Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 40 (2013) 222 – 231

Energy Procedia

European Geosciences Union General Assembly 2013, EGU

Division Energy, Resources & the Environment, ERE

Geological Evolution of the North Sea: Cross-border Basin Modeling Study on the Schillground High

Sabine Heim[a]*, Rüdiger Lutz[a], Susanne Nelskamp[b], Hanneke Verweij[b], Dirk Kaufmann[a], Lutz Reinhardt[a]

[a]Federal Institute for Geosciences and Natural Resources (BGR), Stilleweg 2, 30655 Hannover, Germany
[b]TNO ENERGY/Geological Survey, P.O. Box 80015, 3508 TA Utrecht, The Netherlands

Abstract

This study presents the results of a basin modeling study covering the cross-border area of the southern Schillground High in the Dutch-German offshore area. A high resolution petroleum system model has been constructed with the aim to evaluate the hydrocarbon generation potential of Carboniferous source rocks and their possible lateral migration of the generated hydrocarbons across the political border. Besides the burial history, temperature and maturity evolution, this model displays for the first time in parallel erosion and salt movement events through time with improved details.

Selection and peer-review under responsibility of the GFZ German Research Centre for Geosciences

Keywords: Schillground High platform, petroleum systems modeling, salt movement, petroleum system analysis

1. Introduction

Within the project "Geopotential of the German North Sea (GPDN)" a large quantity of data, provided by research institutions, public authorities and industry partners, as well as research work, was acquired. One project objective is, to provide an overview on the evolution of the hydrocarbon system of the German North Sea. For this purpose different petroleum system models were developed to assess the burial and temperature history of the basin system and to gather and evaluate the source rock potential for natural oil and gas. One of these models is this cross-border study of the Schillground High in the Dutch-German offshore area, which was developed in order to evaluate the hydrocarbon generation and migration from Carboniferous source rocks. Special emphasis was placed on possible lateral migration across the political border, e.g. from the Dutch Central Graben into the German part of the area or from

---

* Corresponding author. Tel.: +49-511-643-2931; fax: +49-511-643-3661.
E-mail address: sabine.heim@bgr.de, sabine.heim@gmx.de

1876-6102
Selection and peer-review under responsibility of the GFZ German Research Centre for Geosciences
doi:10.1016/j.egypro.2013.08.026

the Horn Graben in Germany into the Dutch part. For this purpose a petroleum system model of the study area has been constructed, including all available data, such as distribution, thickness, and depth of the significant stratigraphic horizons, structural information of faults and salt structures, lithology and facies as well as geochemical data. The model is calibrated with temperature and maturity data from wells and publications. For the first time this study reconstructs the basin evolution with a numerical 3D model, including erosion and salt movement events of Zechstein evaporates in the study area. Beside the structural evolution the resulting effects on temperature and pressure, caused by the movement of Permian salt layers, the formation and dynamic of possible oil and gas reservoirs and lateral hydrocarbon migration are of major interest. The model focuses on the Upper Carboniferous coal measures and organic-rich shales. Finally, the basic model data, depth maps and numerous output data, will be available online for experts and the general public on the website www.geopotenzial-nordsee.de.

The Schillground High is a part of the southern North Sea basin and the Central European Basin system (CEBS), respectively. It is a Jurassic stable platform area in the south of the Rynkøbing Fyn High, flanking the Dutch Central Graben in the west. To the south this structural element is bordered by the Terschelling basin and Ameland block, adjacent areas at the eastern flank comprise different faulted zones and platforms of the central German North Sea. This structure, which was highly influenced by fault movements, subsidence and erosion is classified as a structural high, defined by significant erosion down to the basement (i.e. Devonian, “Old Red”), or as platform, characterized by Late Jurassic erosion into the Triassic and the absence of Lower and Upper Jurassic stratigraphic units. For the investigated study we use the term “Schillground High”, following the German terminology. This structural element was recently renamed in the Netherlands as Schill Grund Platform [1, 3], due to the presence of Cretaceous sediments on top of Triassic or Permian rocks.

The platform is covered by Quaternary and Tertiary sediments and a succession of Cretaceous, Triassic and Permian rocks, overlying Carboniferous sediments which act as potential hydrocarbon source rocks. For petroleum systems modelling of this part of the CEBS the stratigraphic units of the Upper Carboniferous (Silesian) are of particular interest. The Silesian formations consist mainly of siliciclastic sediments, which were deposited in a deltaic to fluvial plain environment of a lacustrine basin with numerous marine incursions. A widespread distribution of coal measures in the middle and upper parts of the Silesian formations and the resulting hydrocarbon generation potential are an important exploration target of the petroleum industry since the early 1950s [3]. Besides, the coal-bearing Upper Carboniferous, Namurian and Jurassic shales are considered having a potential for shale gas and might also be a source rock for conventional hydrocarbons.

2. Geological background

2.1. Geological framework

The Dutch-German North Sea can be sub-divided in numerous highs and platforms which are bordered by graben structures [4]. Within the graben structures thick Jurassic sediments were preserved, e.g. the Central Graben shows a complete profile of the Jurassic. In contrast, the platform areas are characterized by the Lower Cretaceous unconformity, reflecting significant erosion with an absence of Lower and Upper Jurassic, and/or Lower Cretaceous sediments and a depth of top Pre-Permian layers at about 3,000 m.

The Schillground High (or Schill Grund Platform in the Netherlands) is one of these prominent structural highs, situated at the SW edge of the central German North Sea, in the Dutch-German offshore area, flanked by the Central Graben (W) and the Horn Graben (E). The stratigraphic profile includes Carboniferous and Permian sediments covered by Upper Cretaceous and younger formations due to deep

Lower Cretaceous erosion. The study area of the Schillground High is part of the CEBS; its evolution was initiated during the Permian comprising extension and subsidence, the accumulation of thick sedimentary series contrasted by almost complete erosion in areas of uplift almost. A comprehensive description of the evolution of the CEBS is given in [4] and for the Dutch and German North Sea in [4, 5]. During the Palaeozoic the general development within this area was dominated by the northward drift of Gondwana and the collision with Laurussia. Thick Namurian siliciclastic sediment sequences, marine and lacustrine shales and turbidites, were deposited followed by sediments deposited in deltas, alluvial plains and fans, which characterize a largely fluvial red-bed environment of the Late Westphalian [1-5].

The Permian is dominated by warm and arid climatic conditions and the deposition of fluvial, eolian and playa-lake sediments [3]. During the Late Westphalian a proto Central Graben is assumed [6]. In Permian and Triassic time the evolution of the Central Graben commenced with extension and subsidence, initiating the accumulation of thick sediment deposits within the graben and an uplift of the adjacent areas dominated by erosion. Until the middle Jurassic this structural evolution was accompanied by salt tectonic processes, affecting the graben structure and the flanking platform. During the Upper Cretaceous the Central Graben was inverted. Rifting and sediment deposition, influenced halokinesis which had a considerable control on the sedimentation pattern [6]. Since the Paleogene continuous sedimentation started and covered the area with several hundred meters of Cenozoic sediments, reaching more than 1,000 m in the Central Graben.

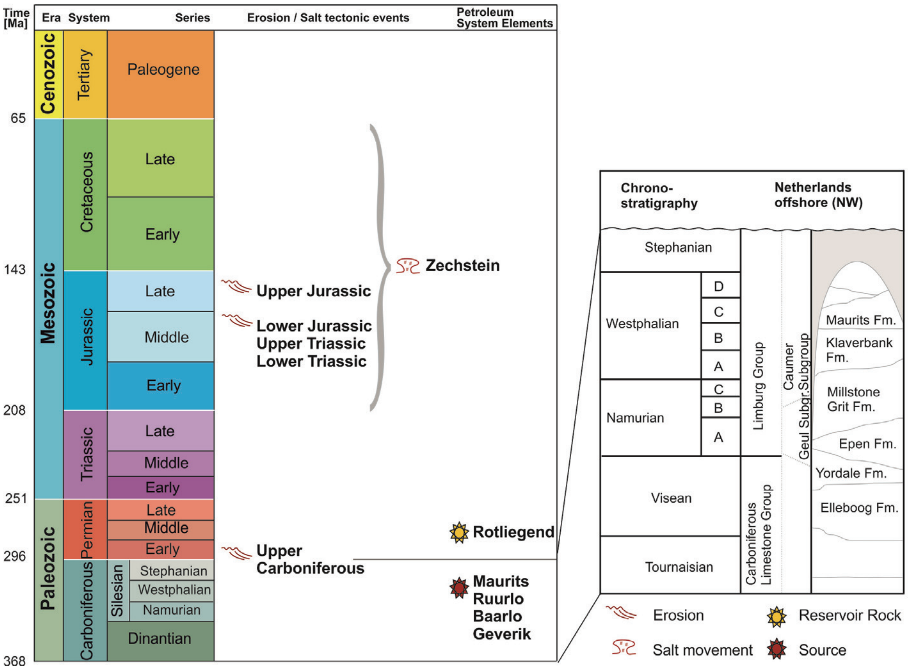

Fig. 1. Stratigraphy of the study area (after Gradstein et al., 2004 and Adrichem Boogaert & Kouwe, 1993-1997)

The Schillground High has been formed as an emergent platform (during Jurassic and earliest Cretaceous) at the eastern flank of the rapidly subsiding Dutch Central Graben and in the north of the Terschelling Basin, which was separated from the Schillground high by the Rifgronden Fault Zone [7].

Most of the Jurassic and Triassic succession was eroded during the Middle and Late Jurassic uplift. From the middle Campanian time on gradual subsidence started and enabled the deposition of a thick Chalk succession [8].

2.2. Lithostratigraphy and facies of the hydrocarbon source rocks

Stratigraphy and lithology used in this model are simplified compilations following the Dutch nomenclature (Fig. 1). For detailed information on the lithostratigraphic units, in particular the Permian and Triassic reservoir rocks (Upper Rotliegend, Volpriehausen Sandstone) and the Zechstein evaporites (seal rocks) as well as on Mesozoic and Cenozoic lithostratigraphic and facies evolution [4, 6, 9]. Below only a brief description of the Carboniferous (Silesian) source rocks is given.

These Silesian coals and organic-rich claystones and shales are the major gas source rocks of the whole North Sea area. Due to the different distribution within the basin, thickness variations, as well as the different burial depth of the Upper Carboniferous sequences high variations in maturity and hydrocarbon generation potential can be assumed. Predominantly siliciclastic sediments, in particular the marine to lacustrine deposits of the Caumer and Geul Subgroups (Limburg Group) are of major interest for the generation of oil and gas. The lowermost Geul group is part of a huge depositional system characterized by sediments deposited in alluvial deltaic to euxinic deep marine environment, encountered over a large stratigraphic range and reflecting the long-term Silesian regression from north to south of the basin. Within this group the marine Geverik Member includes black shales as potential source rocks. In the overlying Caumer Subgroup the change from marine to lacustrine deposition is accompanied by deposition of more lacustrine and delta-sedimentation of the Baarlo, Ruurlo and Maurits formation, which comprises siliciclastic deposits with intercalated coal seams.

3. Petroleum system modeling: input data

The study area of the Schillground High model has a dimension of 100 x 118 km with a grid resolution of 250 x 250 m. The maximum vertical cell thickness, for simulation was set to 400 m. The model was computed at full resolution, with a total grid cell number of around 3 million cells (x-y direction: 301 x 415 grid nodes). The model includes 20 different stratigraphic layers covering a time interval between Dinantian to the Present. Input data for the German part of the 3D basin model were taken from the GTA3D model of the Central German North Sea [12] and from literature. For the Dutch part of the model, TNO provided expertise and data from previous studies of the Dutch North Sea sector [1, 2]. Both map sets were merged and generalized by smoothing the vertical offset at the map boundaries and by removing layer intersections. In order to reconstruct the considered geological processes during basin evolution, the consistent base model of the present-day situation was supplemented by numerous thickness and depth maps for erosion and salt tectonic processes.

The Netherlands part of the Schillground Platform model is based on chronostratigraphic maps of the major horizons of the Dutch NCP-2B area, including the surface morphology, the base Pleistocene to base Dinantian maps, which are available online [13]. For the German part, depth maps including lithostratigraphic units between the base Zechstein and the Upper Miocene were obtained from the GTA3D structural model [12]. These surfaces were generalized or simplified, in particular for the top of the Zechstein, in order to avoid multiple z-values. Due to the lack of data for the Pre-Zechstein in the GTA3D, maps of the base Upper Rotliegend and the uppermost Carboniferous (Westphalian C or roughly Maurits) were constructed, based on literature data [5, 9, 12]. Finally, the maps for the underlying Namurian A to Westphalian A/B are compiled equivalent to the Dutch chronostratigraphic nomenclature of the Ruurlo, Baarlo, Geul/Geverik and Dinantian formations and lateral stratigraphic comparison [7].

Table 1. Input data: Layer, depositional and erosion age and lithology

Model layer horizon	Depositional Age [Ma]	Erosion Age [Ma]	Lithology
Miocene	0-61.0		75% Sand, 25% Shale
Paleocene-Eocene	61.0-98.0		50% Sand, 50% Shale
Upper Cretaceous	144.0-98.0		Limestone (Chalk, typical)
Lower Cretaceous	154.0-149.0	149.0-144.0	75% Marl, 25% Shale
Upper Jurassic	203.0-162.0	162.0-156.0	50% Sand, 50% Shale
Upper Triassic	162.0-203.0	156.0-155.0	50% Shale. 25% Marl, 25% Sand
Lower Triassic	231.0-251.0	155.0-154.0	75% Shale, 25% Silt
Zechstein	251.0-258.0		Salt
Upper Rotliegend II	258.0-277.3		34% Shale, 33% Sand, 33% Silt
Upper Rotliegend I	277.3-280.0		Sandstone
Maurits	290.0-300.0	290.0-280.0	80% Shale, 15% Sand, 5% Coal
Maurits (Coal)	300.0-302.3		Coal (with impurities)
Maurits	302.3-312.3		80% Shale, 15% Sand, 5% Coal
Ruurlo	312.3-313.1		80% Shale, 15% Sand, 5% Coal
Baarlo	313.1-313.6		48% Shale, 25% Sand, 25% Silt, 2% Coal
Geul	313.6-316.4		50% Sand, 50% Shale
Geverik	316.4-326.4		Shale (black)
Dinantian	326.4-359.0		Limestone (shaly)

3.1. Paleo geometry

The geological evolution of the model includes three erosion phases are considered, reflecting the tectonic events of the Variscan (Late Carboniferous to Early Permian), the Kimmerian tectonic phases with a first erosion event, affecting Lower Jurassic and Triassic rocks and a second phase (Late Kimmerian) with an erosion of Upper Jurassic deposits (see Fig. 1). For each erosion event, layer thickness maps were built and included into the program workflow. Upper Carboniferous erosion is based on the map published by [14]. For the Lower Triassic sequences, a compilation of the Early Triassic Bunter and the Middle Triassic Muschelkalk Formations, an initial thickness of approximately 600 m is estimated. Erosion of the Lower Jurassic (initial thickness of 200 m) and subsequent erosion of Upper Triassic sediments (Keuper, initial thickness of 400 m) was included reflecting the Early Kimmerian tectonic phase. Finally, the Late Kimmerian erosion of the Upper Jurassic (initial uniform thickness of 200 m) was included into the modeling workflow.

Modeling of the salt uplift is performed by using the implemented program feature of salt tectonics. With this tool it is possible to move the salt layer upwards with time, and to influence or shape the geometry of the salt layer and the overlying horizons, respectively. For this purpose bottom and top depth maps of the salt layers are manually fixed, in order to avoid distortions and intersections. Altogether 13 depth maps were built from the initial deposition of the Zechstein salt (251 Ma) until Tertiary age (65 Ma). Due to complex interaction between erosion and salt tectonic events, for the simulation the movement of the salt domes has been simplified in the procedure.

3.2. Petrophysics and kinetics

Petrophysical parameter such as lithology and facies information were derived from previous investigations (defined by TNO) or derived from literature [4, 6, 7, 8]. Parameters like the depth dependent porosity, permeability, radiogenic heat or compaction etc. were used as default values from the program (PetroMod®, v.2012.2; Schlumberger). In addition, the temperature boundary conditions for the model, such as heat flow (HF), paleo water depth (PWD) and sediment water interface temperature (SWIT) as well as geochemical borehole data (maturity and temperature) are based on previous studies performed by TNO or were taken from literature [13, 16]. Tab. 1 refers to the layer depositional and erosion age, lithological composition, and the assigned petroleum system element within the model.

Paleo heat flow was determined according to 1D tectonic heat-flow modeling results for five wells in the study area [17]. The paleo water depth trend was determined using geobiological results and the sediment water interface temperature is a combination of the standard temperatures of PetroMod® and refined temperatures for the Tertiary based on geobiological proxies [16]. For calibration purposes vitrinite reflection measurements from the SPBA [4] were used, temperature measurements were provided by TNO. For maturity calculation the kinetic of [18] was used, which allows maturity calculation in the range between 0.3 and 4.5 %R_0.

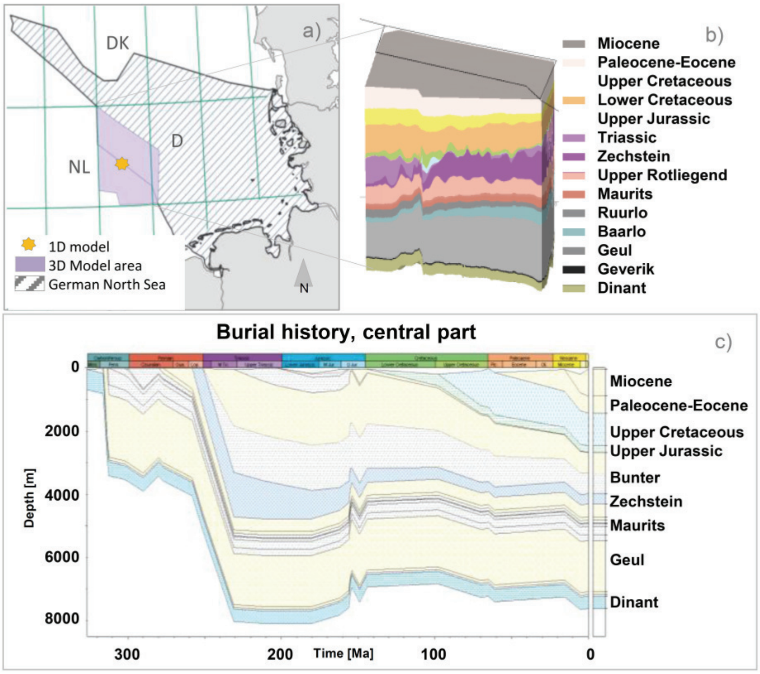

Fig. 2 Location of the Schillground High model in the southern North Sea (a), sketch of the 3D model (b) and an exemplary burial history for the model area (c)

4. Results and Discussion

The 3D structural model of the Schillground High illustrates the spatial distribution of Paleozoic, Mesozoic and Cenozoic deposits down to nearly 7,000 m depth. Zechstein salt structures affected significantly the geometry during the Late Triassic until the end of the Cretaceous. The salt pierced mainly into the Triassic sediments, which reached thicknesses of up to 1,600 m. An increase in temperature (>100 °C) enabled the generation and migration of oil and gas into Upper Rotliegend reservoirs since the end of the Carboniferous.

Depending on the regional occurrence of Upper Carboniferous source rocks hydrocarbon generation and lateral migration had led to the formation of numerous small size reservoirs across the whole model. Fig. 2a shows the model area of the Schillground High, the stratigraphic layers included in the model (Fig. 2b) as well as a 1D extraction reflecting the principle burial history of the modeled area (Fig. 2c). In the northern (N, NW) and southern (S, SE) part of the model maximum burial and temperatures are reached at present-day. In the central and eastern part a first deep burial event took place during the Triassic and Jurassic (Fig. 2c) followed by erosion of up to 1,400 m.

4.1. Erosion events

The main erosion event affecting the Schillground High area took place during the Variscan tectonic phase, leading to an abrasion of Upper Carboniferous to Lower Permian sediments. An Upper Carboniferous erosion map was calculated by subtracting the present-day thickness of the Maurits layer from the initial thickness map of the Westphalian [14]. This gives an erosion map showing non-erosion in the NW and E, and highest erosion in the southern and southwestern part of the modeled area, with up to 580 m erosion of Upper Carboniferous sediments.

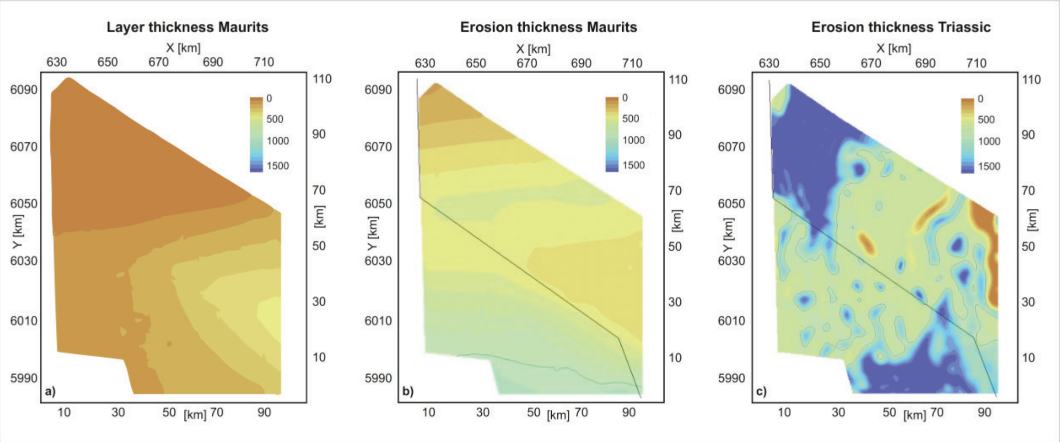

Fig. 3 a) Thickness map of the initial Maurits, b) map of the eroded thickness of Maurits; and calculated erosion maps of the eroded thickness of Triassic sediments (c); black line shows the Dutch-German border in the study area

Fig. 3a and b show the thickness maps for the initial Maurits layer and the calculated erosion thickness maps, respectively. During the Early Kimmerian tectonic phase sediments of the Lower Jurassic and Upper and Lower Triassic were eroded in successive steps to the present-day situation. During the Late Kimmerian phase (149-144 Ma) erosion of Upper Jurassic sediments followed. Fig. 3 c shows the calculated thickness maps for the erosion of Upper and Lower Triassic (between 156 and 154 Ma). The inserted erosion thickness matches with calibrated well data of the southern and northern project area [13]. Due to a lack in available data for the central part of the model area, a verification of the estimated erosion thickness with well data is still pending.

4.2. Temperature and maturation trends

In the central part of the model, where the maximum burial was reached during the Kimmerian tectonic phase, the temperature at the Carboniferous layers (e.g. base Ruurlo, Fig. 4a) exceeds a value of 150 °C since the Middle Triassic. In the outermost northern and southeastern edge of the model area this temperature level is still not reached. Hence, only the areas of present-day maximum burial show slight increases in temperature and maturity since the Late Cretaceous (Fig. 4a). A temperature level of >100 °C for the southern and southeastern part of the model area is reached during the Kimmerian tectonic phase, and again since the Late Cretaceous. After the phase of salt doming (231 to 65 Ma) the increase in temperature induced again hydrocarbon generation in these areas. Figs. 4a and b depict three typical temperature and maturity histories for the base Ruurlo, respectively. The calculated present-day temperature distribution for the base Ruurlo (Fig. 4c) illustrates these three areas with their different temperature evolution. The present-day temperature distributions of two other Carboniferous layers (Geverik, Dinantian) are given in Figs. 4d-e. In general, the temperature maps of all layers show lower values in the northwestern and southeastern parts of the model and higher values in the central part with an increase in temperature from SW to NE.

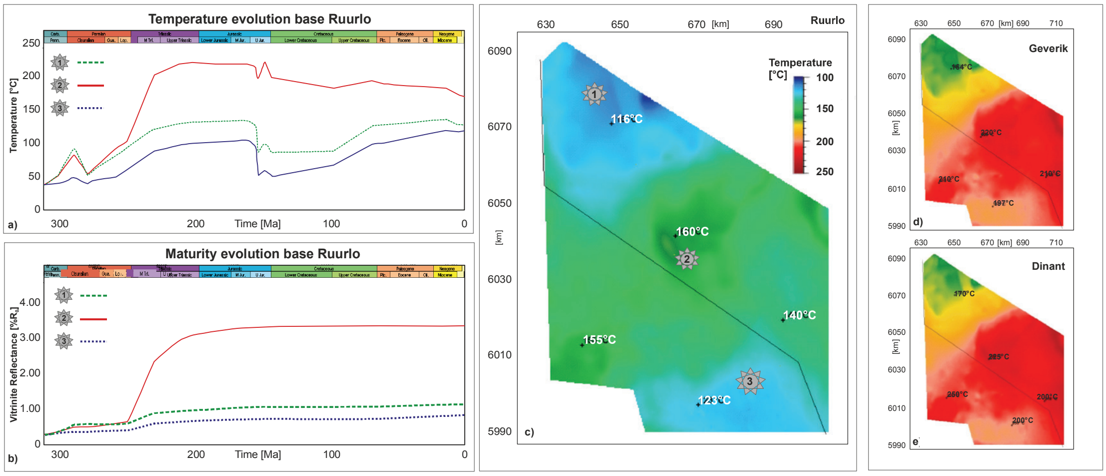

Fig. 4 Temperature (a) and maturity(b) evolution and present-day temperature distribution at the base of the layers Ruurlo (c); and Baarlo (d), Geverik (e) and Dinantian (f)

Due to increased sediment deposition in the Upper Carboniferous and the Mesozoic, the maturity evolution of the Carboniferous source rocks is characterized by two trends, each with two distinct maturation intervals (Fig. 4a). One is the predominance of maturity increase during the Triassic until Late Jurassic (red line, Fig. 4a and b). The other exhibits a low maturity for the Carboniferous and a slight increase in maturity since the Carboniferous until today. Lower maturation occurred in the northern and partly in the southwestern part of the model. For the central part of the model a significant increase in maturity from west to east is given. Due to increased sediment thicknesses of the overlying Geul layer, the deepest Upper Carboniferous layer (Geverik) has an increase in maturity from NW to SE and reaches the oil window (>0.6 %VR_0) during the Late Carboniferous, and maximum maturation (>3.0 VR_0) during the Mesozoic (Fig. 5c). Due to significantly lower sediment thicknesses, the overlying Baarlo to Maurits source rocks have a different trend, where only the central part of the model reaches an increased maturity level (gas window). At the northern edge and partly in the southwestern part, these source rocks are still in the early mature (oil window) stage (Fig. 5b).

A Lower Jurassic source rock (Toarcian/Posidonia shale) was assumed in the model. This layer was deposited and subsequently completely eroded (Tab. A.1). The maturity of the base Upper Jurassic inceases in maturity from E to W. Close to the area of the Dutch Central Graben the base of Upper Jurassic has reached early oil window maturity (Fig. 5a). Thus, a preserved Lower Jurassic source rock would be as well in the oil window.

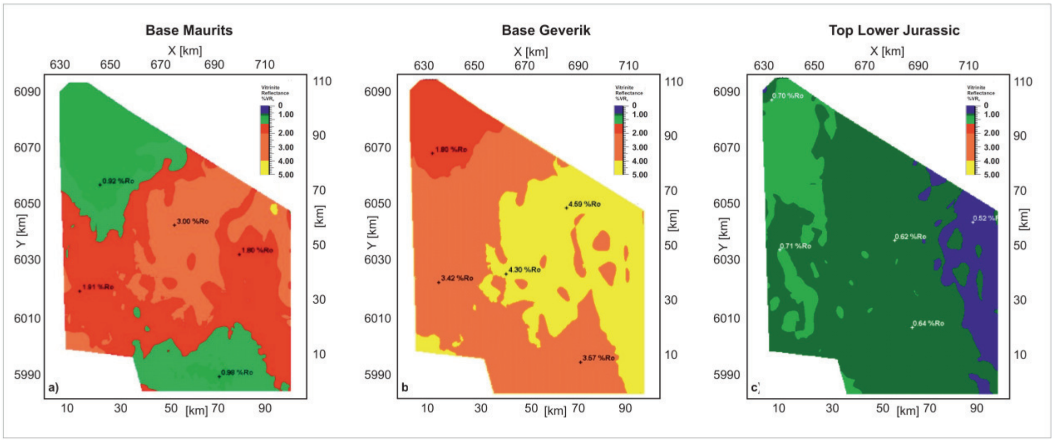

Fig. 5 Present-day maturation distribution for the a) base Maurits, b) base Geverik and c) base Upper Jurassic layer

In general the first hydrocarbon generation from the Carboniferous source rocks started in the Middle Permian (265 Ma); 50 % of hydrocarbons have been expelled at around 240 Ma. The Rotliegend and Zechstein salt act as impermeable layers and accumulations formed in numerous small reservoirs within the Rotliegend sediments. Hydrocarbon migration into Triassic and younger sediments can only occur, where salt is at least temporarily absent or faults acted as conduits. The calculated remaining potential of the Upper Carboniferous indicates no residual potential (i.e. accumulated hydrocarbons in source) for the Geverik layer and a minor residual generation potential for the other Upper Carboniferous layers. In contrast in the northwestern part of the model the Upper Carboniferous layers as well as possible residual Lower Jurassic source rocks are in the oil window at present-day, representing a remaining generation potential for this area. The results for petroleum generation, migration and accumulation indicate that almost all hydrocarbons migrated out of the Schillgrund High area until Late Cretaceous (95 %).

Numerous hydrocarbon accumulations were formed since the Early Triassic but most of them were destroyed shortly after accumulation. For the present-day situation the model shows no significant hydrocarbon accumulation

5. Conclusions

A cross-border 3D basin modeling study was performed for the Schillground High in order to understand the timing of hydrocarbon generation relative to trap formation and accumulation of hydrocarbons. Silesian coals and organic-rich shales are the major gas source rocks within the basin. Due to sediment thickness variations in the Mesozoic overburden the burial depth of the Upper Carboniferous sequences varies resulting in differences in maturity and hydrocarbon generation.

In general maximum values for temperature and maturity of the source rocks were reached during the Early Triassic to Late Jurassic, inducing hydrocarbon generation. Due to the probable loss of the generated hydrocarbons, studies of adjacent areas e.g. the Dutch Central Graben area should especially account for lateral migration (inflow) of hydrocarbons. Larger regional models should be developed to consider the varying migration directions of hydrocarbons through time from the Carboniferous as well as for potential Lower Jurassic source rocks. The basic model data, depth maps and numerous output data, will be available online at the end of the GPDN project.

References

[1] Kombrink H, Doornenbal JC, Duin EJT, den Dulk M, van Gessel SF, ten Veen JH,Witmans N. New insights into the geological structure of the Netherlands; results of a detailed mapping project. *Netherlands Journal of Geosciences* 2012, **91-4**: 419-446.

[2] Duin EJT, Doornenbal JC, Rijkers RHB, Verbeek JW, Wong TE. Subsurface structure of the Netherlands; results of recent onshore and offshore mapping. Netherlands Journal of Geosciences 2006; **85**: 245-276.

[3] Wong TE, Batjes DAJ, de Jager J, editors. Geology of the Netherlands, Amsterdam: Nederlandse Aardolie Maatschappij (NAM); 2007, pp.354.

[4] Doornenbal JC, Stevenson AG, editors. Petroleum Geological Atlas of the Southern Permian Basin Area. Houten: EAGE Publications b.v., 2010, p. 342.

[5] Baldschuh R, Kockel F, Best G, Deneke E, Frisch U, Juergens U, Schmitz J, Sattler-Kosinowski S, Stancu-Kristoff G, Zirngast M. Geotektonischer Atlas von NW-Deutschland/Tectonic Atlas of NW-Germany 1:300.000. Geologisches Jahrbuch A. Stuttgart: Schweizerbart´sche Verlagsbuchhandlung; 2001.

[6] Van Adrichem Boogaert, H.A. & Kouwe, W.F.P., editors. In: Stratigraphic Nomenclature of the Netherlands, revision and update by RGD and NOGEPA, Mededeling Rijks Geologische Dienst; 1993-1997. Internet publishing, www.dinoloket.nl/nomenclature-deep; retrieved: 04.2013.

[7] Gerling P, Geluk MC, Kockel F, Lokhorst A., Lott GK, Nicholson RA. NW European Gas Atlas – new implications for the Carboniferous gas plays in the western part of the Southern Permian Basin. In: Fleet AJ, Boldy SAR editors. Petroleum Geology of NW-Europe. London: The Geological Society; 1999; p. 799–808.

[8] Van der Molen AS. Sedimentary development, seismic stratigraphy and burial compaction of the Chalk Group in the Netherlands North Sea area. Thesis. University Utrecht; 2004, pp. 175.

[9] Plein E., editor. Stratigraphie von Deutschland I – Norddeutsches Rotliegendbecken: Rotliegend-Monographie Teil II. *Courier Forschungsinstitut Senckenberg* 1995; **183**:p.193.

[11] Gradstein FM, Ogg JG, Smith AG. *A Geologic Time Scale 2004*. Cambridge: Cambridge University Press; 2004.

[12] Bombien H, Hoffers B, Breuckmann S, Helms M; Lademann K, Lange M, Oelrich A, Reimann R, Rienäcker J, Schmidt K, Slaby M.-F, Ziesch J. Der Geotektonische Atlas von Niedersachsen und dem deutschen Nordseesektor als geologisches 3D-Modell. *GMIT* 2012; **48**:p.6-13. http://nibis.lbeg.de/cardomap3/?L-CUST-Schnitte=DOCKED

[13] www.nlog.nl/en/pubs/maps/geologic_maps/geologic_maps_3.html / www.nlog.nl/en/activity/activity.html

[14] Krull P. Paläogeographischer Rahmen. In: Wrede V., editor. Stratigraphie von Deutschland V – Das Oberkarbon (Pennsylvanium) in Deutschland. Courier Forschungsinstitut Senckenberg 2005; **254**:p. 13-24.

[15] Brückner-Röhling S, Hoffmann N, Koch J, Kockel F, Krull P: Tiefengas: Kohlenstoff-Potential im Präwestfal des NW-deutschen Beckens. Bundesanstalt für Geowissenschaften und Rohstoffe 1994, Hannover.

[16] Verweij JM, Souto Carneiro Echternach M, Witmans N, Abdul Fattah R. Reconstruction of Basal Heat Flow, Surface Temperature, Source rock Maturity, and Hydrocarbon Generation in Salt-Dominated Dutch Basins. In: Peters K, Curry D, Kacewicz M, editors. Basin and Petroleum System Modelin. 2009, Napa Hedberg Conference/Hedberg Series No. 4; 2012, p. 175-195.

[17] Van Wees JD, Van Bergen F, David P, Nepveu M, Beekman F, Cloetingh SAPL, Bonté D. Probabilistic tectonic heat flow modeling for basin maturation: Assessment method and applications*.* *Marine and Petroleum Geology* 2009; **26**:536-551.

[18] Sweeney JJ, Burnham AK. Evaluation of a simple model of vitrinite reflectance based on chemical kinetics. *American Association of Petroleum Geologists Bulletin*1990; **74**:1559-1570.