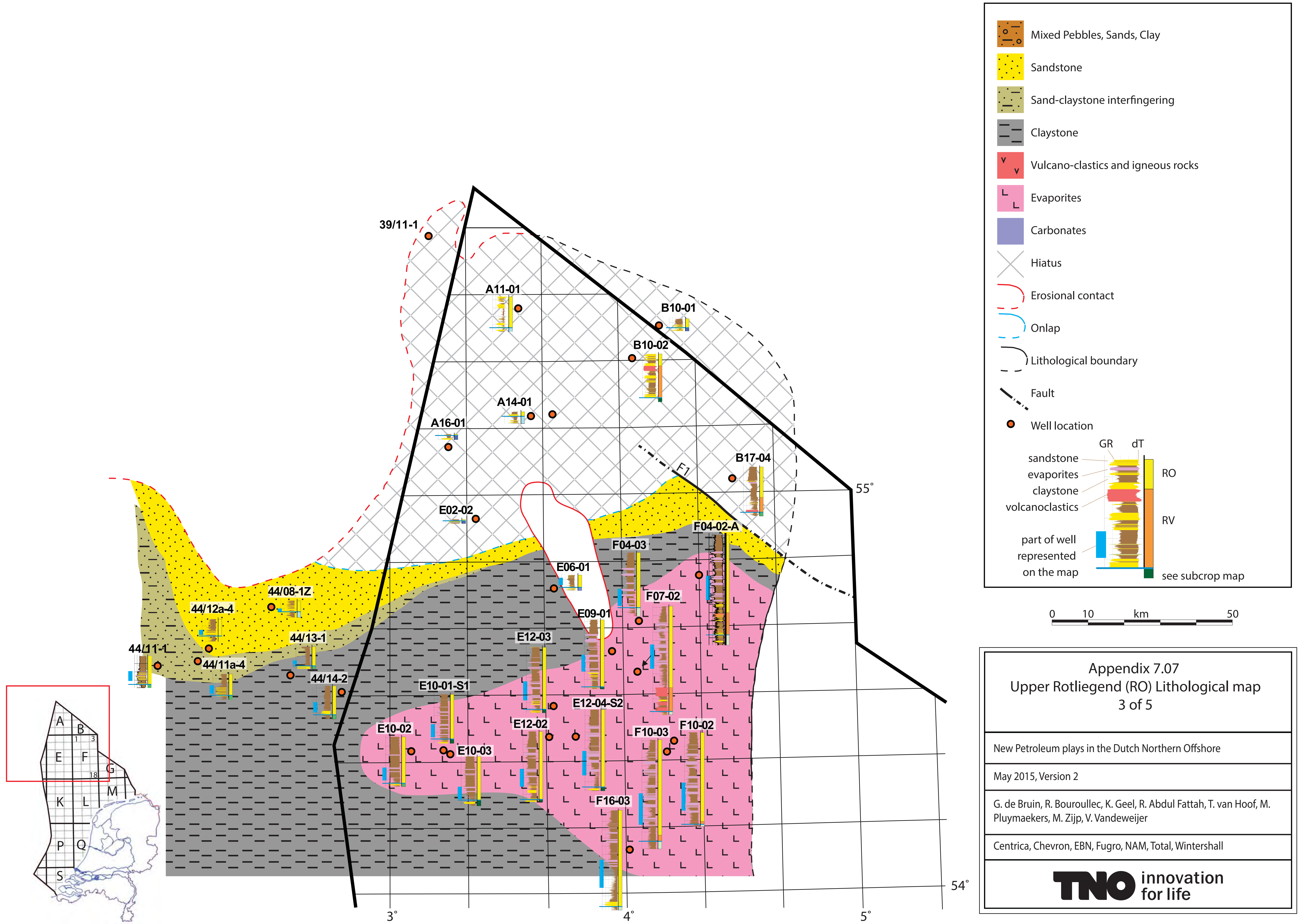

Appendix 7.07
Upper Rotliegend (RO) Lithological map
3 of 5

New Petroleum plays in the Dutch Northern Offshore

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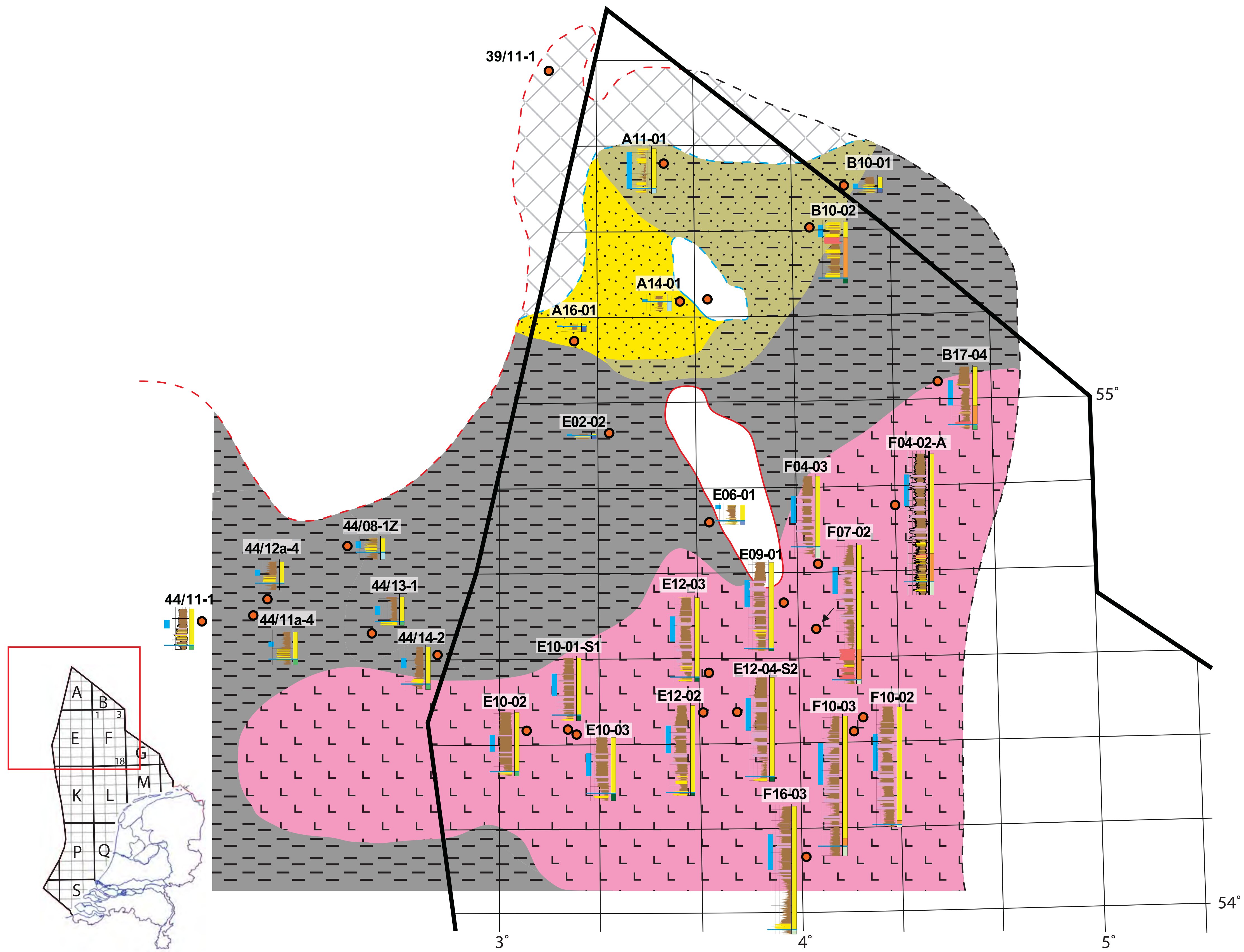

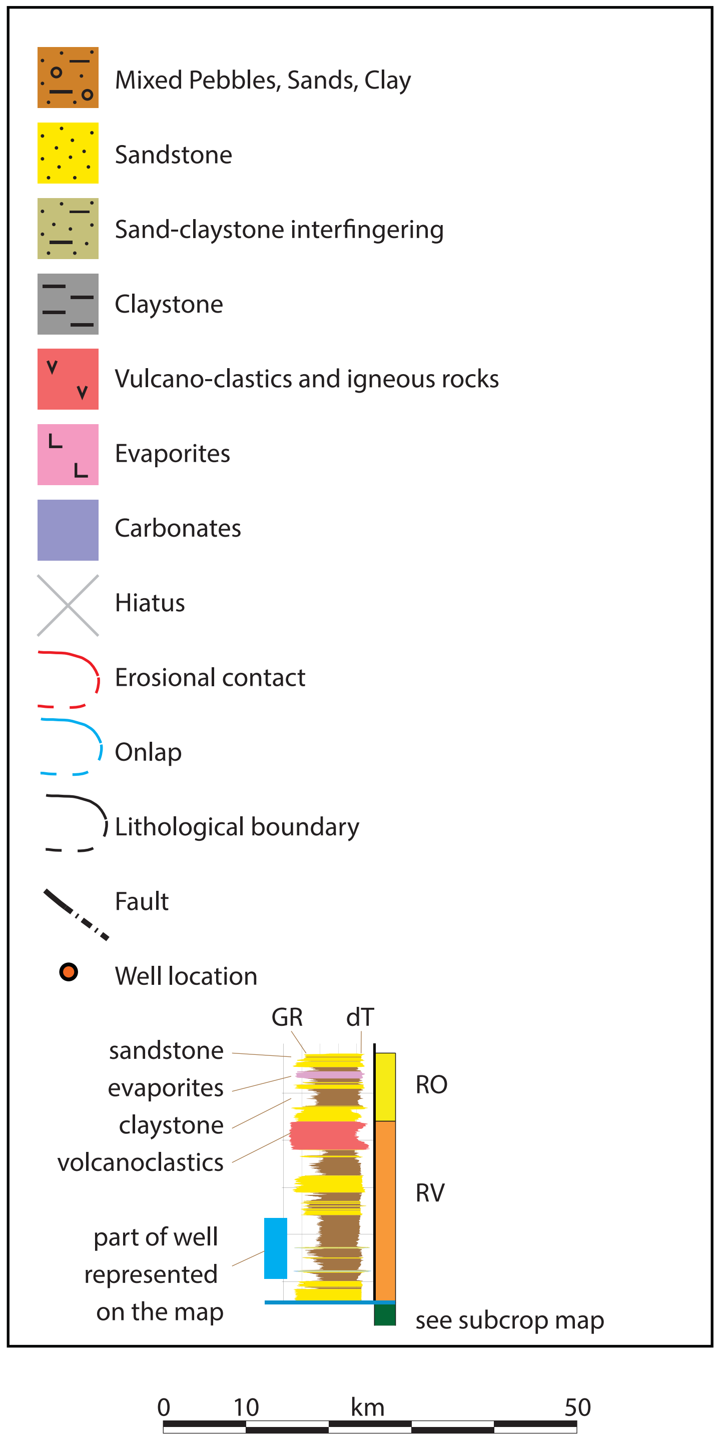

Appendix 7.08
Upper Rotliegend (RO) Lithological map
4 of 5

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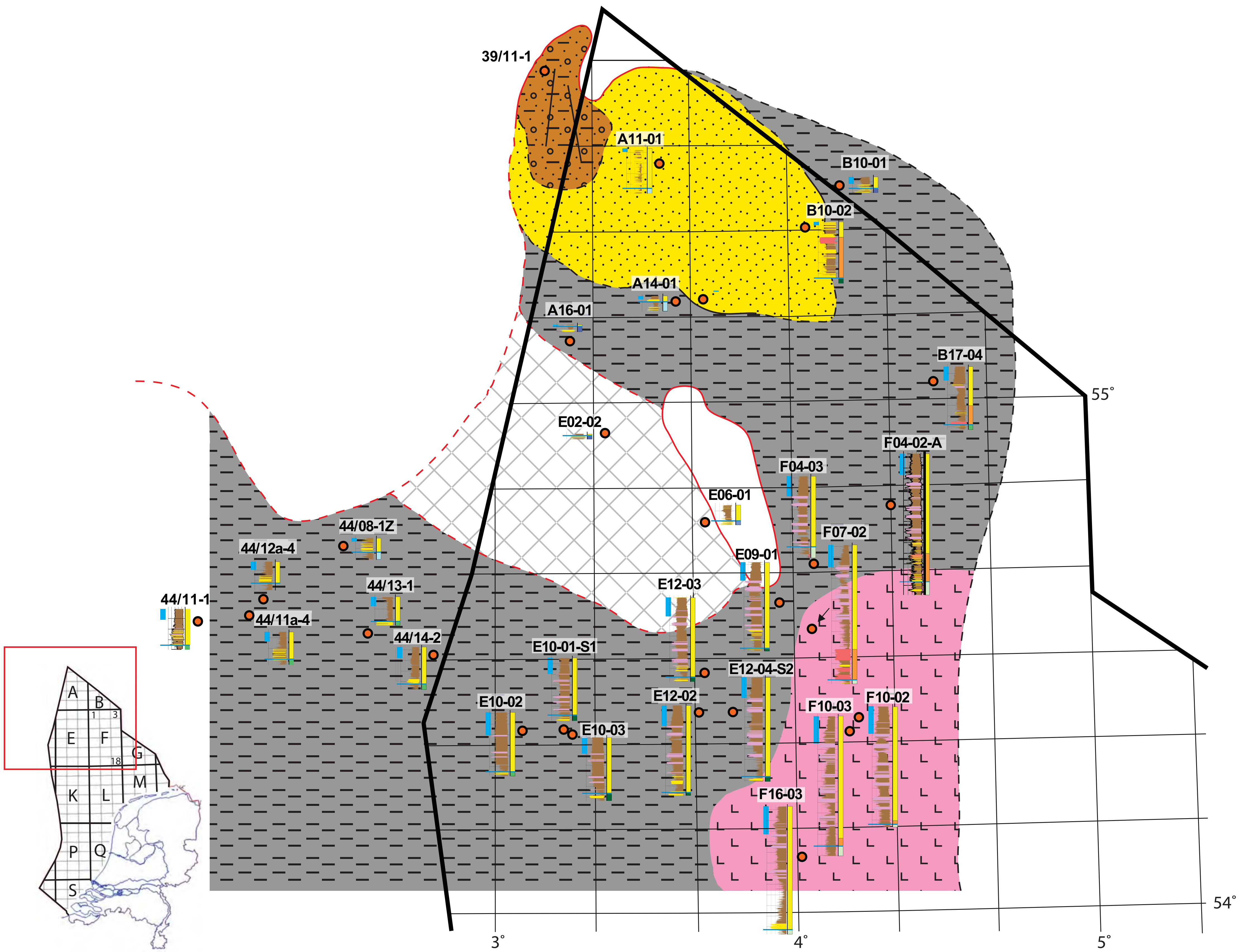

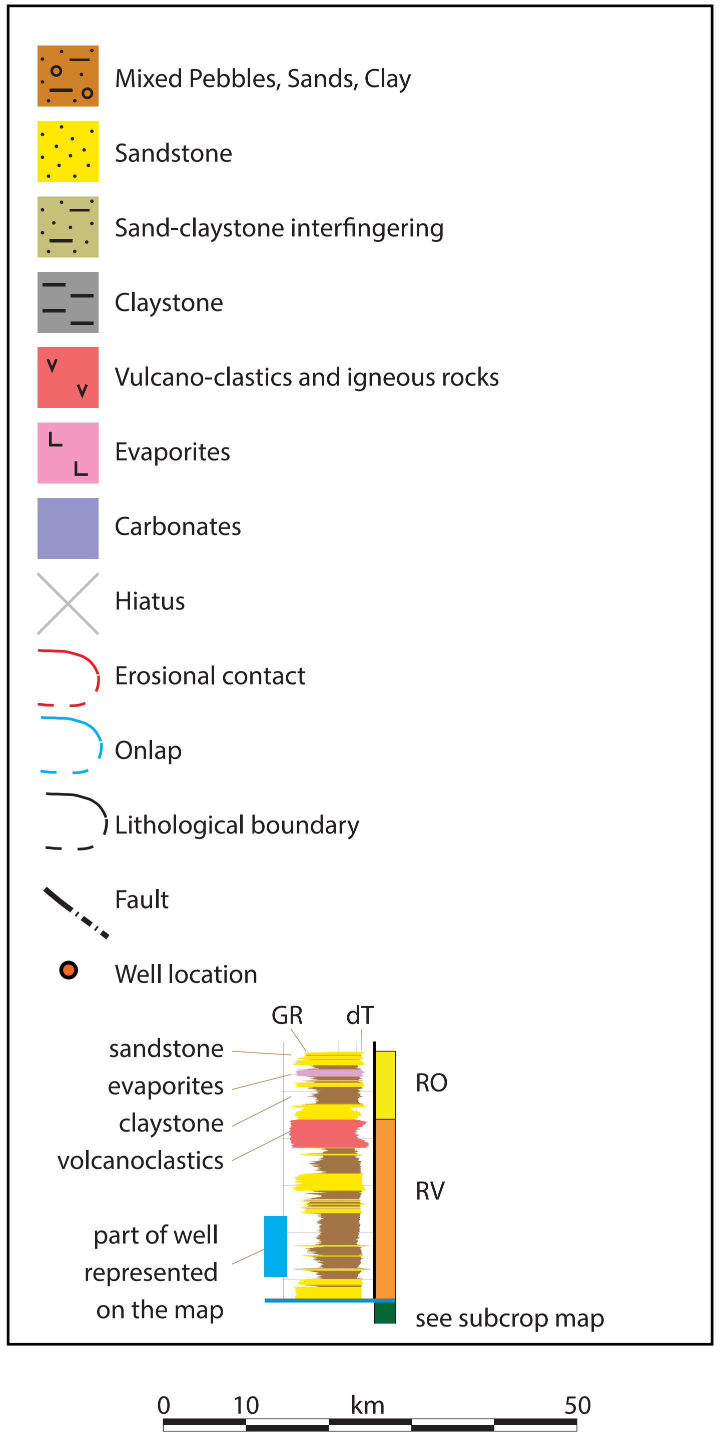

Appendix 7.09
Upper Rotliegend (RO) Lithological map
5 of 5

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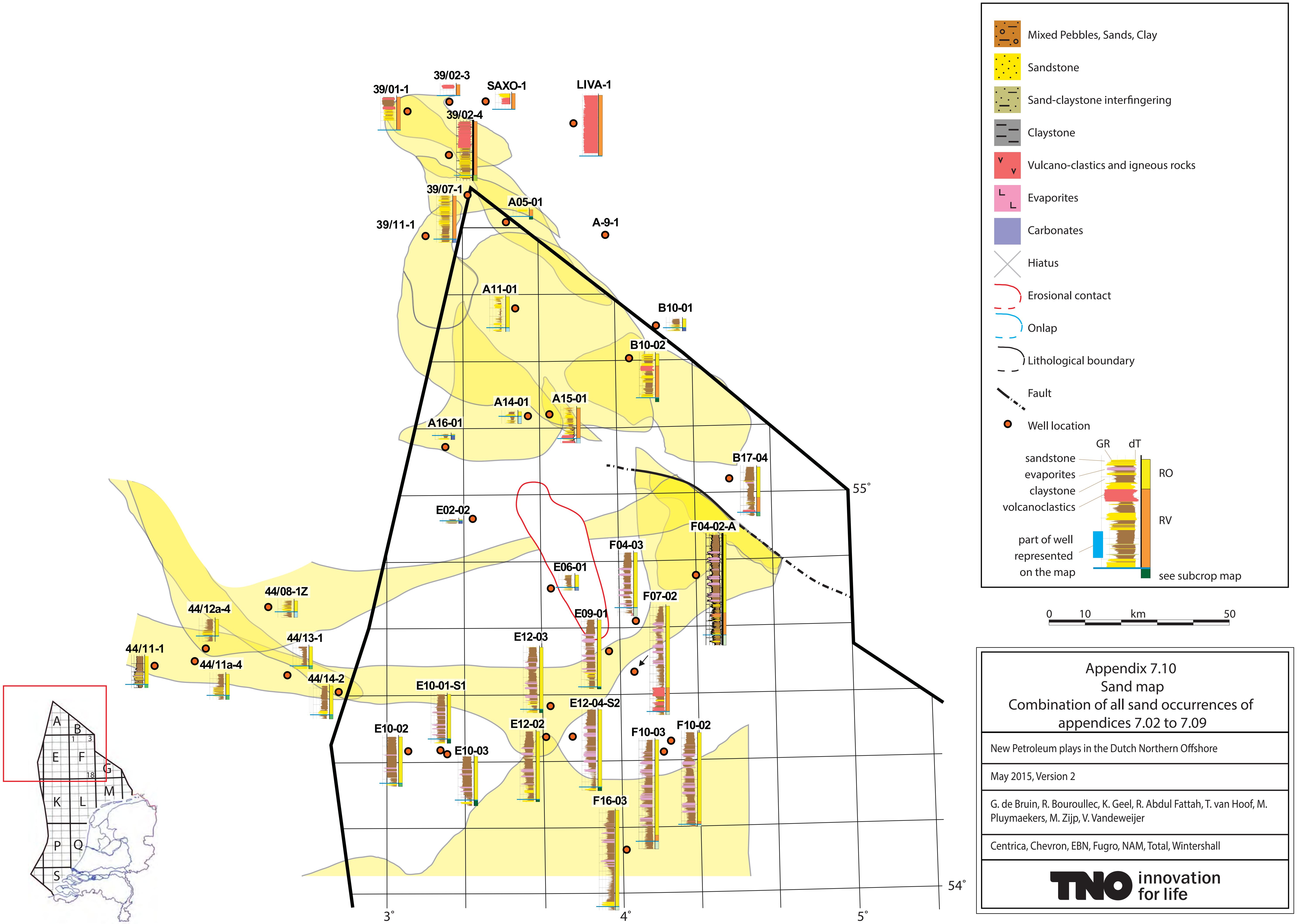

Appendix 7.10
Sand map
Combination of all sand occurrences of appendices 7.02 to 7.09

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May 2015, Version 2

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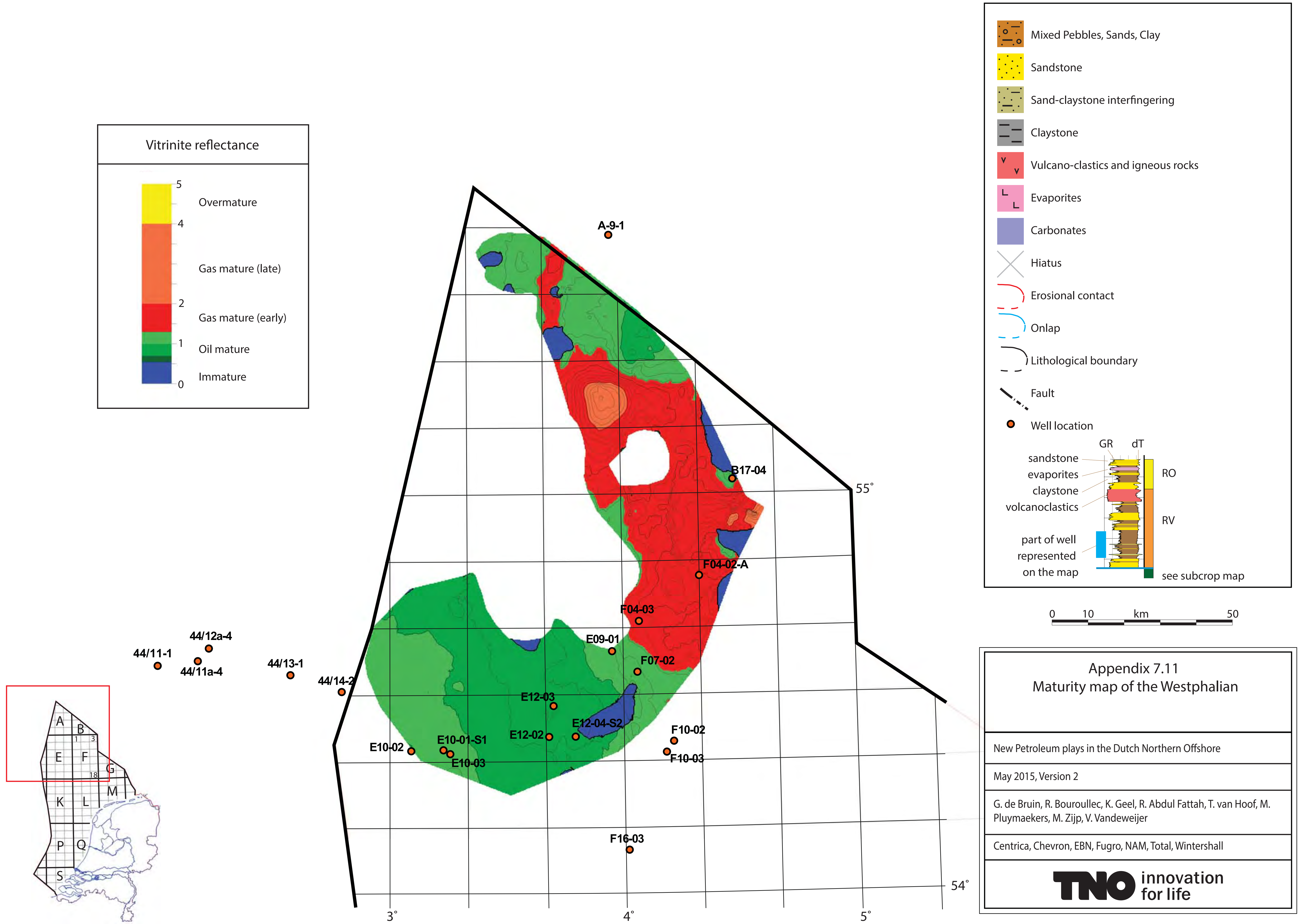

Appendix 7.11
Maturity map of the Westphalian

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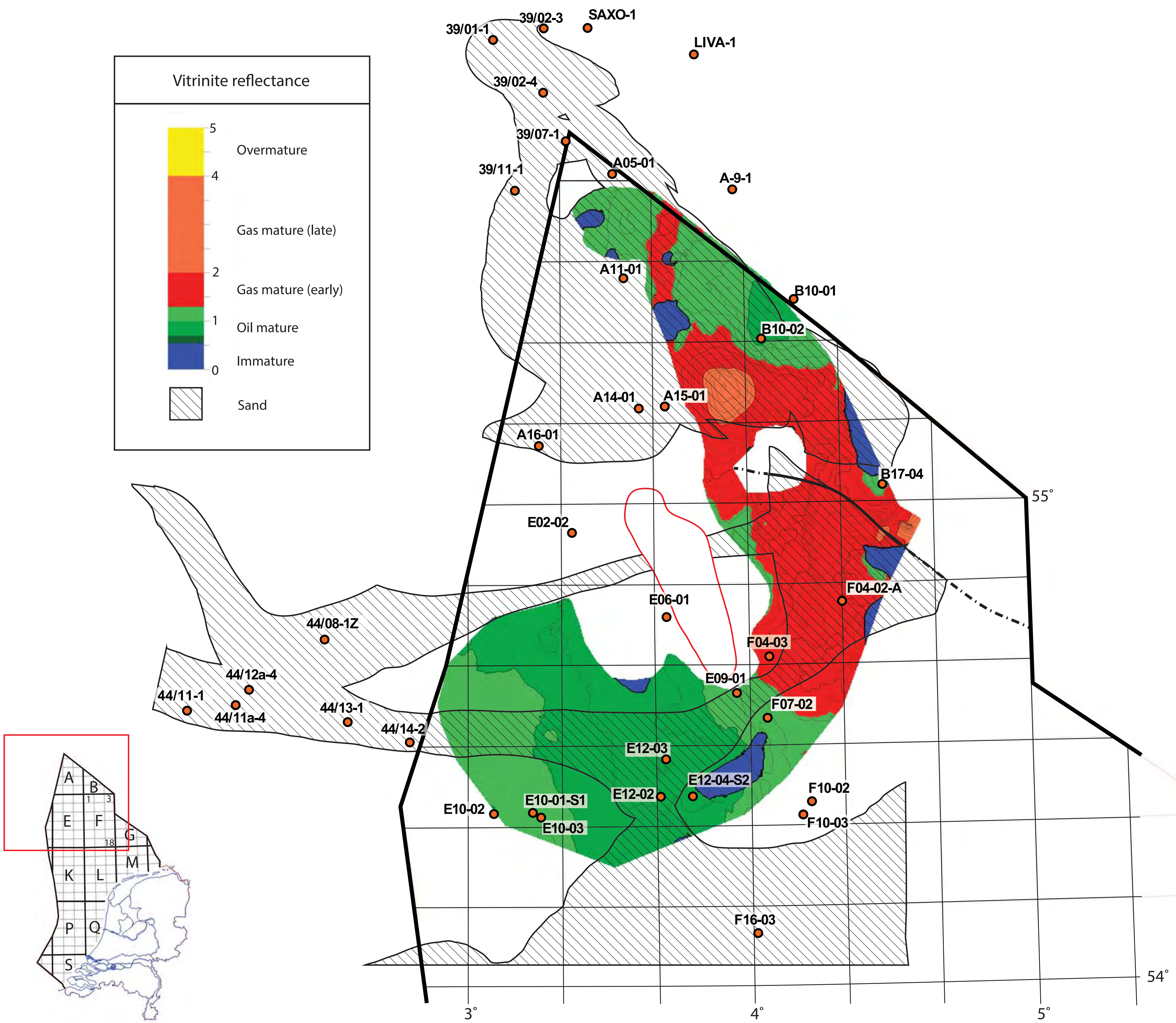

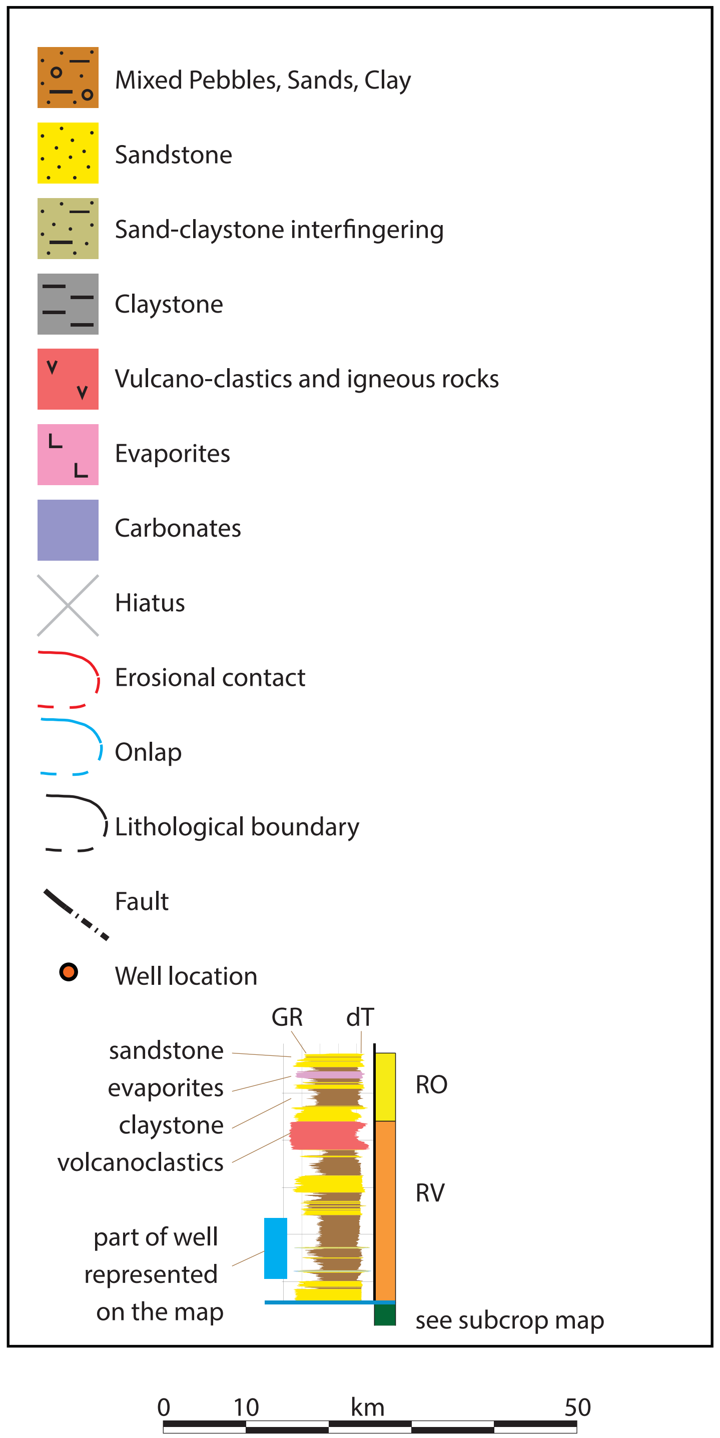

Appendix 7.12
Map of prospective regions
Combination of sand map and
Westphalian maturity map

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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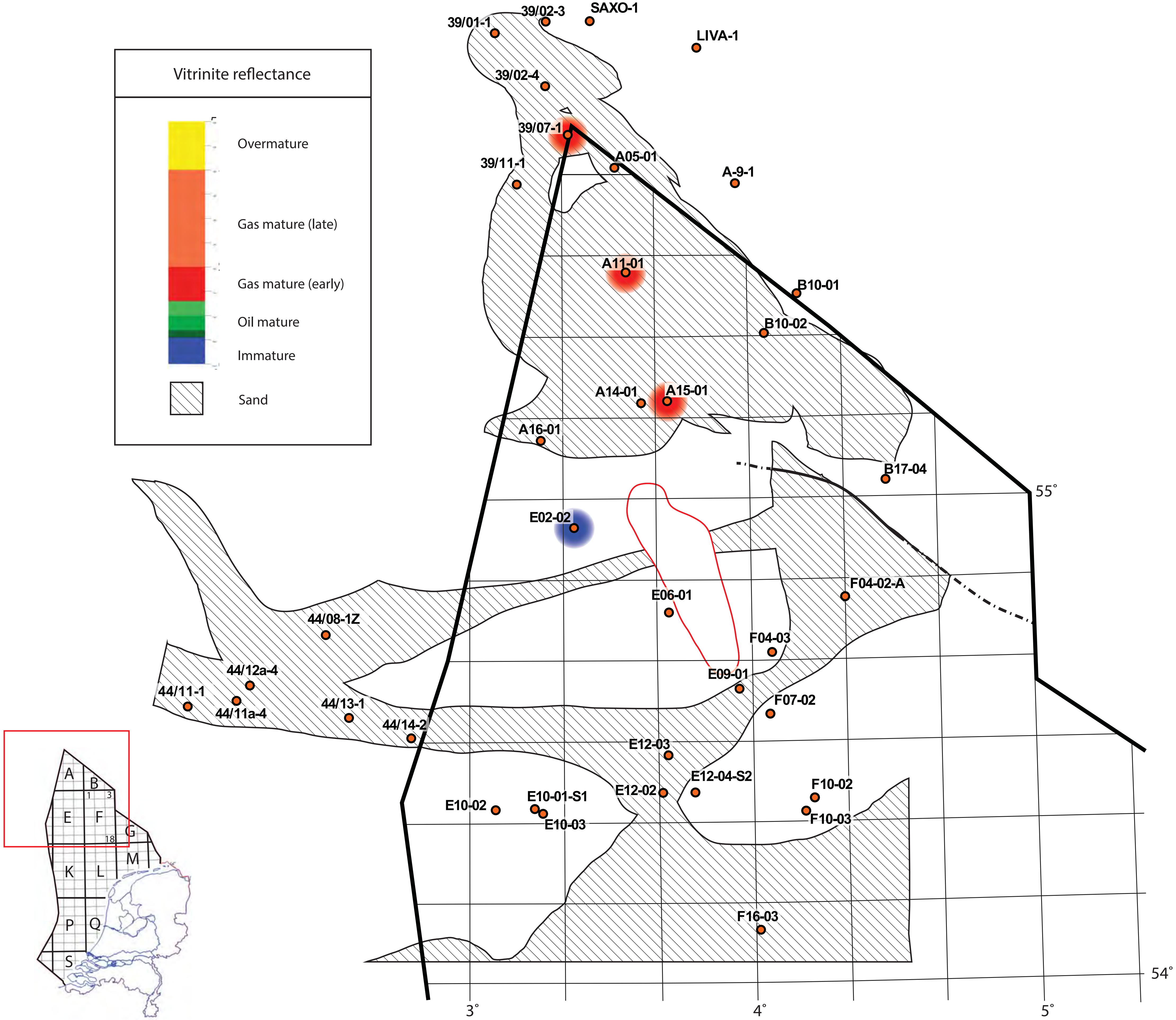

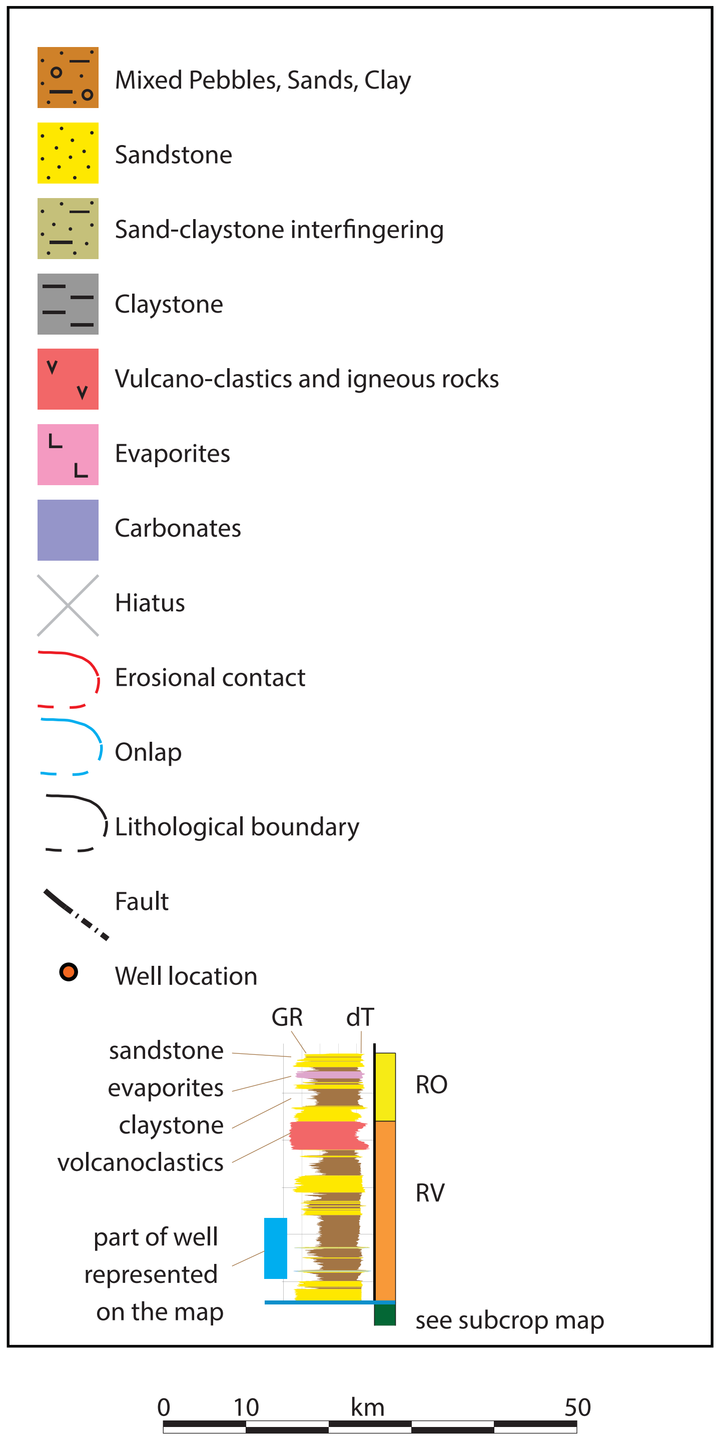

Appendix 7.13
Map of prospective regions
Combination of sand map and
maturity of Scremerston / Elleboog Fm.

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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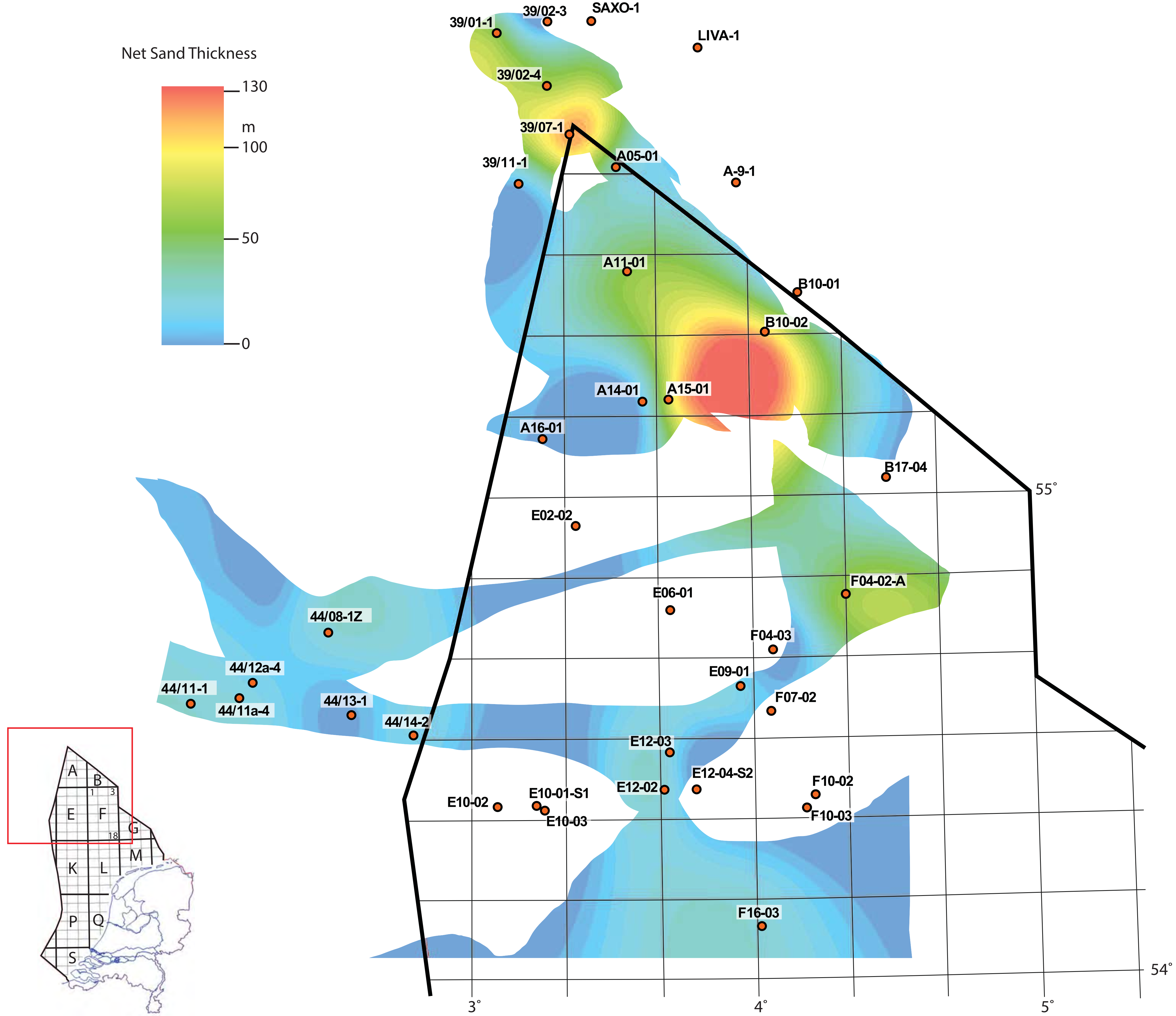

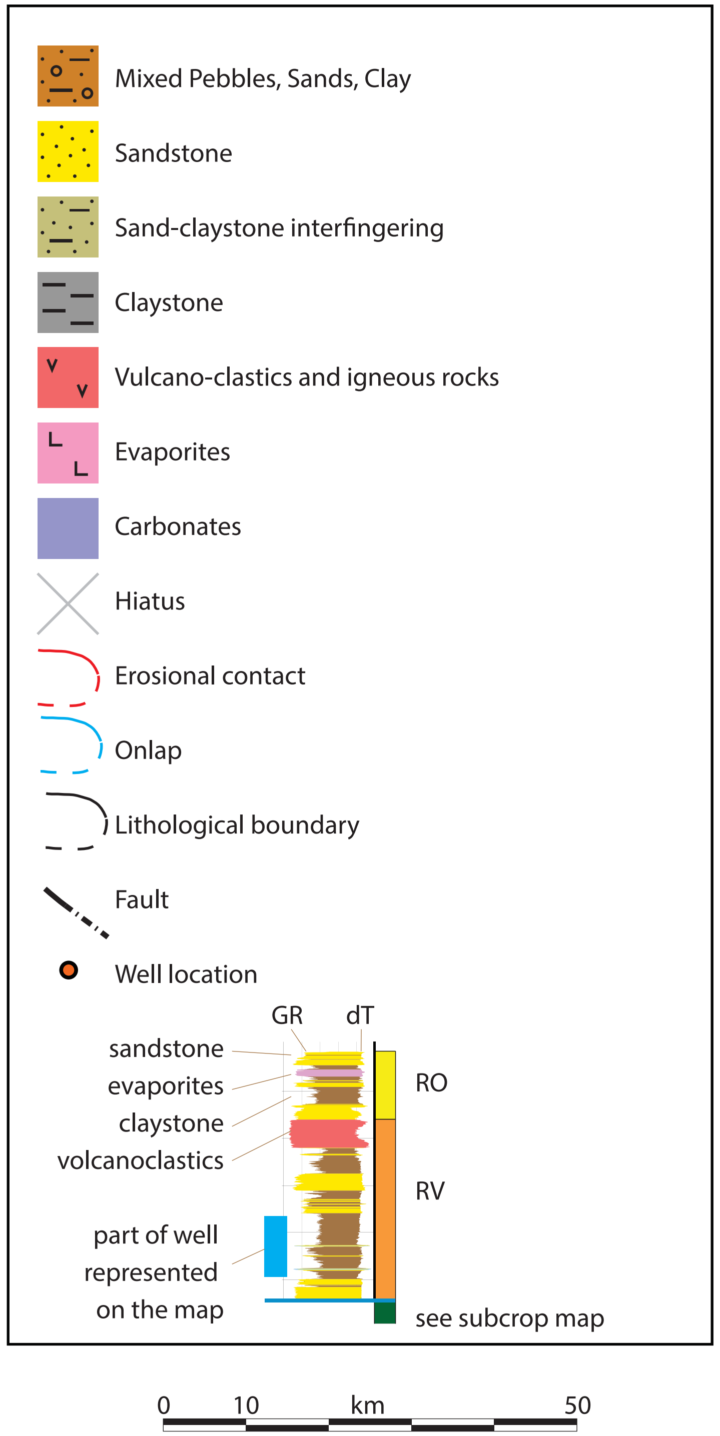

Appendix 7.14
Net Sand Map of the entire Rotliegend
(RO + RV)

New Petroleum plays in the Dutch Northern Offshore

May 2015, Version 2

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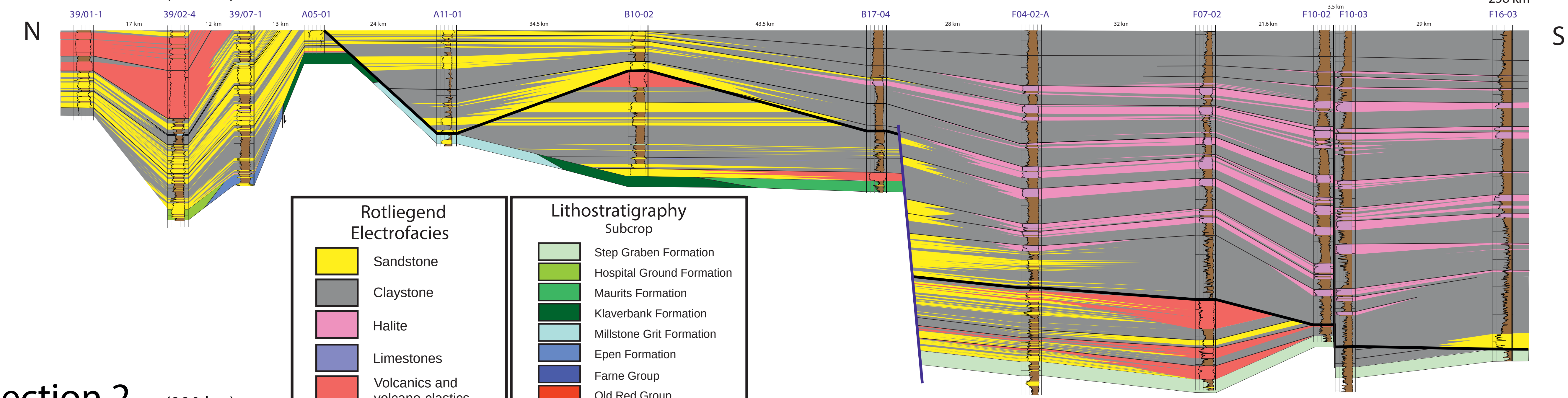
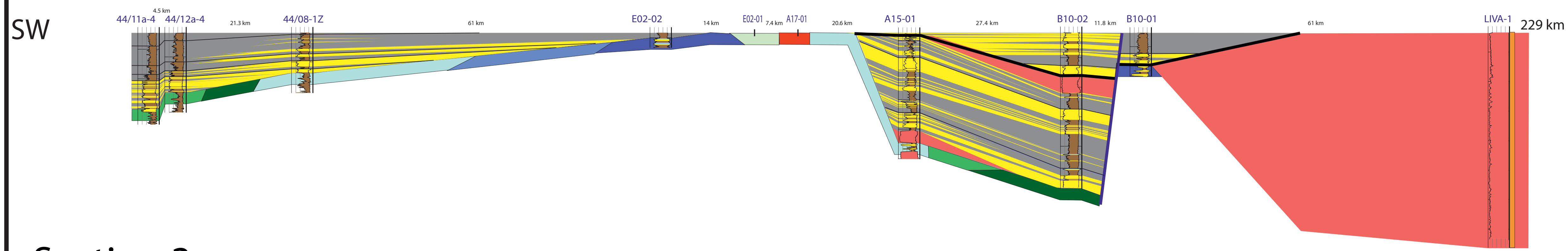
8 Stratigraphic Correlations

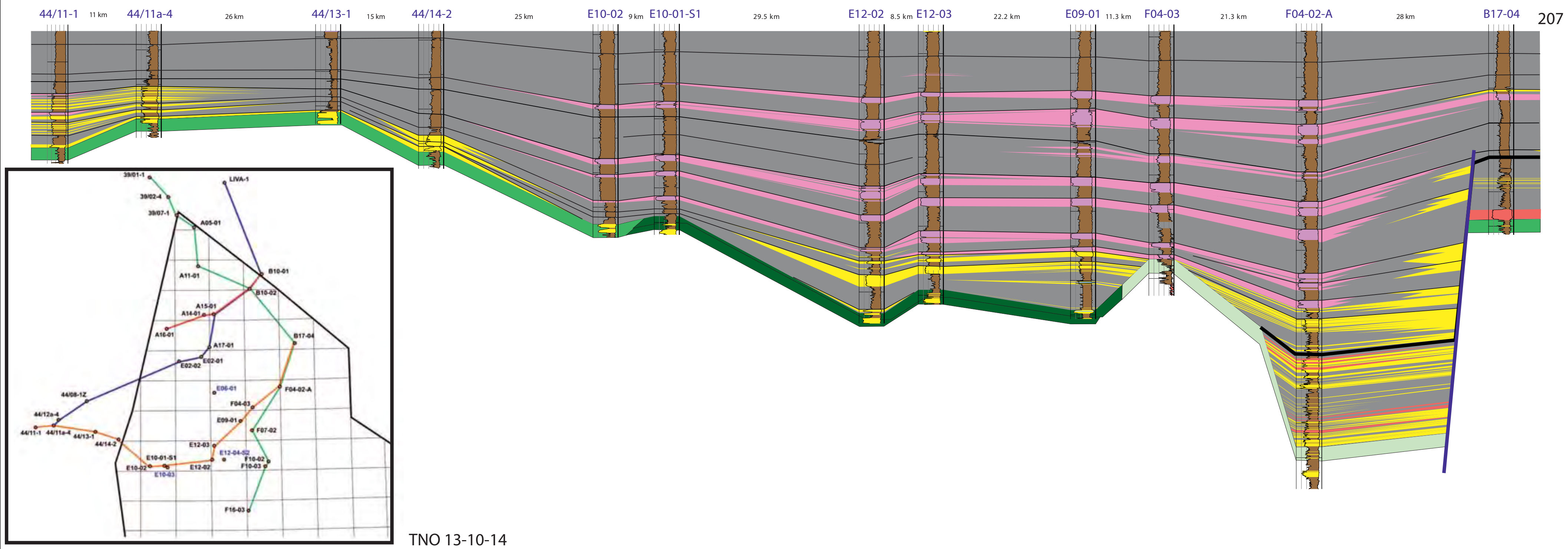
Section 1 (258 km)



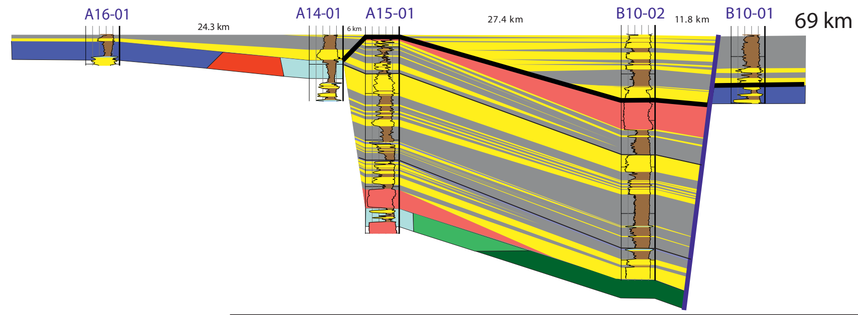
Section 2 (229 km)



Section 3 (196 km)



Section 4 (64 km)



TNO 13-10-14

Appendix 8
Rotliegend well correlation panels

New Petroleum plays in the Dutch Northern Offshore

Januari 2015, version 1

Geert de Bruin, Renaud Bouroullec, Kees Geel,
Rader Abdul Fattah, Tom van Hoof, Maarten Pluymaekers, Mart Zijp

Centrica, Chevron, EBN, Fugro, NAM, Total, Wintershall

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8.1 Cygnus Field

The Cygnus Field is located in UKCS Blocks 44/11a and 44/12a. It was discovered in 1988 by well 44/12-1. Although the field was initially deemed sub-commercial, it has now turned into the largest gas field discovery in the Southern North Sea for 25 years. Gross proven and probable reserves are estimated at around 18 bcm. It will start producing late 2015.

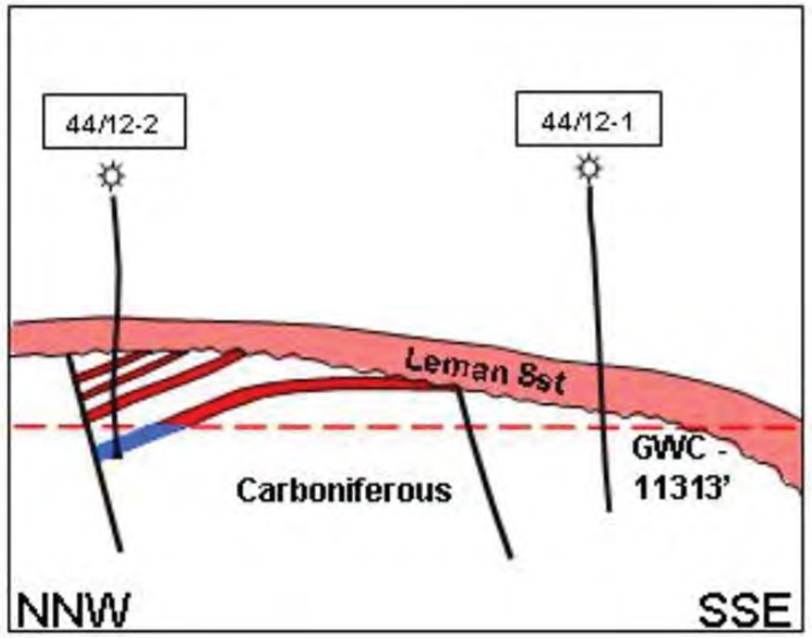


Figure 1 – Cross section through the Cygnus Field (Endeavour, 2007)

Gas is present in both Rotliegend and Carboniferous sandstones (see Figure 1). The Rotliegend sandstones are attributed to the Leman Sst (the UK equivalent of the Slochteren Sst), although it can be questioned whether these sandstones are actually connected to the Leman Sst further south.

In the Cygnus area, the Leman Sandstone Formation contains stacked parallel stratified sandstones, structureless sandstones and more steeply dipping (up to 30°) sandstones categorised as over-steep irregular/wavy laminated sandstones (Fig. 2). It has been interpreted as fluvially dominated sabkha deposits, where transport directions are mostly south to east (Walker, 2009; Figure 3).

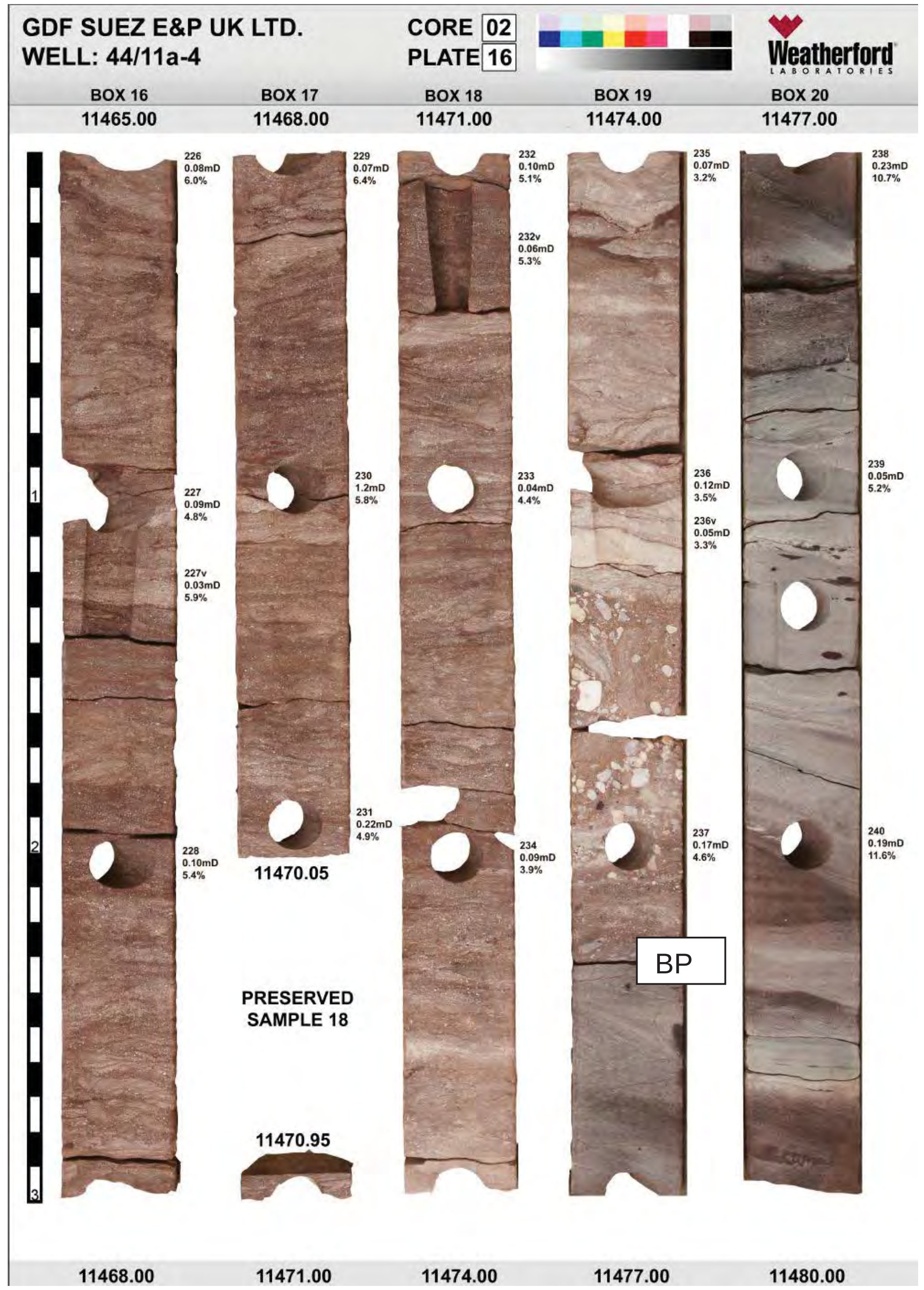


Figure 2 – Cygnus Field core (well 44/11a-4) showing northern fringe Upper Rotliegend sands with the BPU at 11476.5 ft, overlying Westphalian fluvial sands.

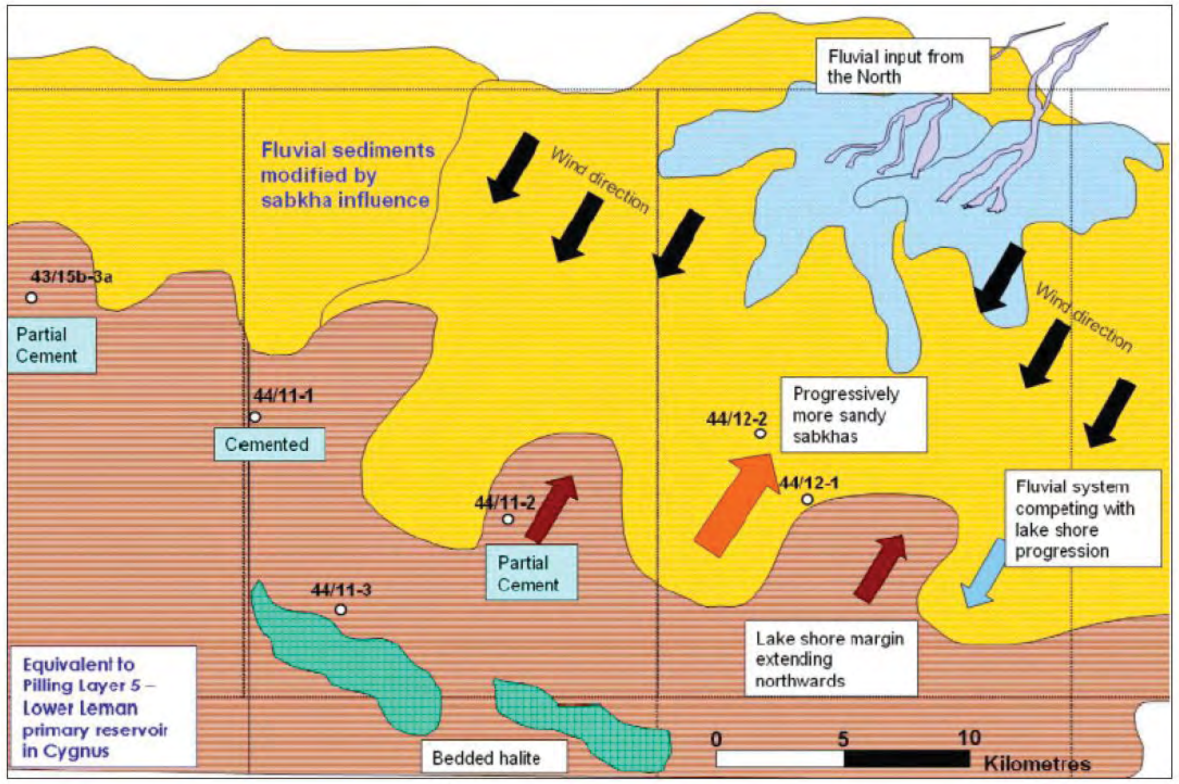
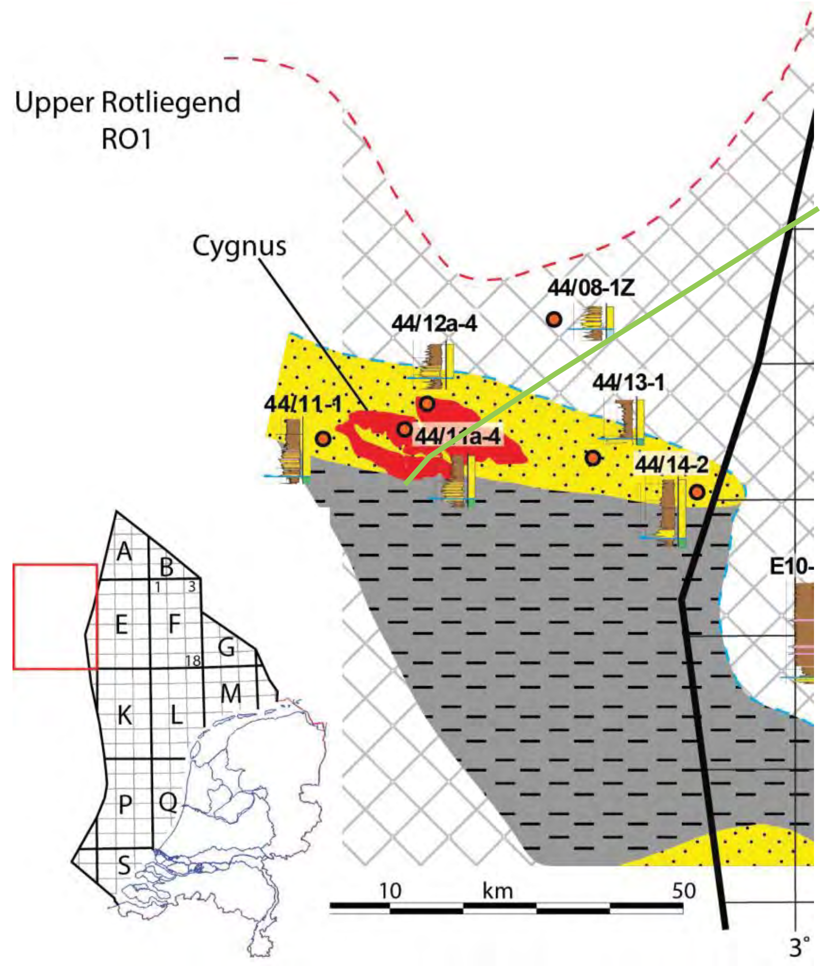


Figure 3 - Deposition of Leman sand (Rotliegendes) by northern trade winds (Eriksfiord, 2009).

Cygnus wells 44/11a-4 and 44/12a-4 are shown in the well sections 3 and 4, and Upper Rotliegend maps 1 and 3 (see Figuress 4 and 5). Both sections show a rapid thickening of the sands in West to Southwesterly direction, which fits well with the paleogeography deduced from image logs-based paleotransport directions.

Reservoir properties in the Rotliegend Sandstones are moderate to good. Porosities are between 10 and 20 %, permeabilities in the millidarcy range, with some thin streaks with tens of millidarcies permeability (Weatherford, 2010).



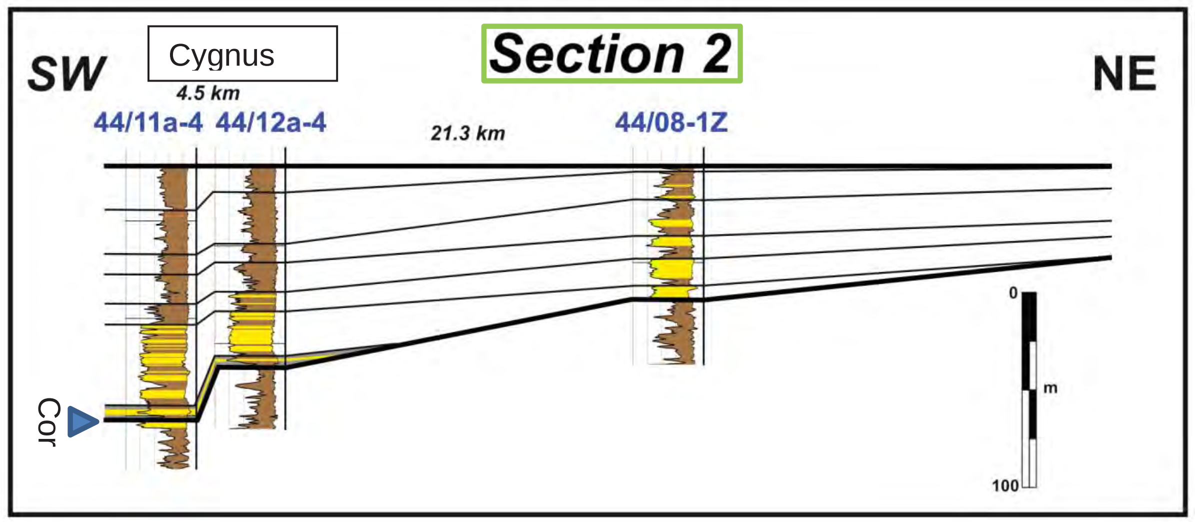
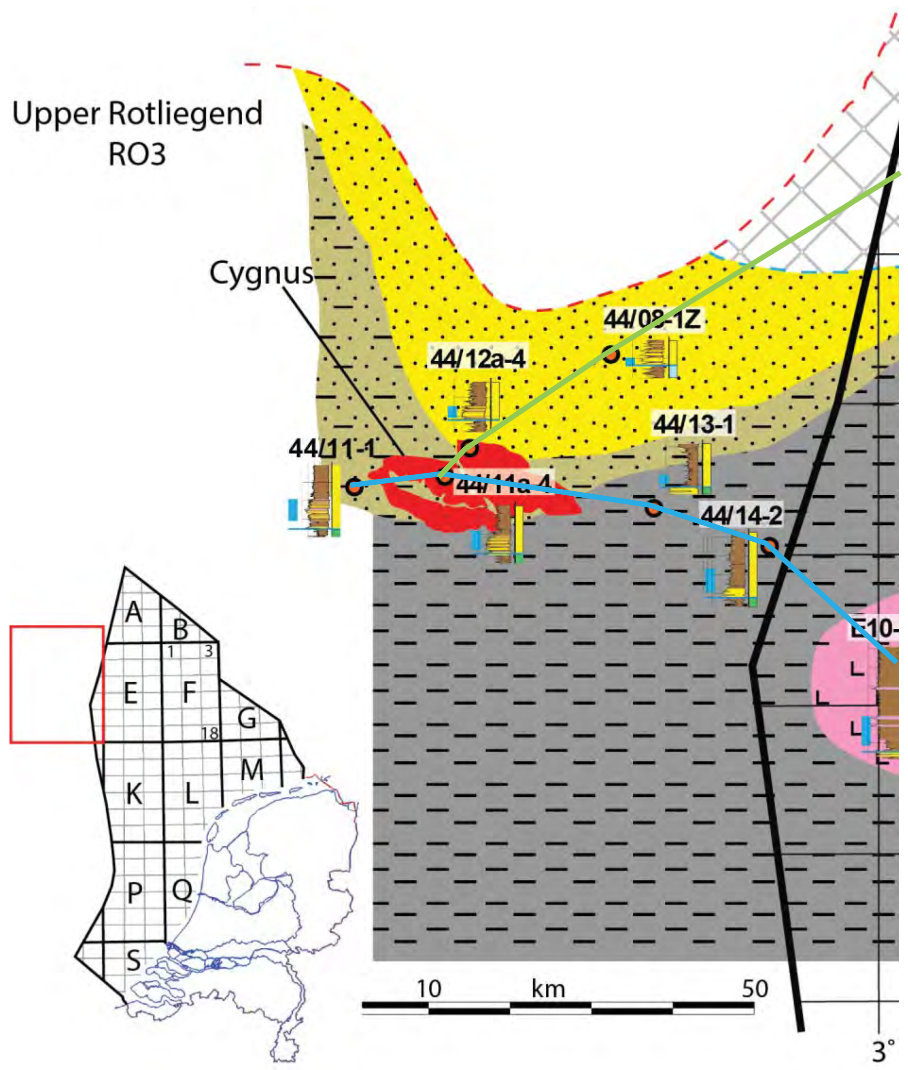


Figure 4: Internal stratigraphy of the oldest unit of the Upper Rotliegend (RO1). South western part of Section 2, a NE/SW oriented well correlation panel. The RO1 interval is represented by the colored interval. Blue triangle indicates the position of the core. Maps and panel have different scales



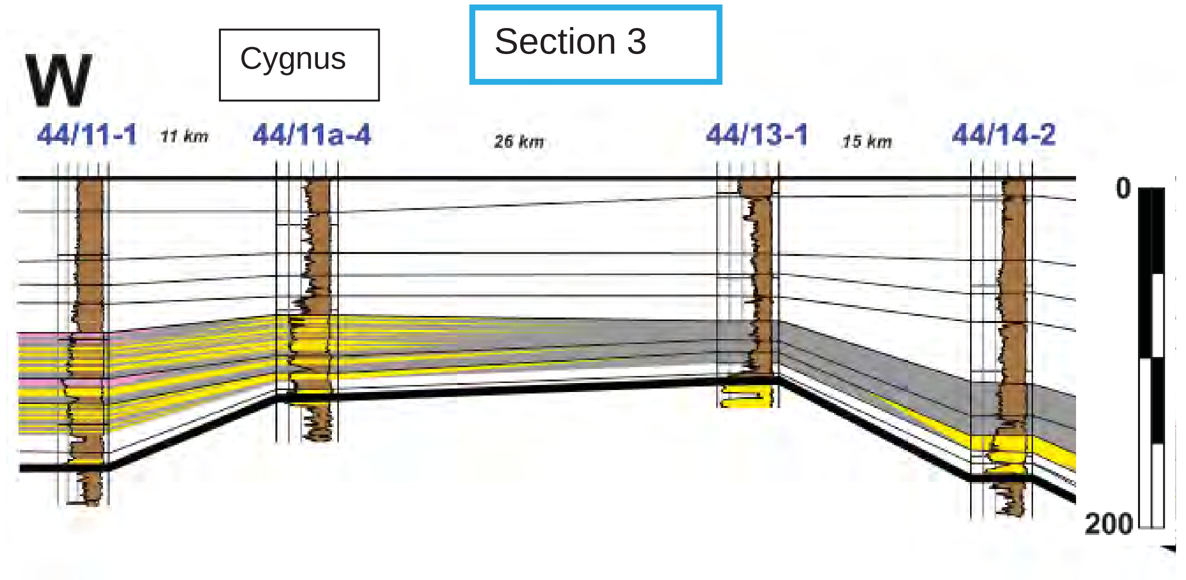


Figure 5: Internal stratigraphy of the middle unit of the Upper Rotliegend (RO3). Western part of Section 3, an E/W oriented well correlation panel and the southern part of Section 2, an SW-NE orientated well correlation pannel. The RO3 interval is represented by the coloured interval. Maps and panels have different scales

References

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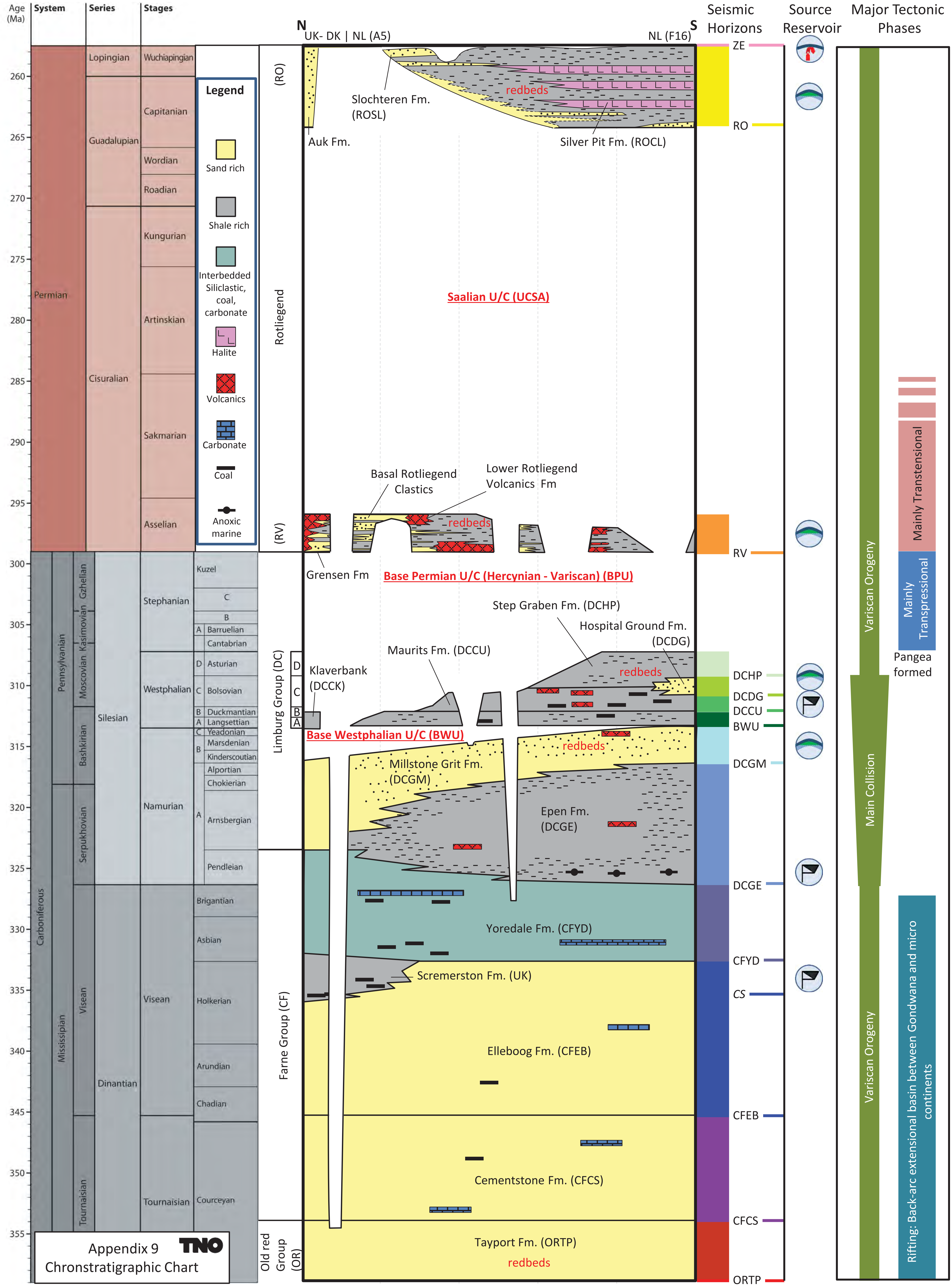
Walker, D (2010) Structural and sedimentological interpretation of Earth Imager and CBIL images from well 44/11a-4, Cygnus Field, UKSNS. Unpublished report, 59 p.

Weatherford (2010) Well: 44/11a-4 Conventional Core Analysis Final Report, Report Number CCA1014. Unpublished report, 124 p.

9 Chronostratigraphical Chart


Age (Ma)
System
Series
Stages
Permian
Lopingian
Guadalupian
Cisuralian
Wuchiapingian
Capitanian
Wordian
Roadian
Kungurian
Artinskian
Sakmarian
Asselian
Legend
Sand rich
Shale rich
Interbedded Siliclastic, coal, carbonate
Halite
Volcanics
Carbonate
Coal
Anoxic marine
Carboniferous
Pennsylvanian
Mississipian
Gzhelian
Kasimovian
Moscovian
Bashkirian
Serpukhovian
Visean
Tournaisian
Silesian
Dinantian
Stephanian
Westphalian
Namurian
Visean
Tournaisian
Kuzel
Barruelian
Cantabrian
Asturian
Bolsovian
Duckmantian
Langsettian
Yeadonian
Marsdenian
Kinderscoutian
Alportian
Chokierian
Arnsbergian
Pendleian
Brigantian
Asbian
Holkerian
Arundian
Chadian
Courceyan
(RO)
Rotliegend
(RV)
Limburg Group (DC)
Farne Group (CF)
Old red Group (OR)
N
UK- DK | NL (A5)
S
NL (F16)
Slochteren Fm. (ROSL)
redbeds
Auk Fm.
Silver Pit Fm. (ROCL)
Saalian U/C (UCSA)
Basal Rotliegend Clastics
Lower Rotliegend Volcanics Fm
Grensen Fm
Base Permian U/C (Hercynian - Variscan) (BPU)
Step Graben Fm. (DCHP)
Hospital Ground Fm. (DCDG)
Maurits Fm. (DCCU)
Klaverbank (DCCK)
Base Westphalian U/C (BWU)
Millstone Grit Fm. (DCGM)
Epen Fm. (DCGE)
Yoredale Fm. (CFYD)
Scremerston Fm. (UK)
Elleboog Fm. (CFEB)
Cementstone Fm. (CFCS)
Tayport Fm. (ORTP)
Seismic Horizons
ZE
RO
RV
DCHP
DCDG
DCCU
BWU
DCGM
DCGE
CFYD
CS
CFEB
CFCS
ORTP
Source Reservoir
Major Tectonic Phases
Variscan Orogeny
Main Collision
Mainly Transtensional
Mainly Transpressional
Pangea formed
Rifting: Back-arc extensional basin between Gondwana and micro continents
Appendix 9
Chronstratigraphic Chart
TNO