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Lithostratigraphic/ chronostratigraphic correlation profiles through the study area

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GENERAL INTRODUCTION

Work package 3 (WP3) of the GeoERA research project „3D Geomodeling for Europe (3DGEO-EU)" aims to integrate existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area between the Netherlands, Germany and Denmark. TNO – Geological Survey of the Netherlands (TNO, NL), the Geological Survey of Denmark and Greenland (GEUS, DK) and the Federal Institute for Geosciences and Natural Resources (BGR, DE) are responsible for the cross-border harmonization in this pilot area.

Harmonized stratigraphic charts for the NL-DE-DK North Sea area are presented in the Deliverable report 3.3: "Harmonized stratigraphic chart for the NL-DE-DK North Sea area", which provides an overview of the relationship of the Dutch, German and Danish North Sea lithostratigraphy.

In this report correlations of the Jurassic and the Rotliegend successions in the NL-DE-DK North Sea area are used to illustrate the stratigraphic variation in the study area and to identify the most essential parameters needed to ensure a successful harmonized cross-border 3D model.

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1 PROJECT BACKGROUND

1.1 Rationales and aims

Harmonization of geological data across geological, topographical, and especially across national borders is one of the most important work steps to create a base for trans-European assessments of resource potentials and possible conflicts of use of European subsurface. In the last decades a variety of different thematic maps were developed, but often not on a similar and consistent data base. Differences in the geological & geophysical interpretation (e.g. stratigraphy, velocity-model, structural interpretation, different methods of assessments) across the borders remain unchanged and were masked by generalizations in an overview scale. In the last years these "border-discontinuities" have become obvious by a variety of 3D-modeling projects. But workflows for harmonization of different geological 3D models are yet not established and proofed.

The GeoERA research project "3D Geomodeling for Europe (3DGEO-EU)" aims to show on the example of cross-border pilot areas (work packages 1 - 3) how harmonization across the borders can be established and maintained with the progress of the national models. The pilot area of work package 3 (WP3) spans thereby the offshore cross-border North Sea area between the Netherlands, Germany and Denmark. In this region, the partners TNO – Geological Survey of the Netherlands (TNO, NL), the Geological Survey of Denmark and Greenland (GEUS, DK) and the Federal Institute for Geosciences and Natural Resources (BGR, DE) intent to integrate existing national (and regional) geomodels into a harmonized, consistent cross-border geomodel of the North Sea area. One of the main tasks of WP3 in this context will be to find and exemplarily test efficient workflows for harmonization or the consistent translation between the established national concepts. The methodologic advantages (agreements on best practices, optimized workflows, etc.) and the gain in experience on cross-border 3D harmonization work will be a keystone for further transnational harmonization projects.

As part of the work integrating regional and national geomodels into a harmonized, consistent cross-border geomodel of the NL-DE-DK North Sea area a correlation of the regional lithostratigraphy are presented. This initial study presents the present-day status for the different countries. Differences in the geological and geophysical interpretation across the borders remain unchanged. The objectives of the study are to show the relationship of the Dutch, German and Danish lithostratigraphy.

Identifying lithostratigraphic discrepancies and their causes represents an important first step in the cross-border harmonization process. The purpose of this report is therefore to compilate and compare the Dutch, German and Danish lithostratigraphy in order to elucidate stratigraphic similarities and discrepancies between the three countries.

The comparison of the lithostratigraphic charts show much resemblances across the country borders, but it is also evident that there is a limitation for harmonization. Especially diachronous units are by nature difficult to correlate. The local distribution and diachronous appearance of specific lithofacies show that a detailed cross-border comparison is often only possible after time-consuming well log correlations applying sequence-stratigraphy. It is in the framework of this report to illustrate/explain the discrepancies in the lithostratigraphy charts as pointed out in report D3.3: “Harmonized stratigraphic chart for the NL-DE-DK North Sea area”.

The results from this report together with the stratigraphical charts in report D3.3: “Harmonized stratigraphic chart for the NL-DE-DK North Sea area” are essential parameters to ensure a successful harmonized cross-border 3D model.

2 MAJOR STRUCTURAL ELEMENTS

The study area is the Greater Central Graben area (*Figure 1*). The area comprises a number of structural elements with individual stratigraphic successions. Figure 1 shows the structural elements related to the Jurassic period. Structural element maps representing other geological periods will be included in the reports associated to the deliverables D3.5 to D3.8.

A lithostratigraphic breakdown for the most significant structural elements has been carried out in the three countries (Report D3.3: “Harmonized stratigraphic chart for the NL-DE-DK North Sea area”).

One significant and cross-border structural element is the Middle Jurassic–Lower Cretaceous Central Graben rift system (*Figure 1*). The Central Graben stretches 250 km from north to south, is 50 km wide on average, ranging from the Norwegian sector through Denmark and Germany and terminates in The Netherlands to the south.

Three depositional domains are distinguished: (1) the primary graben axis, which runs from the boundary of Norway and Denmark all the way to its southernmost tip in the L05 Block in The Netherlands and includes the Søgne Basin, the Tail End Graben, the Salt Dome Province, the German Central Graben and the Dutch Central Graben; (2) the basins adjacent to the graben, which include the Heno and Gertrud plateaus, the Feda Graben in Denmark and the Terschelling Basin in The Netherlands; and (3) the plateau areas which received little or no sediments during the Middle Jurassic–Early Cretaceous rift phase, including the Inge and Mads highs, the Outer Rough Basin, the Step Graben and the Schillgrund, Central Offshore and Cleaverbank platforms in The Netherlands.

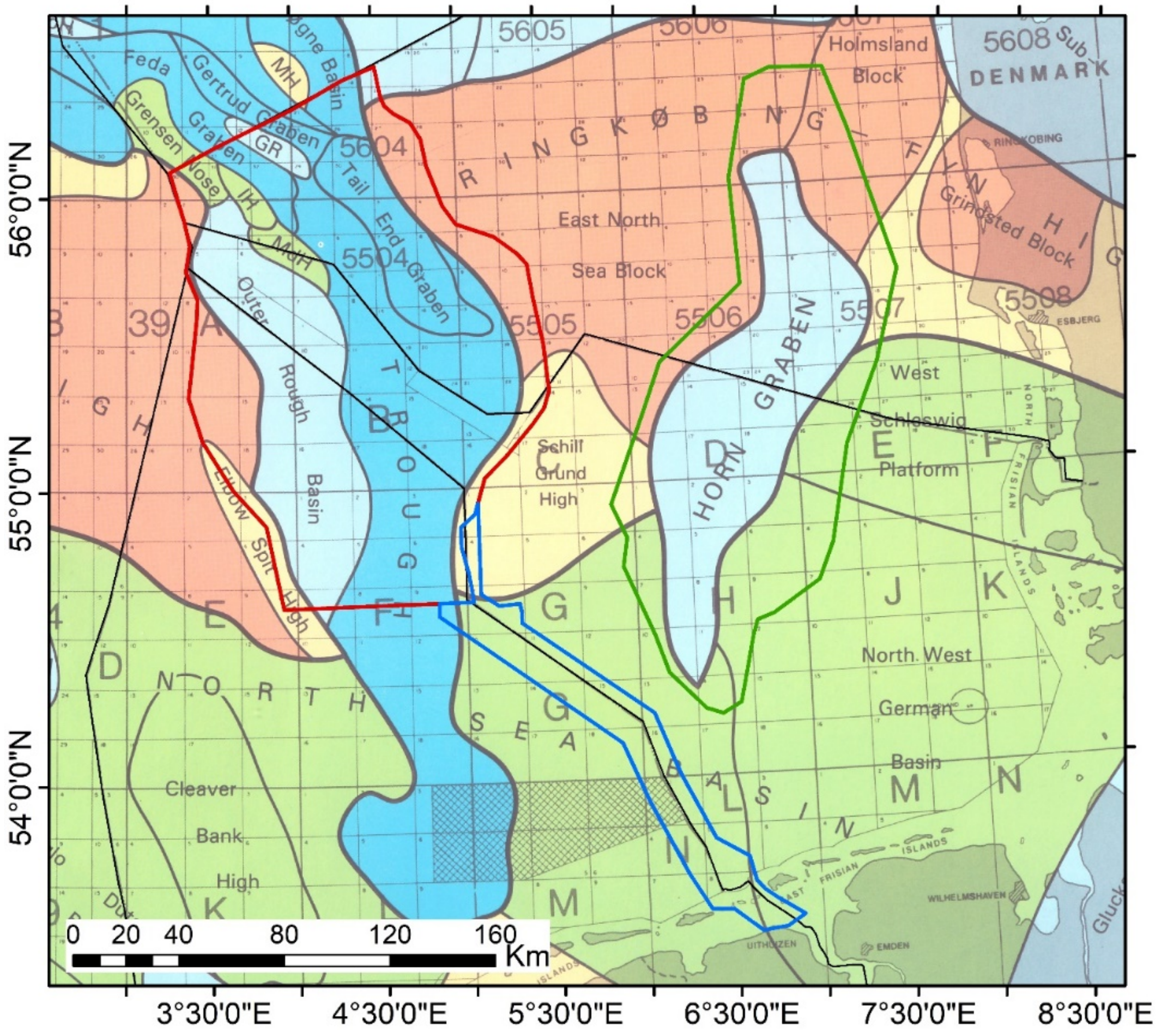

Figure 1. Structural element map for the NL, DE, DK North Sea areas. The study areas for the 3DGEO-EU cross-border pilot study are highlighted in red, blue & green (Thöle et al. 2019). Base map from NOPEC (1988).

3 CORRELATION PROFILES

The comparison of the lithostratigraphic charts for the Danish, German and Dutch Central Graben shows the disparities between national nomenclatures, but also differences in basin development and depositional environment (lateral differences in the distribution of the various lithologies). The stratigraphic succession shows large lateral variation and changes in lithofacies associated with a diachronous development of the Central Graben. A correlation and harmonization between these formations can therefore only be achieved by a detailed chronostratigraphic log-correlation applying a sequence stratigraphic approach.

In order to harmonize the lithostratigraphy between Denmark, Germany and The Netherlands a cross-border correlation of 1) the Jurassic succession in the Central Graben and 2) the Rotliegend succession across the Mid North Sea High have been carried out. The correlation panels are an attempt to demonstrate the relationship and discrepancies in the lithostratigraphy established for the Danish, German and Dutch sectors.

The cross-country comparison of the lithostratigraphy is hampered by differences in nomenclature, differences in the degree of details in the subdivision of the stratigraphic intervals and differences in basin development. The correlation panels in this study have been generated on the basis of slightly different data provided by GEUS, BGR and TNO. An attempt is made to standardize the data by introducing a common layout and color coding of the lithology. Each well is presented by a GR/DT log, a lithology log and a lithostratigraphic column. In the panels the nationally accepted lithostratigraphic nomenclature is used as well as the national correlation is applied.

Due to the current legal situation in Germany, the German wells have to be anonymized in the correlation panels and the logs from these wells have been removed in the log-correlation panels in this report. Only the interpreted formations are shown in the panels together with the depth scale. The logs, however, have been used for correlation purposes.

3.1 Jurassic log-correlation

3.1.1 Jurassic log-panel (Encl. 1)

The Jurassic sedimentary succession was correlated along the axis of the Central Graben from the Danish offshore in the north through the German offshore sector to the Dutch North Sea in the south. The wells used for the cross-border correlation are presented by a GR/DT log, a lithology log and a lithostratigraphic column (*Figure* 2 and Encl. 1. For location see *Figure 3*).

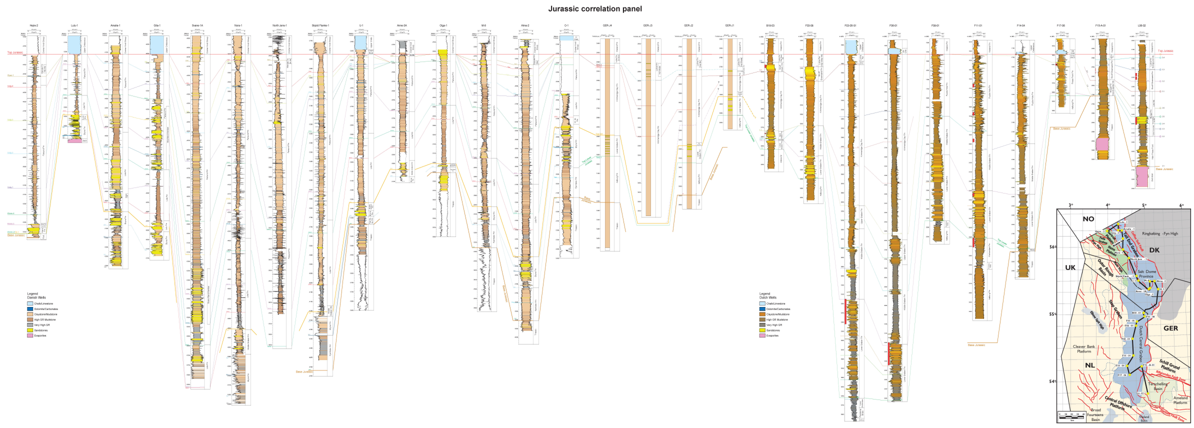

Figure 2. A N-S log correlation of the Jurassic succession between wells in the Danish, German and Dutch Central Graben. The Jurassic log correlation panel is enclosed at the end of this report (Enclosure 1).

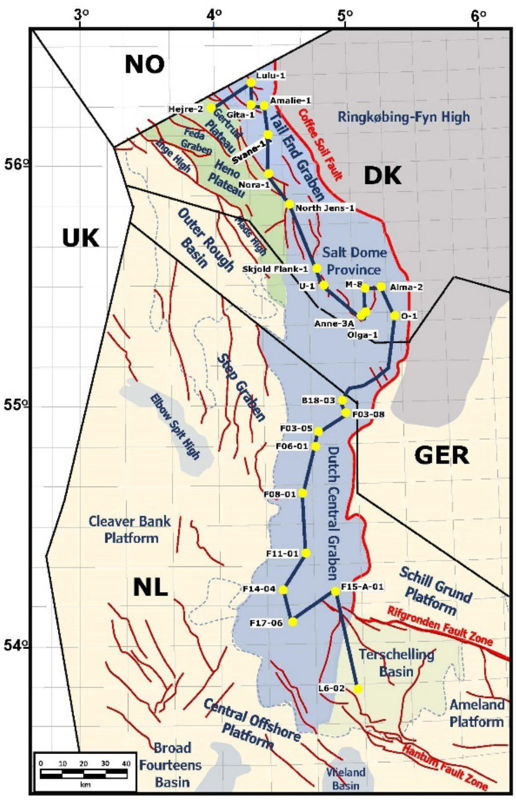

Figure 3. Path of Jurassic correlation profile.

The cross-border correlation is primarily based on the sequence stratigraphic and tectonostratigraphic subdivision of the Jurassic established in Denmark and in the Netherlands. No detailed stratigraphy is available for the German offshore sector. However, the tectonostratigraphic mega-sequences (TMS) defined and described by Verreussel et al. (2018) and Bouroullec et al. (2018), were recently extrapolated and mapped by Müller et al. (in prep) into the German sector of the Central Graben. These seismically mapped horizons facilitate the cross-border correlation with the German wells.

3.1.2 Lithostratigraphy

The lithostratigraphic subdivision of the Jurassic in the Danish, German and Dutch sector is presented in the report D3.3: "Harmonized stratigraphic chart for the NL-DE-DK North Sea area". For the Danish and Dutch wells, the nationally accepted lithostratigraphic nomenclatures are used in the log panel (*Figure 2* and Encl. 1.). For the German wells, the lithostratigraphic subdivision of the Jurassic follows the nomenclature of the Netherlands (Van Adrichem Boogaert & Kouwe 1993-1997). The Dutch terms were adopted here because the Dutch formations were recently mapped by Müller et al. (2019) into the German Central Graben and no formal classification at formation or group level has been so far established for this area of the German North Sea.

The Jurassic succession displays large variations and changes in lithofacies from the basin axis to the adjacent basins and platforms. Deepest marine conditions are in the Tail End Graben (Denmark), more shallow marine conditions prevail in the Southern Central Graben and Terschelling Basin (The Netherlands). The late Jurassic rifting activated faults and salt movement. As a result, the differential vertical movement occurred on a local scale, leading to the diachronous occurrence of lithostratigraphic units.

3.1.3 Jurassic Sequence- and Tectono-stratigraphy

A sequence stratigraphic subdivision of the Jurassic has been carried out in Denmark and the Netherlands.

The sequence stratigraphy for the Jurassic succession in the Danish Central Graben is the result of the PETSYS project and represents a modification of the sequence stratigraphy introduced by Andsbjerg & Dybkjær (2003). The Exxon Group concept is applied for the sequence stratigraphic subdivision (Posamentier et al. 1988; Posamentier & Vail 1988; Van Wagoner et al. 1988). Each sequence is confined by a lower and an upper sequence boundary (SB) and is subdivided into transgressive systems tracts (TST) and a highstand systemstract (HST). The two systems tracts are separated by a maximum flooding surface (MFS). The sequence stratigraphic breakdown for the Danish area is shown in Figure 4.

In the Dutch sector four tectonostratigraphic mega-sequences (TMS) and nine subordinate sequences (TS) are defined and described (Verreussel et al. 2018¸ Bouroullec et al. 2018). Based on detailed palynological analysis and supported by seismic data interpretation (Bouroullec et al. 2018), it has been possible to define a series of tectonostratigraphic mega-sequences (TMS) that reflect the stepwise basin evolution of the Late Jurassic rift phase of the Central Graben. These studies build on earlier work from TNO-Geological Survey of the Netherlands on the Dutch Central Graben (Herngreen et al. 2003; Van Adrichem Boogaert & Kouwe 1993; Abbink et al. 2006; De Jager 2007; Lott et al. 2010; Munsterman et al. 2012).

The mega-sequences are integrated with palynological zonation allowing
1) determination of timing of the rift phases (*Figure 4*) and
2) comparison of the sequences established for the Danish sector (*Figure 4*).

The sequence stratigraphic subdivision in Danish and Dutch Central Graben is compared with the maximum flooding surfaces established by Partington et al. (1993) (*Figure 4*).

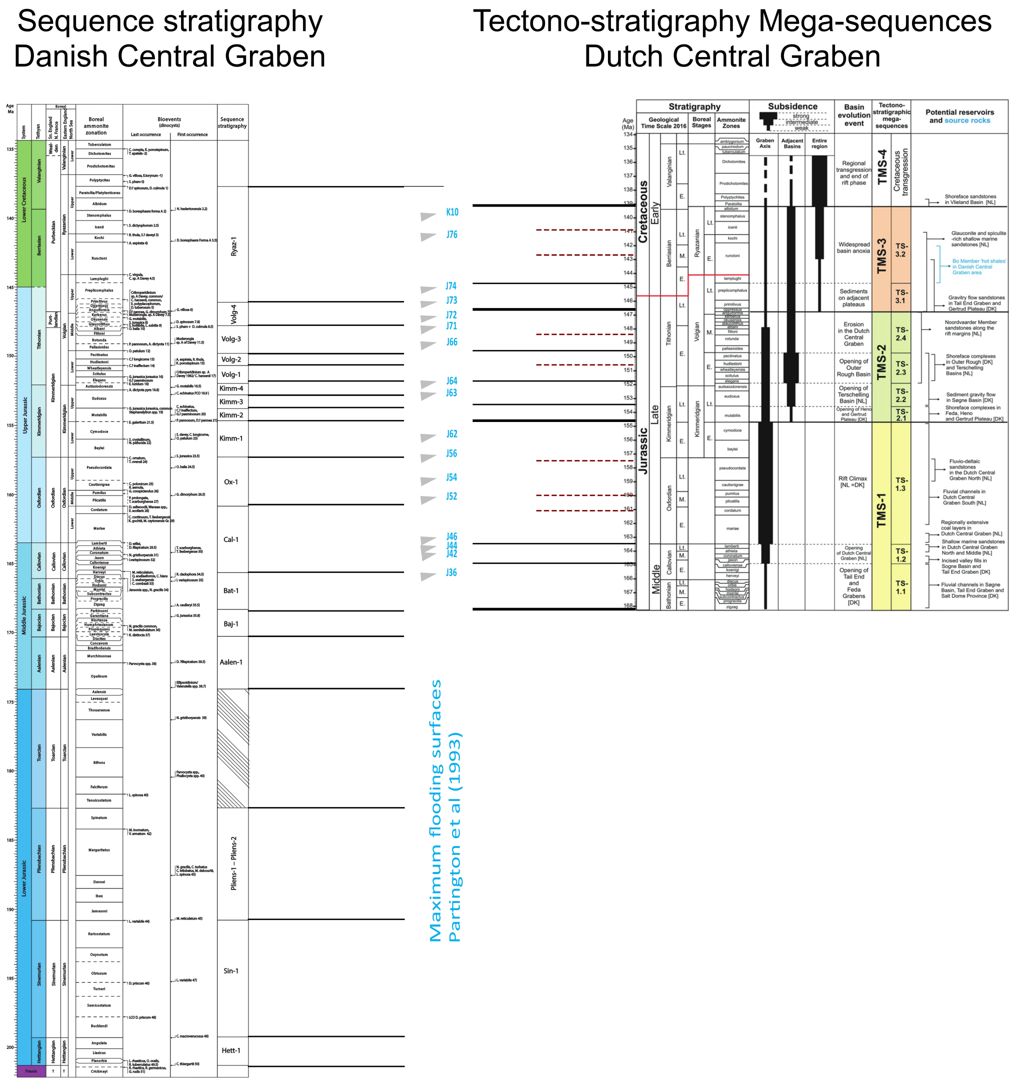

Figure 4. Comparison of the sequence stratigraphic subdivision of the Jurassic in Denmark (left) and The Netherlands (right). The sequence stratigraphic subdivision in the Danish and the Dutch Central Graben is compared with the maximum flooding surfaces established by Partington et al. 1993.

There is a close relationship between the sequence stratigraphic subdivision of the Jurassic in the Danish and Dutch Central Graben and a number of sequence boundaries may be considered to represent regional isochronous surfaces.

Based on the comparison of sequences in the Danish and the Dutch Central Graben in *Figure 4* following sequence boundaries are correlated. (Sequence boundaries refer to the base of a sequence).

Danish Central Graben(1)	Dutch Central Graben(2)	German Central Graben(3)
Ryaz-1	TS-3.2	
	TMS-3	TMS-3
Volg-4	TS-2.4	
Volg-1	TS-2.3	
Kimm-3	TS-2.2	
Kimm-2	TS-2.1 (Base TMS-2)	TMS-2
Ox-1	TS-1.3c	
Cal-1	TS-1.2	
Bat-1	TS-1.1 (Base TMS-1)	TMS-1

(1) PETSYS project
(2) Verreussel et al. (2018) and Bouroullec et al. (2018)
(3) Müller et al. (in prep.)

3.1.4 Basin development

During the Jurassic the Central Graben forms part of a major rift system in the North Sea area. The basin evolution is seen to follow discrete phases with active depocenters and fault patterns changing through time. Four rift phases are defined in the Upper Jurassic and described as tectonostratigraphic mega-sequences (TMS) (Verreussel et al. 2018; Bouroullec et al. 2018). These discrete phases in basin evolution are reflected in the sedimentary record as genetically related accumulations of sediments. Based on the long-distance correlations of wells (*Figure 2*), a stepwise basin evolution pattern is established.

The log correlation through the Central Graben illustrates the basin evolution during the Jurassic. Lower Jurassic deposits are only found in the southern part of the Central Graben, including the German sector and the southern part of the Danish salt dome province. A major hiatus (Mid Cimmerian Unconformity) characterizes the transition from Lower Jurassic to Middle Jurassic. The rifting during Middle and Upper Jurassic started in the north (Danish sector) and prograded southwards during the succeeding phases. Middle Jurassic deposits are found in the entire Central Graben but with the oldest (earliest) deposits in the northern part. The stepwise evolution from north to south continued during Upper Jurassic. At the transition from Jurassic to Cretaceous time the change in tectonic activity gave rise to uplift and truncation of the Jurassic succession which is most obvious in the Danish wells.

3.1.5 *Compilation of the log correlation*

The log correlation displays a basin development giving rise to divergent facies distribution and distribution of sandstone deposits which can be revealed from *Figure 5*.
The time stratigraphic chart displays the generalized time and facies relationship and it is evident that a number of stratigraphic units have a regional extend and can be found in all three countries, whereas a number of depositional units have a local occurrence.

With respect to harmonization of the lithostratigraphy it is obvious that only the main regional wide units could be integrated and redefined; whereas the local formations still have to be ascribed the national nomenclature.

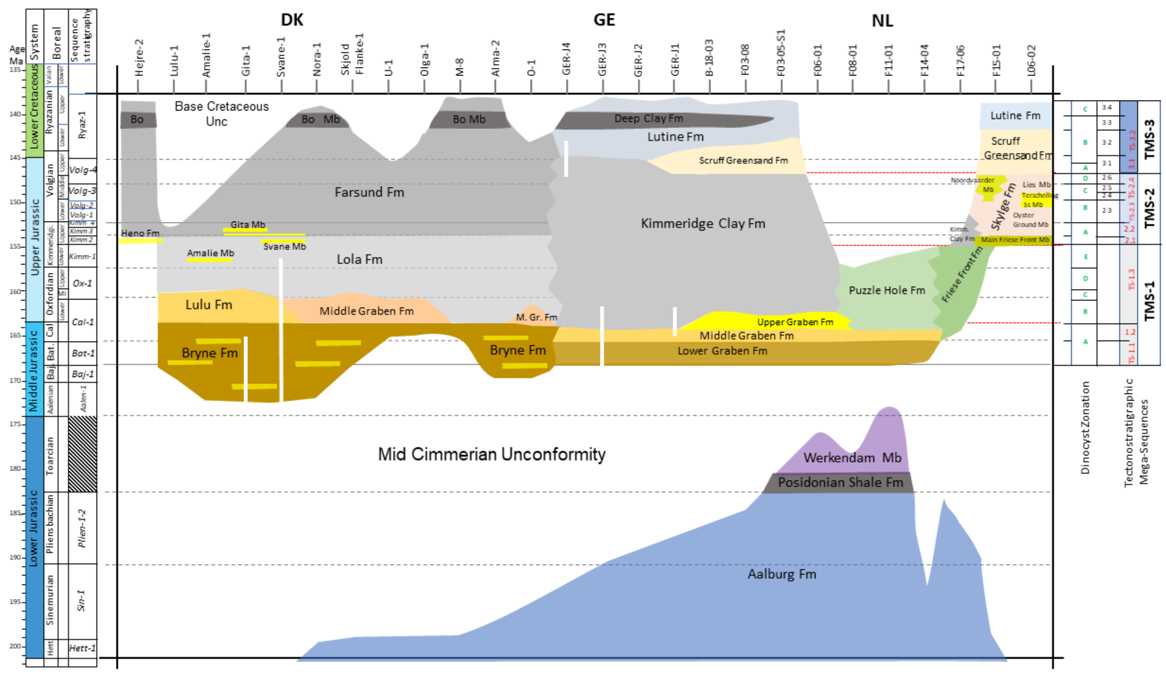

Figure 5. Time stratigraphic panel along the N-S correlation transect through the axis of the Central Graben. The panel displays the generalized time and facies relationships of the Jurassic lithostratigraphic units. The lithostratigraphic units refer to the Danish, German and Dutch stratigraphic nomenclature (Report D3.3: "Harmonized stratigraphic chart for the NL-GE-DK North Sea area"). Comparable time equivalent sequence boundaries in the Danish and Dutch Central Graben are indicated with dashed lines. White columns indicate non-drilled sections.

3.2 Rotliegend log-correlation

3.2.1 Rotliegend log-panel (Encl. 2)

A correlation of the Rotliegend succession from the Dutch sector to the south through Germany into the Danish sector to the north have been generated (*Figure 6* and Encl. 2).

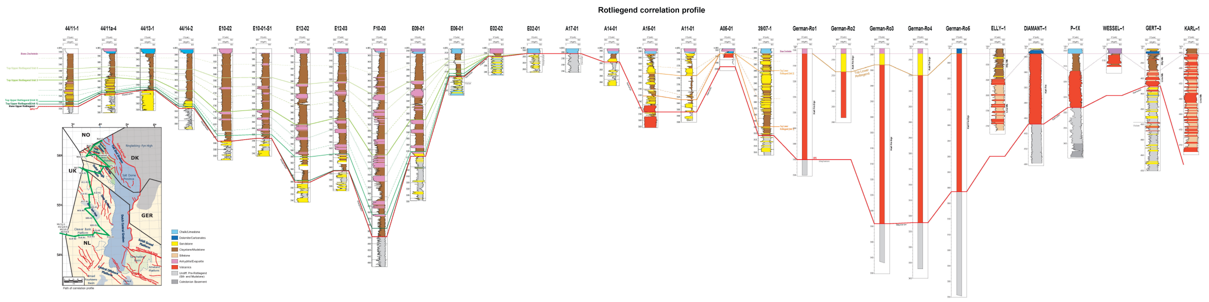

Figure 6. A S-N log correlation of the Rotliegend succession in UK, Dutch, German and Danish wells. The Rotliegend log correlation panel is enclosed at the end of this report (Enclosure 2).

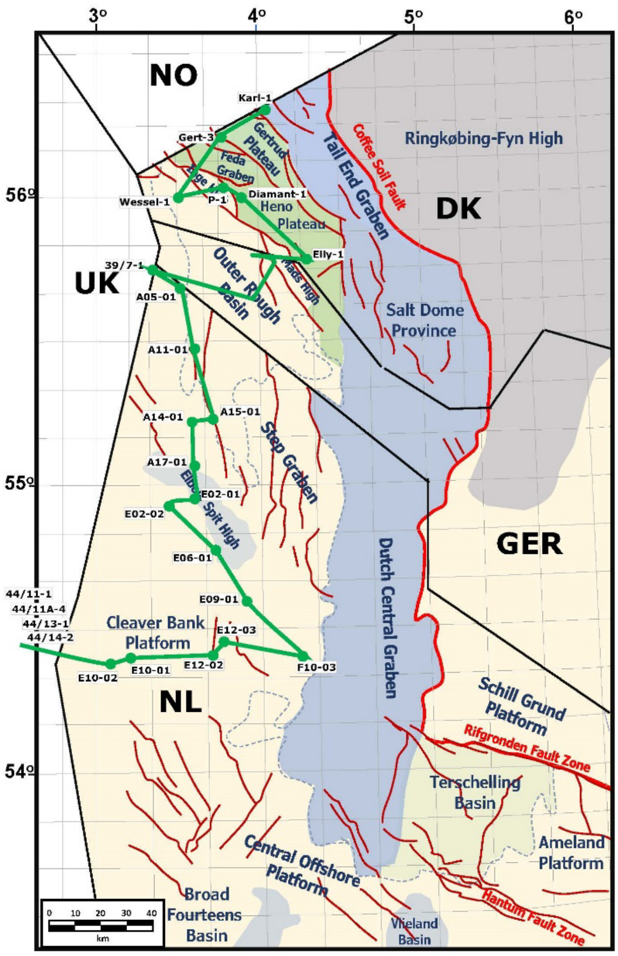

Figure 7. Path of the Rotliegend correlation profile.

The wells are presented by a GR/DT log and a lithology log. The correlation is primarily based on lithostratigraphy and seismic mapping. In the UK/Dutch offshore sector, it is possible to make a detailed subdivision of the Lower and Upper Rotliegend succession whereas only an uncertain subdivision of the Lower Rotliegend volcano-clastic in German and Danish sector is possible.

The correlation panel uses the Base Zechstein as datum. Key correlation surfaces are BPU (Base Permian Unconformity) and BUR (Base Upper Rotliegend). The panel is supplemented with indication of sub-cropping stratigraphic intervals.

The internal correlation of the Lower and Upper Rotliegend in the UK and Dutch wells is based on work carried out at TNO comprising lithostratigraphic and sequence stratigraphic concepts. The correlation of the Rotliegend in the German and Danish wells is less detailed and comprises a number of uncertainties related to the sedimentary intervals. The correlation of the volcanics and volcanoclastic units are of low confidence compared to other lithological units. In addition, the intra Lower Rotliegend correlation is challenging due to its complex depositional setting and the reduced preservation potential in the Dutch sector as a result of the subsequent Saalian erosional events.

The Rotliegend log-panel demonstrates the change in depositional environment from the Southern Permian Basin to the south onto the Mid North Sea High to the north and demonstrates a distinct difference in the basin development in the cross-border study area. Whereas Upper Rotliegend sediments prevails in the Dutch sector and Lower Rotliegend generally is absent, the German and Danish sector is dominated by thick Lower Rotliegend volcanic deposits. Upper Rotliegend sediments are only identified locally in the German and Danish wells.

3.2.2 Lithostratigraphy

The Rotliegend period in the study area is dominated by two major tectonic events: Variscan and Saalian orogeny. As a result of the tectonic events the Rotliegend is subdivided into a Lower Rotliegend sequence and an Upper Rotliegend sequence separated by the Saalian Unconformity representing a major time-gap of up to 30 My.
A lithostratigraphic subdivision of the Rotliegend in the cross-border study area is shown in *Figure 8*.

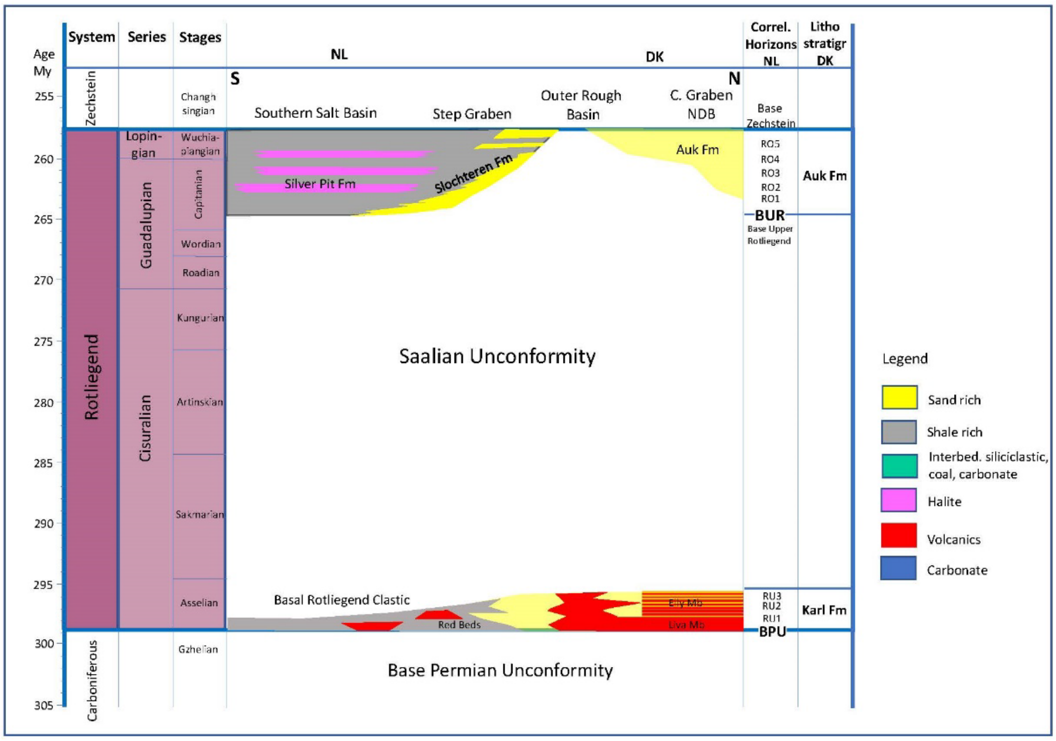

Figure 8. Lithostratigraphic subdivision of the Rotliegend in the cross-border study area. Formation tops utilized in the correlation panel is shown to the right. (Modified from De Bruin et al. 2015 and Glennie et al. 2003)

The Lower Rotliegend is dominated by volcanics and volcanoclastics in the Danish and German sector; whereas clastics, volcanoclastics and minor volcanics prevails in the Dutch sector. In the Danish sector Lower Rotliegend comprises volcanics, volcanics intercalated with lacustrine siltstone and alluvial deposits associated with the Karl Formation embracing the Liva Mb and Elly Mb. In the Dutch sector the Lower Rotliegend is subdivided into 3 layers: RV1, RV2 and RV3 (De Bruin et al. 2015). No feasible subdivision of the volcanic section in Germany is available.

A simplified Upper Rotliegend stratigraphy in the Netherlands is shown in *Figure 8* 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). Upper Rotliegend comprises in the Dutch part halite, sand and fine-grained siliciclastic units. The succession is subdivided into 5 layers (De Bruin et al. 2015, see below) based on incorporation of lithostratigraphic and sequence stratigraphic concepts.

In the Danish and German sector, the Upper Rotliegend comprises the Auk Formation. The Auk Formation corresponds to the Slochteren Formation in the Netherlands where it describes the sandy part of the Upper Rotliegend along the northern margin of the Southern Permian Basin. The Upper Rotliegend onlaps from the SE towards the NW along the northern margin of the basin.

3.2.3 Basin development

The Rotliegend is divided into two groups, the Lower Rotliegend (Clastics, volcanoclastics and volcanics) and the Upper Rotliegend (clastics and evaporites). The Lower Rotliegend is only present in the NE part of the Dutch Northern Offshore since it was eroded (Saalian event) in major parts of the Dutch Offshore. 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 depostional systems

Lower Rotliegend was deposited in a period dominated by volcanic activity throughout North Western Europe. The Lower Rotliegend volcanics are primarily interpreted in the northern part of the Dutch sector, the German and the Danish sector. Lower Rotliegend sediments are restricted to the north-eastern part of the Dutch sector. Conglomerates of Lower Rotliegend age in the southern part of the study area are expected to be remnant of an eroded previously existing Lower Rotliegend package covering a major area of the Dutch North Sea. The Lower Rotliegend in the Dutch sector is divided into three sequences/units (RV1, RV2 and RV3). The lateral extent and paleo-depositional distribution for the three Lower Rotliegend sequence/units is shown on maps constructed by TNO (*Figure 9*, De Bruin et al. 2015).

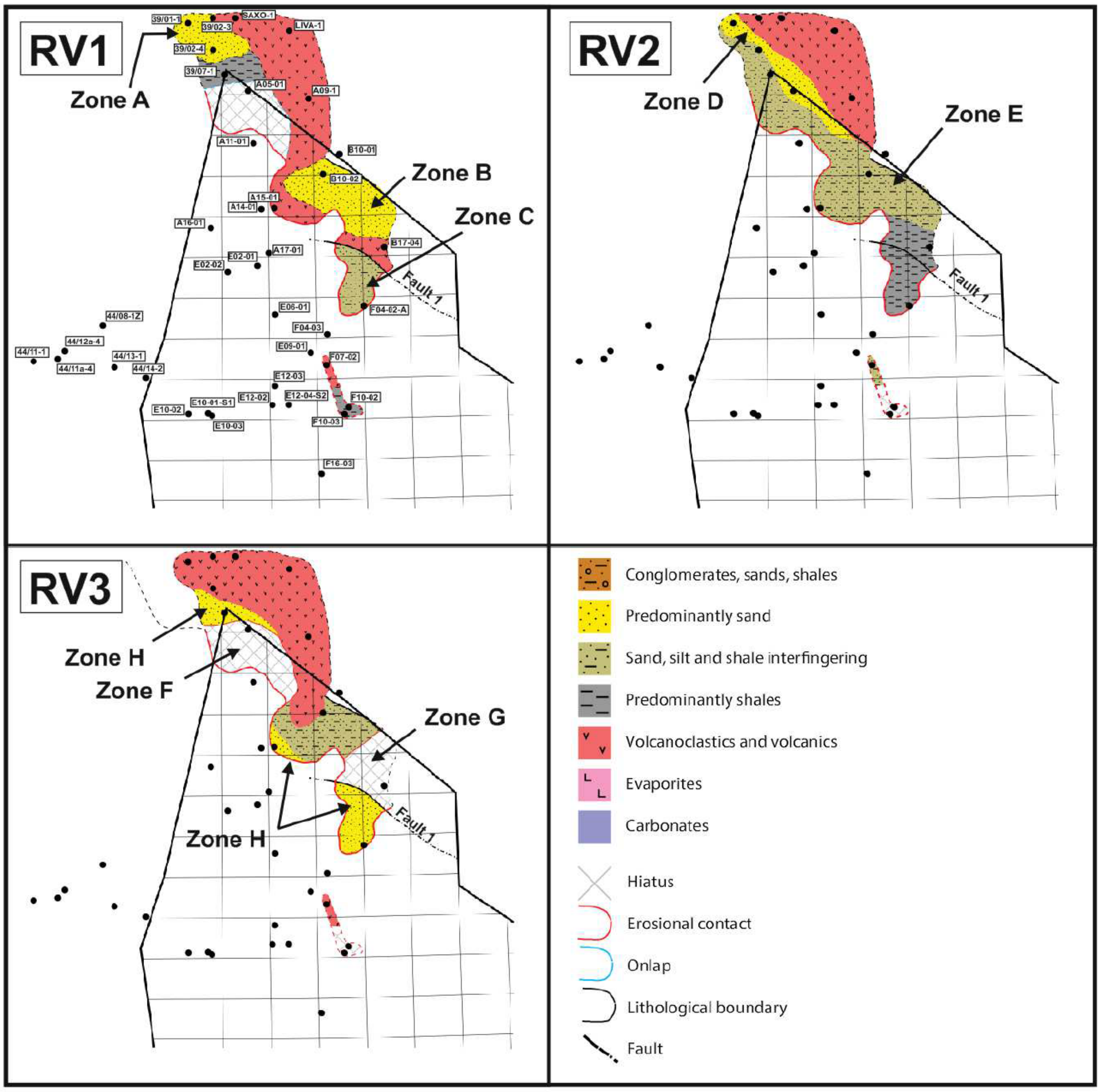

Figure 9. Depositional maps for the three Lower Rotliegend units (RV1, RV2, and RV3).(From De Bruin et al. 2015)

Upper Rotliegend is encountered in the central part of the Dutch sector but is thin or absent in the northern part of the Dutch sector (A05-01; A17-01 and E02-01). Upper Rotliegend is found in the German wells but is generally absent in the Danish wells. In the Dutch sector Upper Rotliegend is divided into 5 individual stratigraphical units (RO1-RO5).

The Upper Rotliegend distribution is confined to the southern half of the study area for the three oldest units (i.e. RO1-RO-3). The two youngest units (RO4-RO5) extend farther north and covers the northen part of the Dutch sector. Possible Upper Rotliegend deposits are recognized in the German wells.
The lateral extent and paleo-depositional distribution for the five Rotliegend sequence/units is shown on maps constructed by TNO (*Figure 10*, De Bruin et al. 2015).

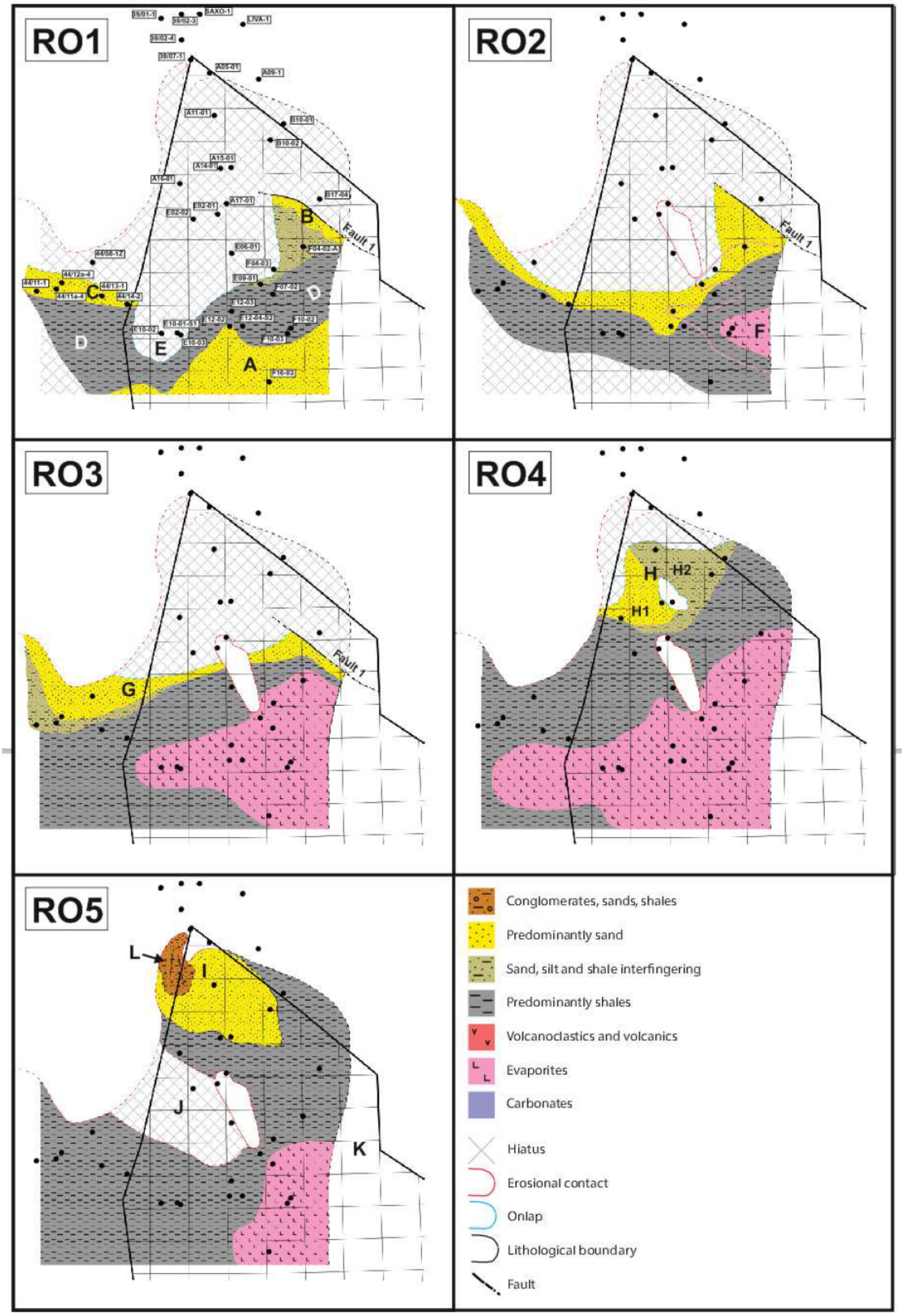

Figure 10. Depositional maps of the five Upper Rotliegend units RO1, RO2, RO3,RO4 and RO5. (From De Bruin et al. 2015).

3.2.4 Compilation of the log correlation

The Rotliegend log correlation clearly demonstrates the change in depositional environment from the Southern Permian Basin to the south onto the Mid North Sea High to the north and demonstrates the differences in the basin development in the cross-border study area. The correlation concurs with the study carried out by TNO in the Dutch sector. Data from this study, however, will make it possible to extend the distribution maps from TNO to the north into the German and Danish sectors.

4 SUMMARY OF CROSS-COUNTRY CORRELATION

The comparison of the lithostratigraphic charts (Report D3.3. Harmonized stratigraphic chart for the NL-DE-DK North Sea area) indicates a limitation for harmonization of the lithostratigraphy across country borders. Especially diachronous units are difficult to correlate and may only be identified from detailed log correlations applying sequence stratigraphy.

In this report a correlation of the Jurassic and the Rotliegend successions across the country borders have been carried out in order to identify the distribution and the diachronous appearance of specific lithofacies.

The correlation panel of the Rotliegend shows a complex stratigraphic and structural setting with a limited contribution to the harmonization across the country borders.

The correlation of the Jurassic is based on a detailed sequence stratigraphic subdivision of the Jurassic succession. The outcome of this correlation is a time related distribution of the sedimentary units. Based on the correlation it has been possible to discriminate local units and put it into a stratigraphic context. A time stratigraphic chart for the Jurassic elucidate stratigraphic similarities and discrepancies between the three countries and is very helpful for harmonization purposes.

REFERENCES

Abbink, O.A., Mijnlieff, H.F., Munsterman, D.K. & Verreussel, R.M.C.H. 2006. New stratigraphic insight in the 'Late Jurassic' of the southern central North Sea Graben and Terschelling Basin (Dutch offshore) and related exploration potential. Netherlands Journal of Geosciences – Geologie en Mijnbouw, 85, 221-238.

Andsbjerg, J. & Dybkjær, K. 2003. Sequence stratigraphy of the Jurassic of the Danish Central Graben. In: Ineson, J.R. & Surlyk, F. (eds) The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, 1, 265–300.

Bouroullec, R., Verreussel, R. et al. 2018. Tectonostratigraphy of a rift basin affected by salt tectonics: synrift Middle Jurassic–Lower Cretaceous Dutch Central Graben, Terschelling Basin and neighbouring platforms, Dutch offshore. In: Kilhams, B., Kukla, P.A., Mazur, S., Mckie, T., Mijnlieff, H.F. & Van Ojik, K. (eds): Mesozoic Resource Potential in the Southern Permian Basin. Geological Society of London, Special Publications, 469. First published online March 15, 2018.

De Jager, J. 2007. Geological development. In: Wong, T.E., Batjes, D.A.J. & De Jager, J. (eds) Geology of the Netherlands. Royal Netherlands Academy of Arts and Sciences. Amsterdam.

De Bruin, G., Bouroullec, R., Gell, K., Fattah, A.R., van Hoof, T., Pluymaekers, M., van den Belt, F., Vandeweijer, V. & Zijp, M. 2015: "New Petroleum plays in the Dutch Northern Offshore", TNO report TNO 2015 R10920. https://www.nlog.nl/dutch-northern-offshore)

Glennie, K., Higham, J. & Stemmerik, L. 2003: Permian. In: The Millennium Atlas Petroleum geology of the central and northern North Sea. Evans, D, Graham, C, Armour, A & Bathurst, P. (editors and coordinators). pp. 91-103. Geol. Soc. London.

Herngreen, G.F.W, Kouwe, W.F.P & Wong, Th.E. 2003: The Jurassic of the Netherlands In: Ineson, J.R. & Surlyk, F. (eds) The Jurassic of Denmark and Greenland. Geological Survey of Denmark and Greenland Bulletin, 1, 217–229.

Jakobsen, F., Britze, P., Thöle, H., Jähne-Klingberg, F., Doornenbal, H., Vis, G-J. Harmonized stratigraphic chart for the NL-DE-DK North Sea area. GeoERA 3DGEO-EU Deliverable 3.3, 30p.

Lott, G.K, Wong, T.E., Dusar, M., Andsbjerg, J., Mönnig, E., Feldman-Olszewska, A. & Verreussel, R.M.C.H. 2010. Jurassic. In: Doornenbal, J.C. & Stevenson, A.G. (eds) Petroleum Geological Atlas of the Southern Permian Basin Area. EAGE Publications b.v., Houten, 175-193.

Munsterman, D.K., Verreussel, R.M.C.H., Mijnlieff, H.F., Witmans, N., Kerstholt-Boegehold, S.J. & Abbink, O.A. 2012. Revision and update of the Callovian-Ryazanian Stratigraphic Nomenclature in the northern Dutch offshore, i.e. Central Graben Subgroup and Scruff Group. Netherlands Journal of Geosciences – Geologie en Mijnbouw, 91, 555-590.

Müller, S., Arfai, J., Jähne-Klingberg, F., Bense, F. & Weniger, P. (2019). Source rocks of the German Central Graben. Marine and Petroleum Geology, 113, pp. 104-120.

NOPEC 1988. North Sea Atlas – Major structural elements map (London)(NOPEC).

Partington, M.A., Mitchener, B.C., Milton, N.J. & Fraser, A.J. 1993. Genetic sequence stratigraphy for the North Sea Late Jurassic and Early Cretaceous: distribution and prediction of Kimmeridgian-Late Ryazanian reservoirs in the North Sea and adjacent areas. In: Parker, J.R. (ed.) Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference. Geological Society, London, Petroleum Geology Conference Series, 4, 347–370.

Posamentier, H.W., Jervey, M.T., & Vail, P.R. 1988. Eustatic controls on clastic deposition I – conceptual framework. In: Wilgas, C.K. et al. (eds): Sea-level changes – an integrated approach. Society of Economic Paleontologists and Mineralogists Special Publication, 42, 109-124.

Posamentier, H.W. & Vail, P.R. 1988. Eustatic controls on clastic deposition II – sequence and systems tract models. In: Wilgas, C.K. et al. (eds): Sea-level changes – an integrated approach. Society of Economic Paleontologists and Mineralogists Special Publication, 42, 125-154.

Stratigraphic Nomenclature of the Netherlands. Link to TNO website

The PETSYS Project (2014): The Jurassic Petroleum System in the Danish Central Graben. Data available through a dedicated web portal service provided by GEUS.

Thöle, H., Jähne-Klingberg, F., Bense, F., Doornenbal, H., den Dulk, M. & Britze, P. 2019. State of the Art Report. GeoERA 3DGEO-EU Deliverable 3.1, 50p.

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P. 1993. Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGEPÅ. Mededelingen Rijks Geologische Dienst 50.

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

Verreussel, R.M.C.H., Bouroullec, R., Munsterman, D.K., Dybkjær, K., Geel C.R., Houben A.J.P, Johannessen, P.N. &. Kerstholt-Boegehold, S.J 2018. Stepwise basin evolution of the Middle Jurassic–Early Cretaceous rift phase in the Central Graben area of Denmark, Germany and The Netherlands. In: Kilhams, B., Kukla, P. A., Mazur, S., Mckie, T., Mijnlieff, H. F. & Van Ojik, K. (eds) Mesozoic Resource Potential in the Southern Permian Basin. Geological Society, London, Special Publications, 469.

ENCLOSURE 1

Jurassic log correlation profile

Jurassic correlation panel

ENCLOSURE 2

Rotliegend log correlation profile

Rotliegend correlation profile