Identifying overlooked exploration opportunities from bypassed pay analysis

Emphasis on the hydrocarbon prospectivity of the Brabant Formation (Bathonian – Oxfordian) in the Roer Valley Graben and West Netherlands Basin

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Chapter 1 Executive summary

Bypassed pay analyses may reveal potentially overlooked exploration opportunities, as recognized by Lutgert et al. (2013). Analysis of a comprehensive petrophysical database reveals the presence of several overlooked exploration opportunities in the Broad Fourteens Basin, West Netherlands Basin and Roer Valley Graben. Untested hydrocarbon potential is recognized in the Chalk, Holland Greensand, Delfland, Brabant Limestone, Middle Werkendam, Lower Muschelkalk, Zechstein Fringe sandstones + carbonates and Westphalian C/D.

In particular, the understudied Middle Jurassic Brabant Formation is an excellent example of an overlooked exploration opportunity. Untested good-quality oil shows are found in more than 10 wells in the Roer Valley Graben and West Netherlands Basin. The main objectives of this study are twofold: 1) to create a conceptual geological model for the Brabant Formation, that can be used to understand and predict reservoir presence and quality on a first-order basis, and 2) to identify trap concepts. This study integrates seismic, well log and core data in combination with study of analogue formations from literature.

The Brabant Formation of the Altena Group (Bathonian - Oxfordian) comprises three re- and transgressive cycles of sandy limestone – marl deposition with an oolitic limestone on top. The present-day distribution of the Brabant Formation is, as a result of uplift and erosion, confined to the Roer Valley Graben, West Netherlands Basin and small areas in the Broad Fourteens Basin and Central Netherlands Basin. The formation is here interpreted to have been deposited on a shallow marine, transport-dominated carbonate ramp with gentle depositional slope (< 0.1º). Consequently, facies belts are wide, lateral facies changes are subtle and vertical facies changes are rapid. This has resulted in “layer-cake”-like stratification in a predominantly aggradational facies architecture. The regressive intervals have reservoir potential, whereas the transgressive intervals have seal potential for oil. Three depositional environments are recognized from cores: upper shoreface or shoal facies (inner ramp), lower shoreface facies (mid ramp) and offshore facies (outer ramp). Sandy calcarenitic and bioclastic grainstones of upper shoreface facies are clearly the most reservoir-prone (ϕ_{Avg} = 11%, K_{Avg} = 10 mD). Storm-influenced marls and calcareous siltstones of lower shoreface facies are potential waste zones with intermediate reservoir and seal properties. Offshore silty marls and claystones have seal potential for oil (ϕ_{Avg} = 8%, K_{Avg} = 0.7 mD) as proven in wells Andel-1 and Lekkerkerk-1. Gross reservoir thickness increases towards former depocentres (Roer Valley Graben, West Netherlands Basin) and is likely at a maximum in fastest subsiding grabens. In contrast, basin margin sequences are thinner and more amalgamated. During syn-tectonic deposition, grabens accumulated thicker sedimentary sequences, most likely still in similar facies. Thus, more potential net pay is expected in areas of higher subsidence (grabens). The area with highest subsidence, highest stacked reservoir potential (i.e. presence of ATBR1, ATBR2 and ATBR3) and most reservoir-prone facies is found in the northwest Roer Valley Graben and border with the West Netherlands Basin. It is speculated that throughout the Middle Jurassic this area was a large shoal, notably shallower than the basin centers of the West Netherlands Basin and Roer Valley Graben. Towards the basin center of the West Netherlands Basin, reservoir quality deteriorates slightly as a result of subtle change to more distal facies. This lateral facies change trend could not be confidently confirmed in the Roer Valley Graben due to lack of well data, but future drilling activities in this area have been planned and may help to understand this.

The Brabant Formation play is proven with two stranded oil discoveries with reservoirs at Brabant level: Andel and Lekkerkerk. Potential is further indicated by good-quality oil shows encountered in more than 10 wells in the Roer Valley Graben and West Netherlands Basin. In this area, prospectivity is demonstrated on several representative seismic sections. Four prospective trap configurations at Brabant level have been identified: fault-dip closures, downfaulted traps, inversion anticlines and sub-unconformity traps. Downfaulted and sub-unconformity traps are undrilled. Risks are primarily prospect-dependent and mainly related to charge and seal. Prospectivity in the Broad Fourteens Basin was not studied and remains speculative, but it is recognized that the formation may be locally truncated here against Vlieland Claystones acting as a seal. Future mapping of the formation will likely result in prospect identification and upgrades the hydrocarbon prospectivity of the Roer Valley Graben, West Netherlands Basin and, possibly, Broad Fourteens Basin.

Chapter 2 Introduction

Recognizing bypassed pay potential may offer exploration opportunities for the oil and gas industry. A commonly used technique to assess bypassed pay potential is through re-evaluation of vintage well log data. EBN, in collaboration with NuTech Energy Alliance, performed a petrophysical re-evaluation of 110 wells in the Broad Fourteens Basin, West Netherlands Basin and Roer Valley Graben (Figure 1; Lutgert et al., 2013). This comprehensive petrophysical database contains modeled reservoir properties, e.g. porosity, permeability, S_W and potential net pay, on high-resolution scale (10-15 cm) of formations in 110 vintage wells in the study area.

The results of this study (Figure 2) highlight the presence of mature plays in the study area. However, less known stratigraphic intervals are also recognized. Among these are the Delfland, Holland Greensand, Lower Muschelkalk, Zechstein Fringe Sandstones and Carbonates, Westphalian C/D and Brabant Formation. These potentially overlooked exploration opportunities were not analyzed in detail in Lutgert et al. (2013). Therefore, the first objective of this study is to validate the overlooked exploration potential in these formations, and identify additional opportunities. These may offer interesting opportunities for the Dutch oil and gas industry.

In particular, the Middle Jurassic Brabant Formation is an excellent example of an overlooked exploration opportunity in the West Netherlands Basin and Roer Valley Graben. There has never been commercial oil production from this potential reservoir, even though in more than 28 different wells untested oil shows are found, clearly demonstrating remaining oil potential. The formation comprises three intervals of sandy limestones alternating with marls, deposited in a predominantly shallow-marine environment in the Roer Valley Graben, West Netherlands Basin, Broad Fourteens Basin and Central Netherlands Basin (Van Adrichem-Boogaert & Kouwe, 1993-1997). However, not much is known about this formation and specific literature is scarce. The main objective of this study is therefore to construct a conceptual geological model for the Brabant Formation, with focus on understanding the depositional and tectonic setting. This is done by integrating seismic, well log and core data. The conceptual model may aid in de-risking reservoir presence and quality in leads. Oil shows in more than 28 different wells show that the formation may be a prospective reservoir. Identifying trap concepts may help to upgrade this prospectivity. So, a second objective of this study is to identify trap concepts at Brabant level. This is done by reviewing seismic, well data and existing play concepts.

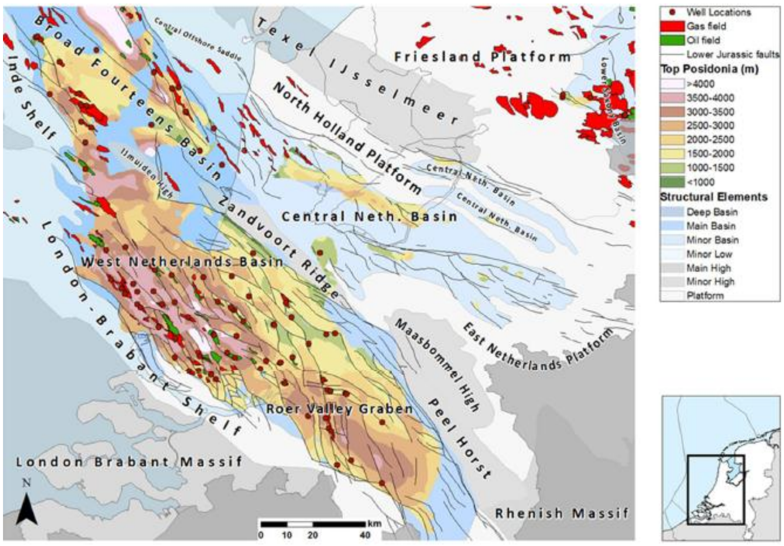


Figure 1. The study area comprises the Broad Fourteens Basin, West Netherlands Basin and Roer Valley Graben. Black dots: wells used in petrophysical evaluation. From Lutgert et al. (2013).

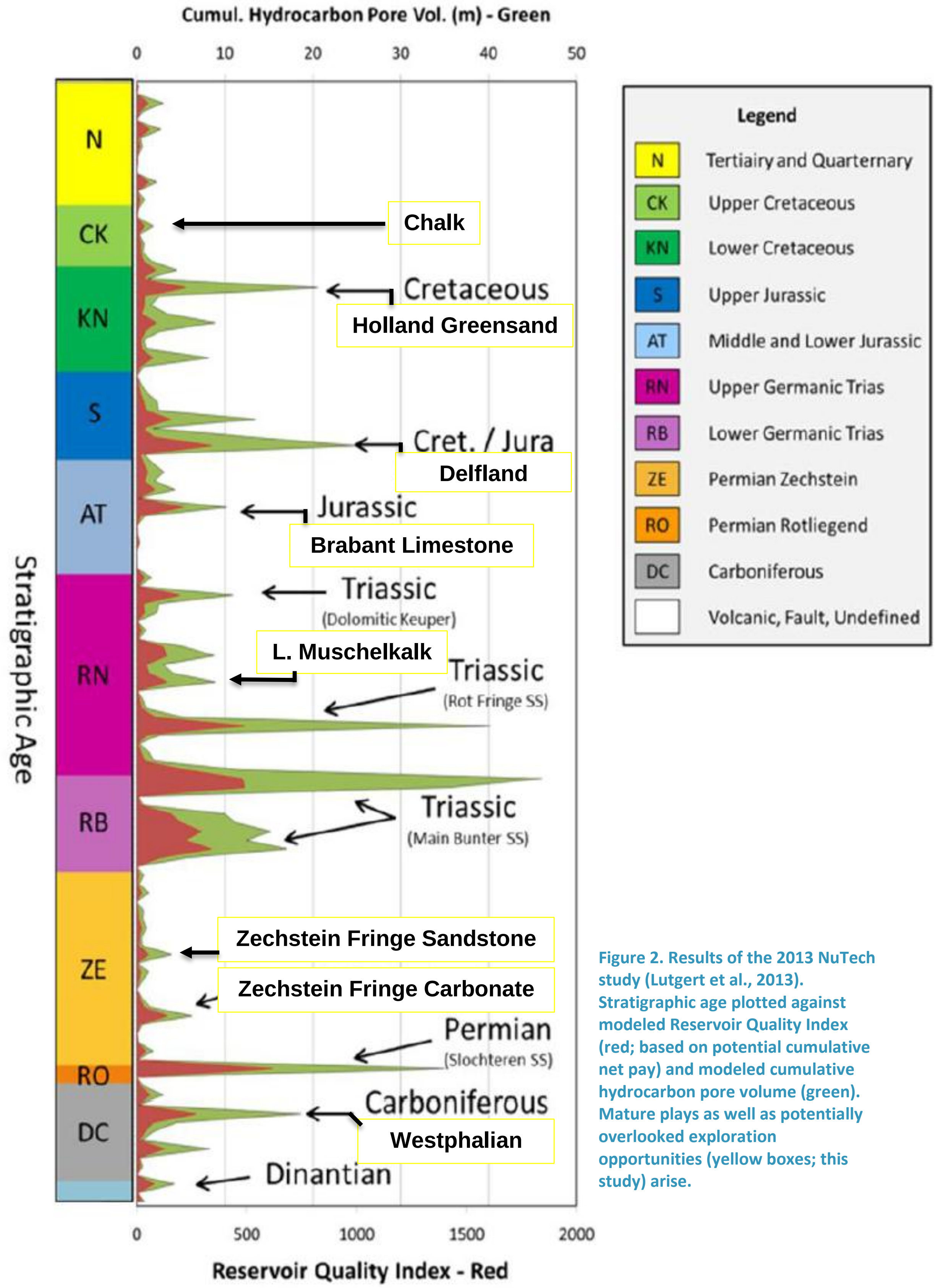


Figure 2. Results of the 2013 NuTech study (Lutgert et al., 2013). Stratigraphic age plotted against modeled Reservoir Quality Index (red; based on potential cumulative net pay) and modeled cumulative hydrocarbon pore volume (green). Mature plays as well as potentially overlooked exploration opportunities (yellow boxes; this study) arise.

Chapter 3 Geological framework of the study area

This chapter is the first in a series to evaluate the overlooked exploration potential in the Broad Fourteens Basin, West Netherlands Basin and Roer Valley Graben. In order to lay a solid foundation for this, a brief summary of the recent geological history of the study area is presented here on a regional scale, beginning with the structural elements in the area (Chapter 3.1), then presenting the geological history from ~Silurian to recent (Chapter 3.2).

3.1 Structural elements

The study area makes up part of the 'Dutch southern on- and offshore basins'. The structural elements are shown in Figure 1 and described below. The synthesis is mainly based on work presented by De Jager (2007) and references therein.

Broad Fourteens Basin (BFB)

The NW-SE trending Broad Fourteens Basin is a strongly inverted rift basin. The main rifting period was Late Jurassic – Early Cretaceous, as for the other basins; minor faulting also occurred in the Permian and Triassic. Late Cretaceous inversion almost entirely removed the Upper Cretaceous Chalk and in part the Lower Cretaceous. Zechstein salt acted as a detachment zone for the inversion process. The boundary to the east to the Central Netherlands Basin is gradual. To the north it is bounded by the Cleaverbank Platform.

West Netherlands Basin (WNB)

The West Netherlands Basin is a NW-SE trending rift basin in the southern on- and offshore Netherlands. Rapid fault-bounded subsidence related to rifting and thermal doming occurred in Late Jurassic – Early Cretaceous. The basin is characterized by a thick Upper Jurassic synrift sedimentary sequence (Delfland Group). Its north(eastern) part was strongly inverted during the Late Cretaceous and Paleogene. Its dominant NW-SE structural trend probably already existed since the Silurian-Devonian Caledonian orogeny (De Jager, 2003). The boundary to the Roer Valley Graben in the southeast is gradual and its tectonic history less well understood. The southern transition to the London Brabant Shelf and Massif is marked by a fault zone. In the north, the WNB is separated from the Broad Fourteens and Central Netherlands basins by a fault zone which incorporates the Zandvoort Ridge.

Roer Valley Graben (RVG)

The NNW-SSE trending Roer Valley Graben in the Dutch southern onshore Netherlands comprises the eastern extension of the Sole Pit - Broad Fourteens - West Netherlands Basin rift system. It is a rift basin consisting of several fault-bounded halfgrabens. Main rifting periods are in the Late Jurassic - Early Cretaceous and Oligocene - recent. It developed on pre-existing sedimentary basins of Carboniferous, Triassic and Early-Mid Jurassic age. Rapid fault-bounded subsidence commenced in the Late Jurassic with deposition of Delfland sandstones and shales. Thickness variations in the Altena Group may already point to increased subsidence in the Early-Mid Jurassic in axial parts of the basin. The (Early) Cretaceous history is poorly understood due to missing sediments of this age. Rapid subsidence re-commenced in the Oligocene and continues to present-day, as evidenced by the active Peel Boundary Fault. Strong Late Cretaceous inversion affected only the north(eastern) part of the basin, whereas mild inversion affected also the middle part of the basin. As for the West Netherlands Basin, its structural trend was probably already established during Paleozoic times. The basin is bounded to the northeast by the fault zone of the Peel Block and Maasbommel High, and to the south by the London Brabant Shelf and Massif (Campine Block).

London-Brabant Massif (LBM)

The London-Brabant Massif is located to the south of the West Netherlands Basin and Roer Valley Graben and is officially defined as the area where Upper Cretaceous or younger sediments overlie Cambro-Silurian rocks. Only the southernmost part of the Zeeland province is attributed to the LBM. The Massif acted as a stable high area over much of geological history, where erosion and/or nondeposition prevailed.

3.2 Geological history

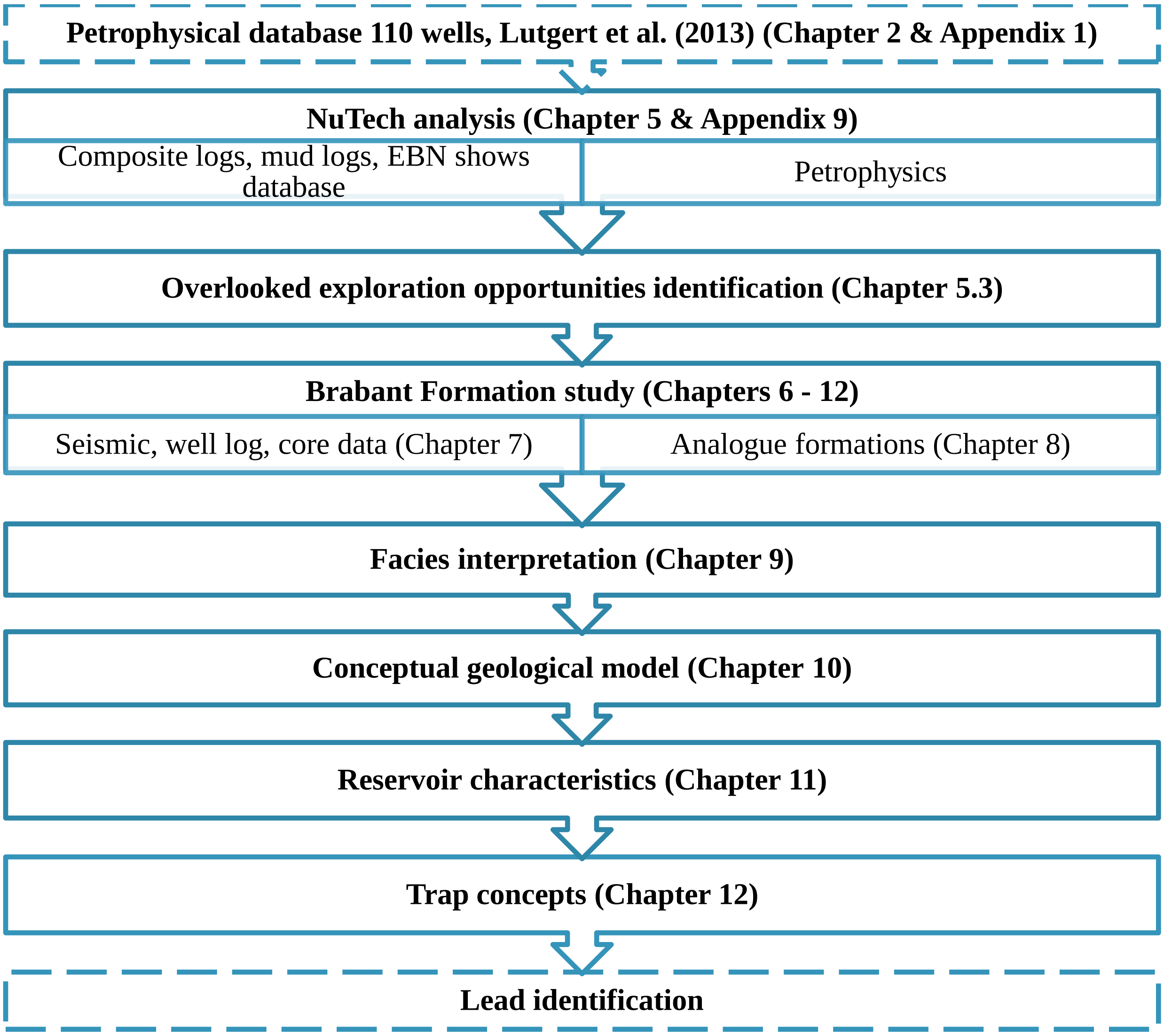
The petroleum geological history of the Netherlands started in the mid Paleozoic with the collision of Laurentia and Baltica: the Caledonian orogeny. This large-scale mountain building event occurred from the Ordovician to Silurian (500 to 400 Ma). The Netherlands was located ~30° south of the equator. The orogeny formed in a dominant NW-SE structural trend. This trend became later an important and persistent structural feature throughout the entire Dutch subsurface. Deformed Caledonian sequences form the basement rocks for the overlying, younger sedimentary sequences. The first sediments deposited on the basement are likely of Silurian and Devonian age, but they have rarely been encountered in boreholes.

During the Carboniferous, Laurussia and Gondwana collided to form the supercontinent Pangea: the Variscan orogeny. During this time, the Netherlands drifted northwards, passing the equator into the humid equatorial climate belt. Sedimentation in the foreland of the Variscan orogeny in the Carboniferous consisted primarily of Dinantian platform carbonates, Namurian marine deposits and Westphalian upper coastal plain facies. Late Carboniferous – Early Permian uplift, folding and erosion produced an important regional unconformity: the Base Permian Unconformity.

By Early Permian times, a large, regionally subsiding basin (Southern Permian Basin) established, trending all the way from the UK to Poland. In this basin, Late Permian eolian and fluvial clastics of the Rotliegend Group accumulated, followed by several marine trans- and regressions depositing carbonates and evaporites of the Zechstein Group. Triassic to Middle Jurassic sedimentation took place in the Southern Permian Basin in relative tectonic quiescence (thermal subsidence). In general, sediments consist of sandstones, claystones, marls, carbonates and anhydrites of the Germanic Trias Group (Main and Upper Buntsandstein, Muschelkalk, Keuper). The Lower to Middle Jurassic Altena Group consists of predominantly fine-grained lithologies (claystones, bituminous shales and siltstones), deposited in widespread epicontinental seas that spread across northwest Europe. The bituminous claystones of the Posidonia Formation form an important oil source rock in the Netherlands. The top of the Altena Group consists of a regressive, shallow marine carbonate succession (Brabant Formation).

In the Late Jurassic, rifting commenced in the Broad Fourteens Basin, Central Netherlands Basin, West Netherlands Basin and Roer Valley Graben. The syn-rift basin fill in these transtensional pull-apart basins consists primarily of continental sandstones and shales of the Delfland and Breeveertien Formation, deposited in a coastal plain setting. This Late Kimmerian rifting event had a pronounced effect on the present-day structuration of the Dutch subsurface. Extension rates decreased during the Early Cretaceous; the basins passed into the post-rift thermal subsidence stage. During the Late Cretaceous, widespread marine transgression caused the deposition of thick chalk sediments all over the Netherlands. Compressional stresses in the south, related to the Alpine collision, caused large-scale basin inversion in the Dutch southern on- and offshore basins during the Late Cretaceous and Early Tertiary. The inversion process was rather continuous, but four accelerated pulses have been recognized (De Jager, 2003): each basin reacted differently to different pulses and to varying degree, depending on structural style. In the West Netherlands Basin, transpressional stresses formed several positive flower structures. During the Tertiary, the basins were under the influence of rapid subsidence and high sedimentation rates, caused by westward prograding delta systems of the Eridanos River. In the Roer Valley Graben, thick sedimentary sequences accumulated from the Oligocene to recent.

Chapter 4 Workflow



Study workflow. Dashed boxes indicate previous or future study work.

4.1 Data input

Data input for the NuTech analysis is the in-house 2013 NuTech study database by Lutgert et al. (2013). This comprehensive database consists of petrophysical well log interpretations of 110 vintage wells, modeled by NuTech Energy Alliance. Petrophysical properties as V_{Clay}, porosity, permeability, S_W, lithology, bound *vs.* free water, pore size distribution and net pay are recorded in this database on sample level (10-15 cm) for each well. Hydrocarbon show data comes from an in-house EBN oil and gas shows database. This database qualifies shows as 'poor', 'fair' and 'good'. Additional hydrocarbon show data for the Brabant Formation comes from manually checking mud and composite well logs. These are public and provided through the "Nederlands Olie- en Gasportaal" website (www.nlog.nl). 3D seismic data (TerraCube onshore) and vintage 2D seismic lines (digitized and phaseshifted by Van Der Kroef (2014)) are used for seismic analyses. Fault framework interpretations are provided by Van Der Kroef (2014). Well log data comes from the 2013 NuTech study database (petrophysical log interpretations) and NLOG website; this data has been loaded in Petrel software for correlations. Cores of the AND-04, AND-03-S2, VEH-01 and LOZ-01 wells are provided by the NAM corestore. AND-03-S2 core has been slabbed on request by NAM (Jan Tillema).

4.2 Methodology NuTech analysis

Lutgert et al. (2013) showed there is good correlation between modeled NuTech hydrocarbons and hydrocarbon shows qualifying as 'good' in the EBN oil and gas shows database. This preliminary analysis is done in this study into more detail, by looking specifically at the level of each exploration opportunity. To validate each exploration opportunity identified in Lutgert et al. (2013), a detailed analysis of the NuTech petrophysical database is first carried out. This analysis focuses on making sure that modeled hydrocarbons are actually truly present in the formation. This is done by manually checking all composite well logs, mud logs and well reports searching for oil and/or gas shows. This is done in combination with calibration to the in-house EBN oil and gas shows database. If via both ways no hydrocarbons appear to be present, the petrophysics will be checked to validate potential hydrocarbon presence. This is done because hydrocarbons can still be present, even if they are not or poorly recorded during drilling. Reasons for this may be drilling with heavy mud weights or mud cake formation in the borehole. In addition, the analysis allowed to assess the reliability of the NuTech modeling.

In order to assess the remaining potential, untested hydrocarbon shows for each formation are compared with modeled reservoir properties and number of producing fields in the area. A prioritized list is made based on these three characteristics, in combination with local geological knowledge of the formation. The formation's remaining exploration potential will be discussed.

In these ways, the 2013 NuTech study database will be analyzed and quality-checked. This results in a prioritized list of several overlooked exploration opportunities: formations exhibiting fair-good reservoir properties but potentially overlooked by the industry (for whatever reason). Such targets may form interesting exploration opportunities.

In particular, the Brabant Formation shows high priority and classifies as an interesting overlooked opportunity. This formation has been studied into more detail.

4.3 Methodology Brabant Formation study

The main focus of this study is a Brabant Formation scoping study. It focuses on constructing a conceptual geological model for the formation and identification of trap concepts.

Since there is almost no specific literature about the Brabant Formation, a literature study concerning the Jurassic and post-Jurassic tectonic and depositional history of the Roer Valley Graben has been carried out.

The conceptual geological model is approached from the seismic, well log and core scale. At the seismic scale, 3D and 2D seismic has been analyzed for seismic character of the formation, as well as thickening/thinning trends. At the well log scale, wireline logs in combination with biostratigraphic reports and lithostratigraphic well tops are used to identify correlation surfaces (maximum flooding surfaces, sequence boundaries) and aid in correlation. Lithostratigraphic correlations are made to recognize stratigraphic build-up (sedimentary stacking patterns), thickening/thinning trends and possible proximal/distal trends. At the core scale, sedimentary facies and depositional environments are identified from facies analysis of the AND-04 and AND-03-S2 cores, and from cuttings descriptions in composite well logs. In particular, the reservoir/seal potential of the facies is addressed.

Time-equivalent carbonate successions, comparable to the Brabant Formation, have been studied from the Weald Basin (UK) and Paris Basin (France), as well as from the Sole Pit Basin (UK). Concepts used to explain these formations and other, comparable “layer-cake”-like carbonate successions such as the Muschelkalk have been adopted and used in the conceptual geological model.

The results of the seismic, well log and core scale observations and interpretations are integrated in a conceptual geological model. The model is briefly explained in terms of the depositional, tectonic, climatic and diagenetic setting, although focus is on the depositional and tectonic setting.

Facies interpretation from core is calibrated to well log data using cuttings descriptions from logs and cluster analysis (*K*-Means Clustering). On the basis of this, facies interpretation is carried out in Petrel for wells holding sufficient log data (gamma ray, resistivity, sonic). The relative fraction of each facies per lithostratigraphic interval has been plotted to create a facies distribution map.

On the basis of the conceptual geological model and facies distribution map, first-order predictions about reservoir sweetspot location (presence, thickness and quality) can be made. Reservoir characteristics are studied using poroperm crossplots based on core plugs, and based on NuTech well log interpretations. First-order seismic interpretation of several seismic lines (no mapping) is carried out to show different trap geometries in which the formation may occur. On the basis of this, in combination with well data analysis and evaluation of existing play concepts, four prospective trap concepts are identified in the study area. These are discussed in a petroleum geological context (source, reservoir, seal, timing, migration, risks) and may help to upgrade oil prospectivity in the study area.

Chapter 5 NuTech analysis

The petrophysical log interpretation has been carried out by NuTech Energy Alliance, a USA-based petrophysical analysis consulting company with good reputation in petrophysical well log interpretation (Lutgert et al., 2013). This chapter summarizes the results and reliability of their modeling, as well as how this has helped in the identification of several overlooked exploration opportunities.

5.1 NuTech's interpretation workflow

NuTech followed a specific interpretation workflow during petrophysical analysis of the 110 selected vintage wells from the Broad Fourteens Basin, West Netherlands Basin and Roer Valley Graben. Most of these vintage wells suffer from poor vertical resolution. NuTech applies a resolution enhancement technique and performs a textural analysis on a well-by-well basis.

Resolution enhancement is achieved by using the second derivative of the log curve with the best vertical resolution in the available log data set, often shallow or microresistivity. This curve is used to 'boost' the other curves with poorer vertical resolution. This is based on deconvolution and the assumption that the second derivative of the microresistivity (e.g. the inflection points of microresistivity peaks) corresponds to lithological bed boundaries. Vertical resolution for all wells is boosted to either 10 or 15 cm.

The textural analysis models lithology and petrophysical properties (porosity, permeability, S_W, bound *vs* free water *vs* free hydrocarbons), so that potential net pay zones can be identified. The technique behind this relies on calibration to Nuclear Magnetic Resonance (NMR) data. NuTech calibrates conventional well log responses (such as gamma ray, SP, resistivity and porosity-indicating logs) to synthetically modelled NMR outputs from an extensive database with over 100,000 wells, using a neural network. In this way, NuTech is able to determine critical petrophysical parameters such as porosity, permeability, Sw and thus potential net pay, using only conventional log data as input. As no NMR data is available in any of the 110 wells in the study area, outcomes are uncalibrated and therefore uncertain. In this study, it is assumed that NuTech's in-house well database contains a sufficiently large number of wells with similar log responses to ensure robust interpretation.

This allows identification and risk-rating of potential net pay zones. All depth samples are risk-rated. NuTech used petrophysical cut-off criteria to identify the potential net pay zones. Only samples with more than 40% hydrocarbon saturation and permeability >0.1 mD are included in the analysis. Samples that fall in this class are added up per stratigraphic formation, and ranked according to stratigraphic age. This results in a 'cumulative potential net pay' for each formation. This is multiplied by the average risk-rate of the pay zone (i.e. reservoir quality). This results in a Reservoir Quality Index (RQI). The higher the RQI, the more potential net pay can be expected for that formation. The RQI corresponds to the red curve in Figure 2.

5.2 Results of NuTech's modeling

The NuTech analysis focuses on analyzing the Lutgert et al. (2013) petrophysical database to validate modeled hydrocarbon presence. The detailed analysis and results per exploration opportunity are presented in Appendix 9; hydrocarbon shows in overlooked exploration opportunities are listed in Appendix 2.

From the results of this analysis, it can be concluded that in some formations NuTech's model works reasonably well, whereas in other formations the model is less reliable. Well-modeled formations are generally sandstone and sand/shale formations (Delfland sand/shales, Zechstein Fringe Sandstones, Westphalian sand/shales), preferably gas-prone (Zechstein Fringe, Westphalian) and with abundant input logs available. In carbonate and/or anhydrite-rich formations (Dolomitic Keuper, Muschelkalk, Brabant Formation, Chalk Group), the model is far less reliable. It appears that NuTech's model often misinterprets low gamma ray and high resistivity for porous, hydrocarbon-bearing limestone when in fact, this should be anhydrite or tight water-filled limestone. This leads to false high hydrocarbon saturations, 'false pay'. Examples of this are shown in Figure 5 of Appendix 9.

So, factors that appear to play a dominant role in model accuracy are 1) availability of input logs, 2) standard model input parameters that were used, 3) insufficient reservoir parameter information to calibrate the model to (i.e. insufficient poroperm from core data), 4) show type (gas vs. oil), and 5) dominant formation lithology (sand vs. carbonate/anhydrite).

In general, increasing the amount of input logs increases accuracy of modeling results (see Figure 11 of Appendix 9). However, it appeared that this relationship does not always hold.

The standard model input parameters used by NuTech are constant for each well. These are the reference matrix density, matrix fluid density, matrix sonic velocity, formation water resistivity and the "m" and "n" exponents of the Archie equation. In cases of model failure when abundant input logs are available, it seems that these standard input parameters are incorrect and that the model is not calibrated. Possibly the "m" exponent in Archie (cementation factor), often taken constant in the model at 2, may play a big role in modeling of carbonate formations.

In addition, core plug measurements are generally scarce, and typically only available for well-studied reservoir formations. So, lack of calibration to core data may also play a role in model accuracy.

Moreover, it appears that NuTech's model accuracy is higher for gas-prone formations (Permian and Triassic age sourced by Westphalian) than for oil-prone formations (Late Jurassic-Early Cretaceous age sourced by Posidonia). This may be related to the more pronounced effect of gas on wireline log response (neutron, density, resistivity). In addition, since the Netherlands is a gas country, there are far more gas than oil wells, so statistically the model may be better calibrated to gas as well.

There are a wide range of other factors that may play a role when comparing mud log shows with modeled hydrocarbon shows. For example, show logging in open hole may have influenced gas readings during mud logging and cause overestimation of the mud log show. In contrast, mud cake formation and high mud weights used during drilling may suppress gas shows.

To conclude, NuTech modeling results are generally best in sand-prone formations, where abundant input logs are available and predominantly gas shows are found (e.g. Rotliegend, Bunter, Zechstein Fringe Sandstone Members). Modeling results are less reliable in carbonate- and/or anhydrite-rich formations such as the Dolomitic Keuper, and to a lesser extent Muschelkalk, Brabant Formation and Chalk.

5.3 Overlooked exploration opportunities

The RQI, or 'cumulative potential net pay', for each formation has been plotted against the number of producing fields per reservoir in Figure 3. Only producing fields and fields abandoned after production in the study area have been taken into account. Poorly modeled lithologies ('false pay'), such as the Dolomitic Keuper, are omitted. The RQI of the Bunter, Vlieland Sandstones and Zechstein

Fringe Sandstones has been grouped together, e.g. the Bunter consists of the cumulative RQI's of all Triassic reservoir sandstones.

The graph shows that the Bunter clearly has the highest RQI and most producing fields (75), predominantly gas fields. This is no surprise - the Bunter is a mature play in the area (De Jager et al., 1996). Other prolific reservoirs in the area are found in the Vlieland Sandstones (KNNS), Alblasserdam (SLDN; Delfland), Rotliegend (RO), Zechstein 3 Carbonates (ZEZ3C; Plattendolomit), Holland Greensand (KNGLG), Zechstein Fringe Sandstones (ZEFR) and the Middle Werkendam Member (ATWDM).

Five formations with relatively high RQI and no producing fields are identified in the area. From poor to good RQI, these are the Zechstein 1 Fringe Carbonate (ZEZ1F), Lower Muschelkalk (RNMUL), Chalk Group (CKGR), Hellevoetsluis Fm (DCDH; Westphalian C/D Sandstones) and Brabant Formation (ATBR). The hydrocarbon potential in these formations, in combination with the Holland Greensand, Delfland, Lower Muschelkalk and Zechstein Fringe Sandstones, is discussed into more detail below. A summary of this assessment is given in Table 1, including a priority per formation for follow-up studies, based on untested hydrocarbon shows, producing fields and modeled reservoir properties. They are briefly discussed according to stratigraphic age (from youngest to oldest).

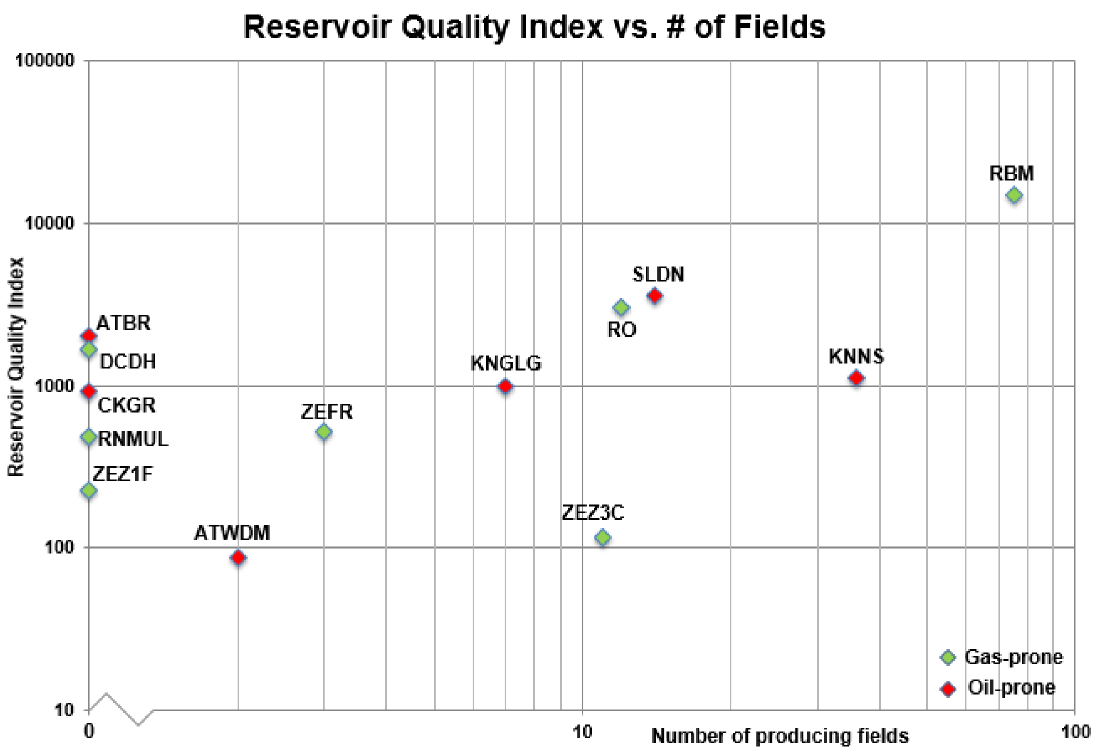


Figure 3. RQI plotted against number of producing fields per stratigraphic formation. 5 formations plot on the y-axis (0 fields): potentially overlooked exploration opportunities. These are the Zechstein 1 Fringe Carbonate (ZEZ1F), Lower Muschelkalk (RNMUL), Chalk Group (CKGR), Hellevoetsluis Fm (DDH) and Brabant Limestone (ATBR). Other remaining potential may exist in the Middle Werkendam Member (ATWDM), Zechstein Fringe Sandstones (ZEFR) and Holland Greensand Member (KNGLG).

Table 1. Summary of the exploration potential assessment for the potentially overlooked exploration opportunities, identified in this study and Lutgert et al. (2013). For 5 opportunities, no fields exist in the study area (green). Last column shows interpreted priority (high, medium, or low) for follow-up studies, based on an assessment of untested hydrocarbon shows, modeled reservoir properties and already producing fields in the study area. See text below for explanation per formation.

Overlooked exploration opportunities	Producing fields			Fair/good quality untested hydrocarbon shows (# of wells)			Modeled reservoir properties *(underlined = unreliable)*	Priority
	RVG	WNB	BFB	RVG	WNB	BFB		
Chalk Group	0	0	0	0	4	0	Poor - Fair	Low - Medium
Holland Greensand	-	7	-	-	6	-	Fair – Good	Medium
Delfland subgroup	0	14	-	10	9	-	Excellent	High
Brabant Formation	0	0	0	22		0	Fair	High
Lower Muschelkalk	0	0	0	11			Excellent	Medium
ZE Fringe Sandstones	-	3	-	-	10	-	Good	High
ZE 1 Fringe Carbonate	-	-	0	-	-	7	Fair	Medium
Westphalian C/D	0	0	-	8		-	Good	Medium

5.3.1 Chalk Group

The Upper Cretaceous Chalk Group (CKGR) comprises a thick sequence of carbonate rocks (bioclastic and marly limestones) that were deposited over large parts of northwest Europe during widespread marine transgression. The sequence was deposited in most of the Netherlands, but subsequently eroded in areas subjected to inversion. The formation onlaps onto the London-Brabant Massif. It is deposited in water depths of 50 – 300m, but towards the London-Brabant Massif, a more shallow-marine environment prevailed where occasionally glauconitic sandstones interfinger with limestones.

A poor correlation between NuTech's modeled shows and mud log shows (Appendix 9) indicates that NuTech's petrophysical model is unreliable in this limestone formation. Average modeled reservoir properties (unreliable) are poor to fair (ϕ = 15%; K = 1 mD; S_W = 69%; Appendix 1). The Chalk is a proven reservoir in many oil and gas fields in the Danish sector of the North Sea. In the Dutch sector, the only producing Chalk field is the Hanze field. In 2012, Wintershall discovered oil in the Chalk in the F17 block. No commercial Chalk discoveries have been made in the study area, but 4 wells are found with good-quality oil and gas shows, of which 1 well has been production-tested at Chalk level. P15-01 (Amoco, 1974) tested both oil and gas at reasonable rates (150 BOPD and 1,800 MCF/D, respectively) but the well was plugged back and abandoned, for unknown reasons. These findings may indicate remaining potential. A recent study by Rodriguez et al. (2014) in the UK sector of the North Sea addresses the prospectivity of this formation in the Sole Pit Basin. This potentially indicates that remaining potential may exist on a large, North Sea-wide scale. The proven play in the Danish, UK and Dutch northern sector, in combination with few good-quality hydrocarbon shows and moderate production-test results in the West Netherlands Basin, may indicate that the Chalk has some upside potential in the study area. Due to the limited amount of hydrocarbon shows and worse NuTech reservoir properties however, it is here interpreted as a low- to medium-priority target.

Major uncertainties in Chalk exploration are (distribution of) intra-Chalk reservoir/seal properties, i.e. when does it behave as a reservoir and when as seal. Current studies investigating this may elucidate this in the near future. Trap style and charge may also be challenges. At least one trap structure has been identified on seismic in the P11a/b-block (E. Rosendaal, pers. comm.). It is not known at this time whether there is more trap potential for the Chalk in this area. In some places, the long migration pathway from possible source rocks such as the Posidonia may be a significant charge risk.

5.3.2 Holland Greensand Member

The Lower Cretaceous Holland Greensand Member (KNGLG) is a glauconitic, transgressive, very fine to fine-grained sandstone deposited in a roughly NW-SE trending direction in the on- and offshore WNB (Figure 4). It shales out rapidly towards the north into the Middle Holland Claystone, while towards the south, the Spijkenisse Greensand Member may represent more proximal facies (Van Adrichem-Boogaert & Kouwe, 1993-1997). The abundant occurrence of the radioactive mineral glauconite may have led to too pessimistic assessments of reservoir quality in the past.

A fair correlation has been found between NuTech's modeled hydrocarbon shows and mud log shows (Appendix 9). Modeled reservoir properties for this formation are reasonably good: average $\phi = 25\%$ and $K = 40$ mD (Appendix 1). 23 oil and gas shows in 19 wells are found in this formation. Of these, good hydrocarbon shows in 9 wells are proven pay: production from this reservoir comes from 7 fields in the Rijswijk concession. It can be regarded as part of the Late Jurassic-Early Cretaceous play, where hydrocarbons are trapped in inverted anticlines in the West Netherlands Basin (De Jager et al., 1996). However, 6 wells have good-quality untested oil shows and point to remaining oil potential. The abundant producing fields, in combination with relatively few hydrocarbon shows, are reason to interpret this formation here as a medium-priority target for follow-up studies.

It is speculated here that the short shale-out distance of this formation towards the north (Van Adrichem-Boogaert & Kouwe, 1993-1997) into the Middle Holland Claystone may point to stratigraphic trap potential. The Middle Holland Claystone would then provide both side and top seal. Understanding reservoir quality and lateral facies change is a pre-requisite for successful exploration.

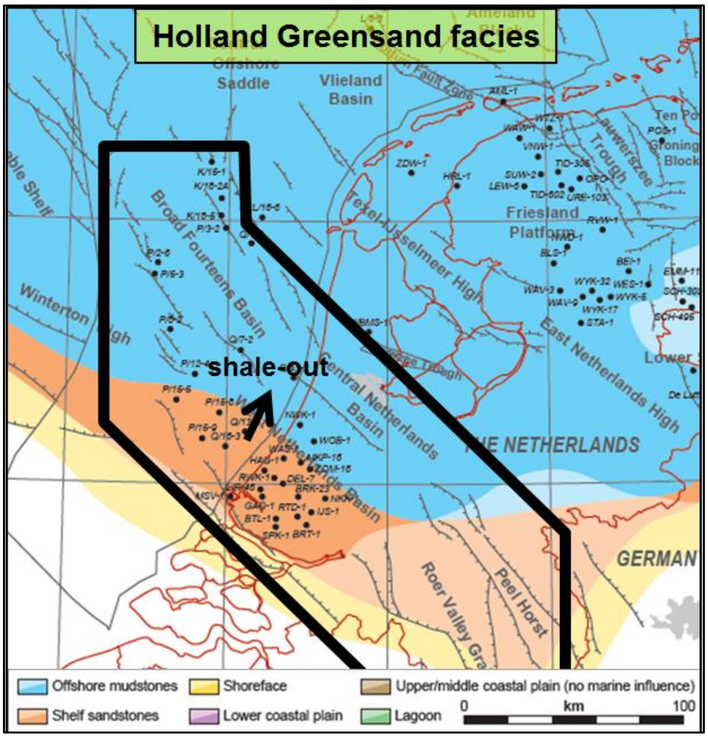


Figure 4. Holland Greensand facies map (Jeremiah et al., 2010) showing the rapid northward shale-out into the Middle Holland Claystone. It is speculated here that this may offer stratigraphic trap opportunities. Study area outlined in black.

5.3.3 Delfland subgroup

The Late Jurassic – Early Cretaceous Delfland subgroup (SLDN) is composed of continental sandstones, shales and coal seams deposited in lower/upper coastal plain settings as braider-river and meandering valley fills. The oldest deposits (Late Oxfordian) are found in the Roer Valley Graben and rest unconformably on limestones and marls of the Brabant Formation. The early syn-rift Delfland sequence in the Roer Valley Graben is poorly understood (DeVault & Jeremiah, 2002).

The reasonable correlation between NuTech's modeled shows and mud log shows (Appendix 9) indicates that NuTech's petrophysical model is reasonably reliable for this oil-prone formation. Modeled reservoir properties are excellent: average ϕ = 16% and K = 91 mD (Appendix 1). In the study area, most produced oil from Delfland reservoirs comes from 12 fields in the Rijswijk concession. Abundant (100+) good-quality oil shows in over 50 wells in the Roer Valley Graben and West Netherlands Basin clearly indicate the prospectivity of this proven play. Most of these oil shows are proven pay. However, 19 different wells have untested, good-quality oil shows, of which 10 are located in the Roer Valley Graben. There are no fields currently producing from Delfland reservoirs in the Roer Valley Graben. It is therefore concluded that there is still considerable remaining oil potential for the formation in this basin. It is here interpreted as a high-priority target and may be interesting for a follow-up study.

In general, excellent porosities and permeabilities are found in the stacked reservoir-prone channel sandstones. Main risk is likely to be reservoir connectivity and seal integrity of the intra-Delfland shales. The shales can be sealing for oil as proven in fields in the Rijswijk concession. The near-transparency of the formation on seismic makes it difficult to predict reservoir and seal presence and quality. The lateral equivalent of the Delfland in the Broad Fourteens Basin (Breeveertien Formation) has not been studied but may have remaining potential as well.

5.3.4 Brabant Formation

The Middle Jurassic Brabant Formation comprises an up to 350m thick sequence of sandy limestones and marls with two stranded oil discoveries: Andel and Lekkerkerk. Untested oil shows are found in 29 wells scattered over the West Netherlands Basin and Roer Valley Graben (Figure 5). Most oil shows are of fair to good quality (22) and are situated in the (north)western sector of the Roer Valley Graben and Lekkerkerk-Moerkapelle area of the West Netherlands Basin. Quality of the oil shows varies from poor fluorescence indications (7) to good streaming and blooming cuts (10), to tested and produced intervals (3). Appendix 3 lists all the wells with oil shows + depth intervals and descriptions, that have been found in the Brabant Formation. Drill-stem tests from at least three different wells have produced small (sub-commercial) hydrocarbon volumes from the Brabant Formation: Moerkapelle-06-S1 (oil), Lekkerkerk-01 (oil) and the Andel 1-6 wells (oil and gas). Reservoir intervals are most often sandy limestones or calcareous sandstones, occasionally silty marls.

Two stranded oil discoveries with reservoirs at Brabant level are known in the area and discussed below: Andel and Lekkerkerk.

Andel field

The Andel stranded field was discovered by well Andel-01 in 1949 (NAM). The field is located in the NW Roer Valley Graben on a regional, inverted high (inverted horst block) (Figure 6A). The field contains oil in stacked reservoirs of the Delfland, Brabant (ATBR1-2-3) and Middle Werkendam formations. The seismic is not very clear over the structure as a result of extensive fracturing and faulting: it appears that the trap is structurally relatively complex and compartmentalized. This is also evidenced by the Andel-1 to -6 wells, which encountered some intervals at Brabant level to be hydrocarbon-bearing, whereas others were water-bearing. Biodegraded, heavy oil (16-20º API) and gas were produced from the Brabant interval. Oil flow rates were generally low (30 BOPD) whereas gas flowed at a rate of 31k m^3/d gas. This initial reasonable gas flow rate decreased significantly following an acid frac. Average Brabant porosity is estimated at 15% and average permeability at 0.1 – 3.3 mD. The high oil viscosity and reservoir compartmentalization could have been reasons for the abandonment of the field.

Lekkerkerk field

The Lekkerkerk stranded field (West Netherlands Basin) was discovered by well LEK-01 in 1959 (NAM). The trap is a fault-dip closure (Figure 6B) and contains oil at two separate levels, the Delfland and Brabant Formations (ATBR3). Top seal is provided by intra-Delfland shales and Upper Brabant Marl, respectively. Lateral seal is probably provided by the sealing fault and juxtaposed Delfland shales. For the Brabant interval, average porosity is assumed at 25% with a minimum net pay of 10m. A DST produced “10-15% oil” (1.7 m^3 22º API). STOIIP estimates for the field range from 1 to 2 million m^3 proven and an additional 0 – 0.5 million m^3 expected (TNO fact sheet, 2009). However, after testing, the well was plugged and abandoned.

Due to 1) the high modeled Reservoir Quality Index with fair reliability as identified by the NuTech modeling, 2) abundant good-quality, untested oil shows in the area, 3) presence of two stranded oil discoveries with reservoirs at Brabant level, and 4) no fields producing from Brabant level in the study area, the Brabant Formation proved to be the top-priority formation with the highest remaining exploration potential. It was selected as the primary research objective of this study. Results of this are given in Chapters 6 to 12.

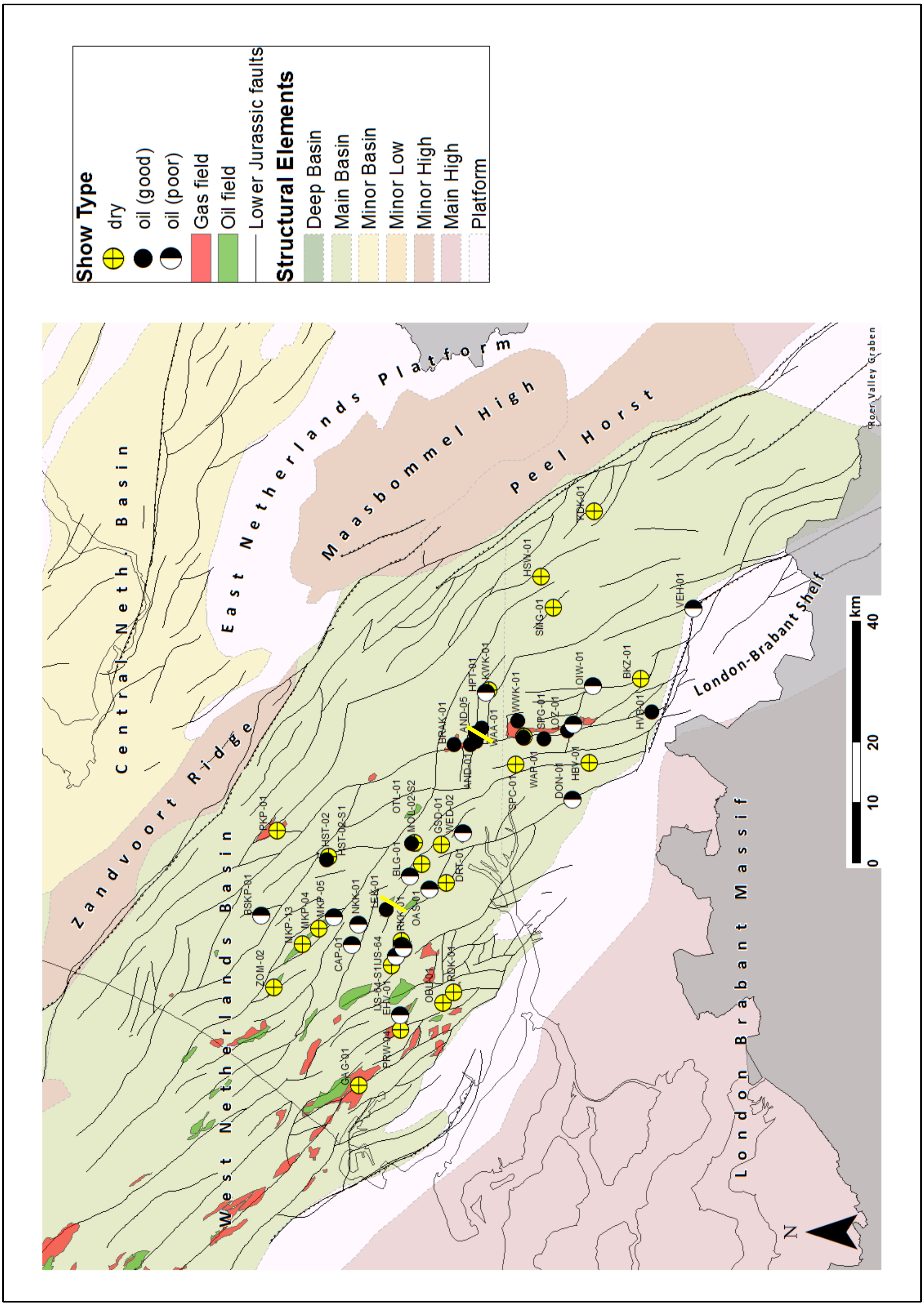


Figure 5. Map with dry wells and wells with oil shows (ranging poor - good) in the Brabant Formation. Yellow lines show seismic lines over the Andel and Lekkerkerk stranded fields (Figure 6). Structural elements outline comes from EBN ArcGis database.

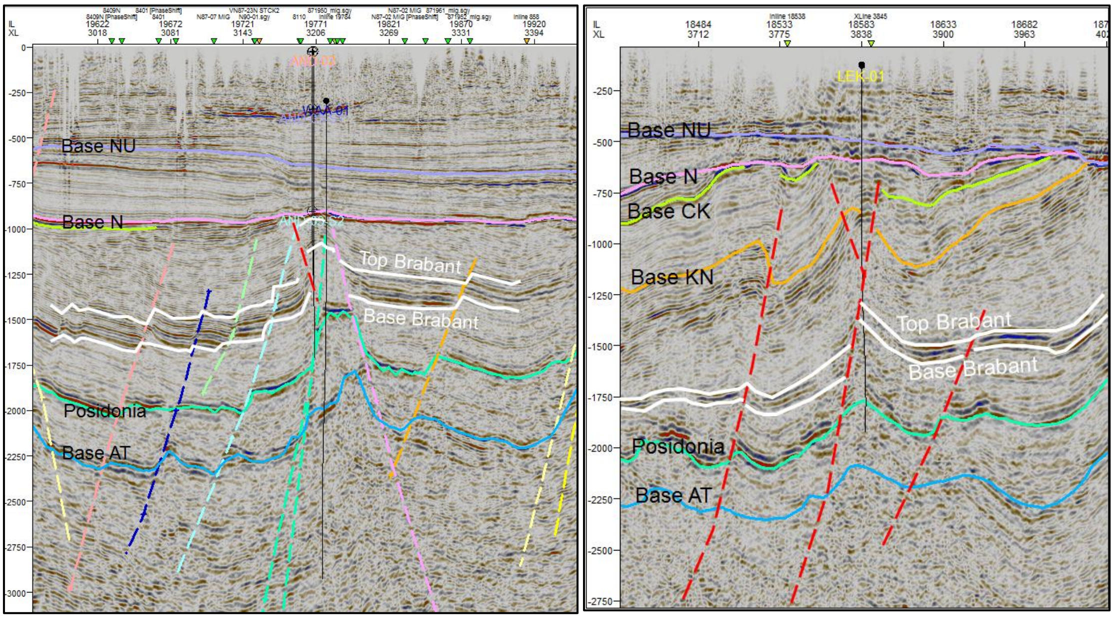


Figure 6. A) SW-NE seismic line (random line 3D Terracube onshore) over the Andel stranded field. The inversion trap contains oil in stacked reservoirs (SLDN, ATBR, ATWDM). B) SW-NE seismic line (3D Terracube onshore) over the Lekkerkerk stranded field, showing the fault-dip closure at Brabant level. Faults by Van Der Kroef (2014). See text for details, for location see Figure 5.

5.3.5 Lower Muschelkalk

The Late Triassic Lower Muschelkalk Formation (RNMUL) is a roughly 100m thick sequence of marls, dolomites and limestones. It is interpreted to have been deposited on an epeiric carbonate ramp in a shallow- to open-marine setting, with occasional restricted conditions that led to the deposition of evaporites in the southern onshore (Van Adrichem-Boogaert & Kouwe, 1993-1997; Borkhataria et al., 2005).

A poor correlation between NuTech's modeled shows and mud log shows (Appendix 9) indicates that NuTech's petrophysical model is unreliable for this gas-prone formation. Average modeled reservoir properties are good but unreliable (ϕ = 10%; K = 60 mD; Appendix 1). Two producing fields (De Wijk and Coevorden) in the eastern part of Holland indicate the possible commerciality of this potential reservoir. Reservoirs are porous, laterally continuous dolomitic marls formed on the inner ramp of a storm-dominated epeiric carbonate ramp (Borkhataria et al., 2006). It may be that a similar depositional environment prevailed in the northern part of the study area (Broad Fourteens Basin, Central Netherlands Basin) for the Lower Muschelkalk, as pointed out by Borkhataria et al. (2006) (Figure 7).

In addition, in well P06-A-02-S1, heavy mud weights were used during drilling of the Muschelkalk section in anticipation of Triassic salts – minor gas shows of 200 ppm were measured. A subsequent increase in gas concentration was measured upon decreasing the mud weight. This may indicate that, at least in this well, the gas show has been suppressed by the heavy mud. It is not known at the moment whether this is a unique case or has occurred consistently in more wells, but this phenomenon may have potentially affected more wells. If this is true, this formation may bear more prospectivity than currently thought.

In the study area, untested oil and gas shows of poor, fair and good quality are found in 11 different wells. Above-mentioned findings may indicate upside potential in the Lower Muschelkalk. Exploration should focus on identifying possible inner-ramp reservoir facies in the Broad Fourteens

Basin, which may be present according to Borkataria et al. (2005). Understanding the depositional model is a pre-requisite for understanding reservoir quality, details are found in Pöppelreiter & Aigner (2003) and Borkhataria et al. (2006). The Upper Muschelkalk is considered to be less prospective, since facies maps show presence of non-reservoir rocks in the study area (Borkhataria et al., 2005).

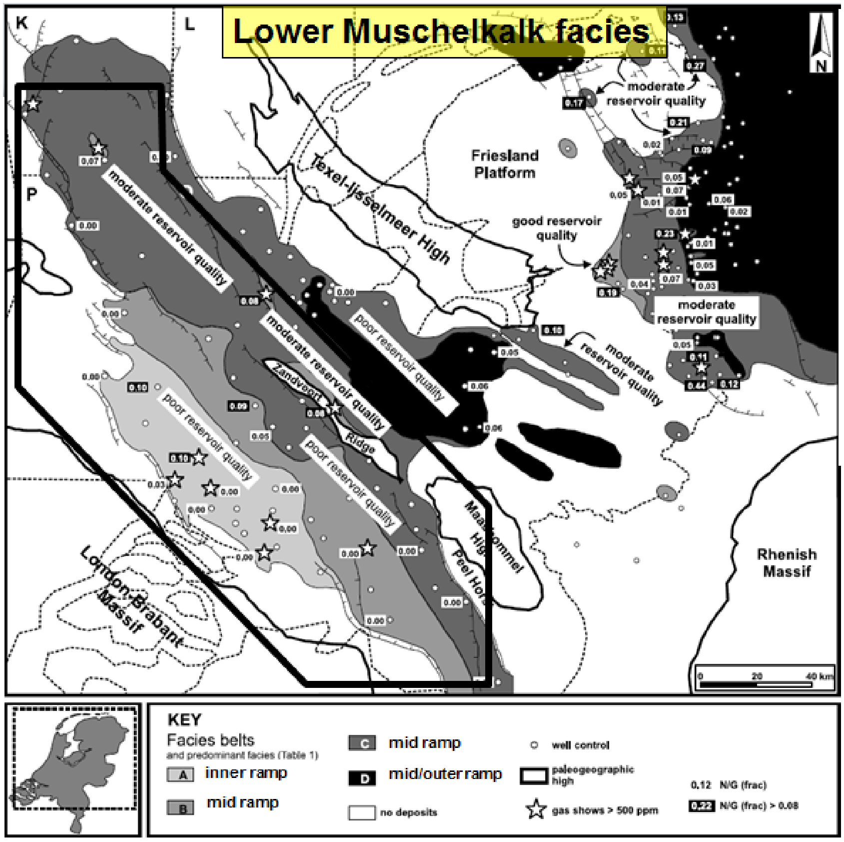


Figure 7. Lower Muschelkalk facies map, after Borkhataria et al. (2006). Shallow-marine carbonates form the reservoir of the De Wijk field in eastern Netherlands. Shallow-marine carbonates may also be present in the northern part of the study area as indicated on this map. Study area outlined in black.

5.3.6 Zechstein Fringe Sandstone Members

The Zechstein Fringe Sandstone Members (ZEZ1S, ZEZ2S, ZEZ3S, ZEZ4S) are the clastic fringe facies-equivalent of the basinal Zechstein evaporites and carbonates. The formation has been deposited in the Southern Permian Basin during the Late Permian, following clastic Rotliegend deposition. The Zechstein ranges in thickness at the basin fringe from 0 to 50 meters; maximum thickness in the Southern Permian basin centre is ~1500m. At the southwestern basin fringe near the London-Brabant Massif, continental, fine- to coarse-grained clastics were deposited in a restricted area offshore West Netherlands Basin.

A good correlation between NuTech's modeled shows and mud log shows (Appendix 9) indicates that NuTech's petrophysical model is reliable for this gas-prone formation. Average modeled reservoir properties are moderate (ϕ = 9%; K = 5.6 mD; S_W = 40%; V_{Clay} = 0%; Appendix 1). Three fields are currently producing from Zechstein Fringe Sandstone reservoirs in the offshore West Netherlands Basin. Overlooked pay is demonstrated by well P18-01 (Amoco, 1988; suspended) with an unperforated, 40m thick sandstone interval with good-quality gas shows. In combination with 10 good-quality untested gas shows, this indicates remaining gas potential. This potential and industry awareness has recently been confirmed by a recent DANA well (2014, dry) that targeted this formation.

Sandy, reservoir-prone facies are only present offshore West Netherlands Basin (Figure 8). They are generally underlain by Rotliegend clastics. The sequence may be overlain by Zechstein Carbonates or

Lower Bunter claystones (Rogenstein) that may provide top seal, or unconformably overlain by Vlieland Claystones acting as a seal. Trap types would be simple fault-dip closures.

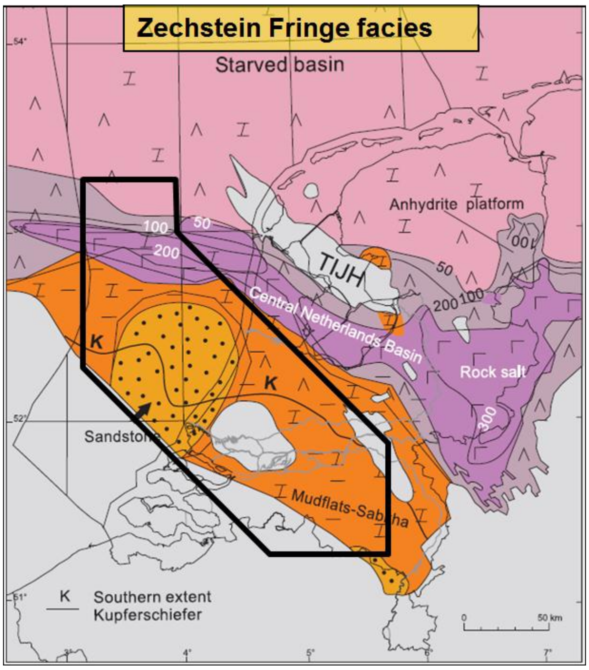


Figure 8. Facies map for the Zechstein 1 Fringe Sandstone showing sandstone deposition in the offshore WNB (Geluk, 2007). Study area outlined in black.

5.3.7 Zechstein 1 Fringe Carbonate Member

The Late Permian Zechstein 1 Fringe Carbonate Member (ZEZ1F) is the carbonate-fringe equivalent of the basinal Z1 carbonate and anhydrite sequences. It is primarily found along the fringe of the Southern Permian Basin. The unit consists of grey limestone or dolomite with occasionally minor anhydrite.

A moderate to good correlation between NuTech's modeled shows and mud log shows (Appendix 9) indicates that NuTech's petrophysical model is reliable for this carbonate formation. This may be due to the fact that often abundant input logs are available for this formation – the well's target is often found stratigraphically just below or above this formation (Rotliegend, Zechstein 2 or 3 carbonates). Average modeled reservoir properties are poor (ϕ = 6%; K = 3 mD; Appendix 1). In the study area, untested good-quality oil and gas shows are found in 7 different wells in the Q-blocks. Recent work on Zechstein-2 carbonate platforms in the Dutch northern offshore by Tolsma (2014) indicates that there is still remaining potential for exploration for Zechstein carbonates. These findings may indicate remaining oil and gas potential in the Zechstein 1 Fringe Carbonate.

In general, best reservoir facies are often found on the platform (stromatolite facies) or platform-slope edge (ooid shoals). This platform and platform-slope edge belt runs from the offshore Q blocks towards the onshore to the northeastern part of the Utrecht license (Figure 9). Producing fields in Zechstein 2 and 3 carbonates onshore Noord-Holland provide proof that reservoir facies may be present. Presence of reservoir-prone reef facies in the Zechstein 1 Carbonate is likely controlled by paleotopography at the end of Rotliegend deposition (Geluk, 2000; K. Geel, pers. comm.). Thus, exploration should focus on reconstructing paleogeography and topography at the end of Rotliegend times. Seal may possibly be provided by Zechstein anhydrite (if present) or claystones, but remains a risk. Presence of charge may also be a risk.

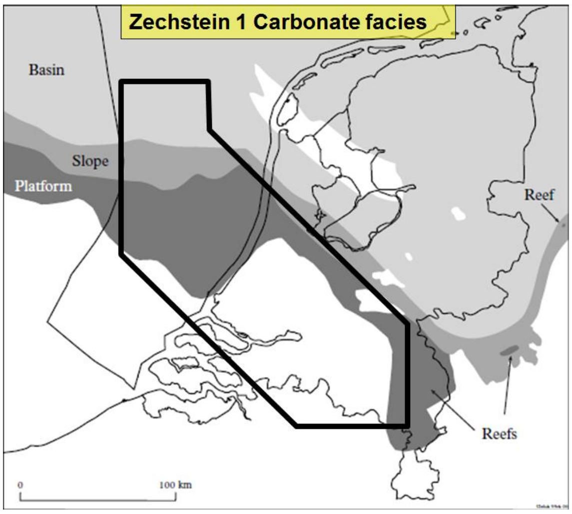


Figure 9. Facies map for the Zechstein 1 Carbonate (Geluk, 2000). Potential reservoir facies may occur in the northern part of the study area, trending towards the onshore in a NW-SE direction.

5.3.8 Westphalian C/D

The Carboniferous (Westphalian C/D) deposits of the Hellevoetsluis Formation (DCDH; Figure 10) comprise a sequence of continental sandstones and shales, with occasional coal seams (Van Adrichem-Boogaert & Kouwe, 1993-1997). The formation has been deposited in the foreland basin of the Variscan orogeny.

A good correlation between NuTech's modeled shows and mud log shows (Appendix 9) indicates that NuTech's petrophysical model is reliable for this sand/shale formation. NuTech's reliable interpretation for this formation may aid in delineating areas with good reservoir properties. Average modeled reservoir properties are moderate to good (ϕ = 11%; K = 12 mD; Appendix 1). Untested good-quality oil and gas shows are found in 8 different wells. There are currently no producing fields from this formation in the study area. These findings indicate overlooked exploration potential.

The gas and oil shows are predominantly found in wells in inverted settings. Further study of these wells may reveal how these reservoirs in inverted settings were charged. The coaly sequence indicates gas source rock potential as well. Main risks are thought to be top and side seal and juxtaposition (De Jager & Geluk, 2007). Exploration should therefore focus on seal risk/quality.

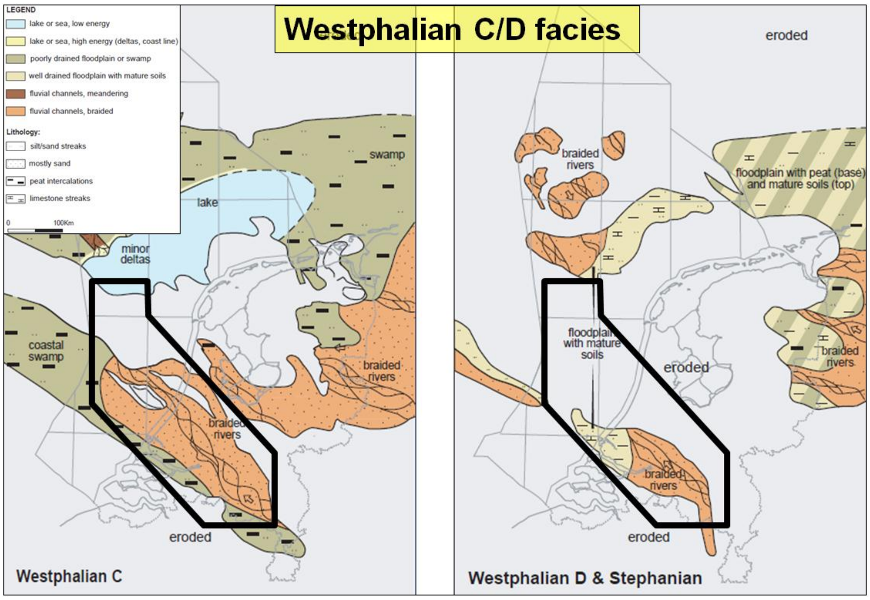


Figure 10. Westphalian C/D facies map (after Van Buggenum & Den Hartog Jager, 2007) showing the braided river facies in the West Netherlands Basin and Roer Valley Graben.

Chapter 6 Geological setting of the Brabant Formation

In Chapter 5, the Brabant Formation was identified as the primary research objective of this study as a result of its high remaining exploration potential. The workflow outlined in Chapter 4 is continued and in the next chapters (Chapters 6 – 12), the Brabant Formation will be studied into more detail with the objectives to construct a conceptual geological model and to identify potential trap concepts.

This chapter will provide a summary of the depositional characteristics and local geological history of the study area in the Roer Valley Graben from the Jurassic onwards (Chapter 6.1) and a general description of the stratigraphy of the Brabant Formation (Chapter 6.2).

Two maps are shown below, the first one showing the regional paleogeography at the onset of the Bathonian (constructed from Ziegler, 1982 and Wetzel et al., 2013). The second map shows the thickness of the Altena Group sediments in the Roer Valley Graben and West Netherlands Basin by Worum et al. (2005). It indicates the outline of the Mesozoic basins and main depocentres during Lower and Middle Jurassic (Brabant) times. Also, two regional cross sections are presented showing the block-faulted nature of the area.

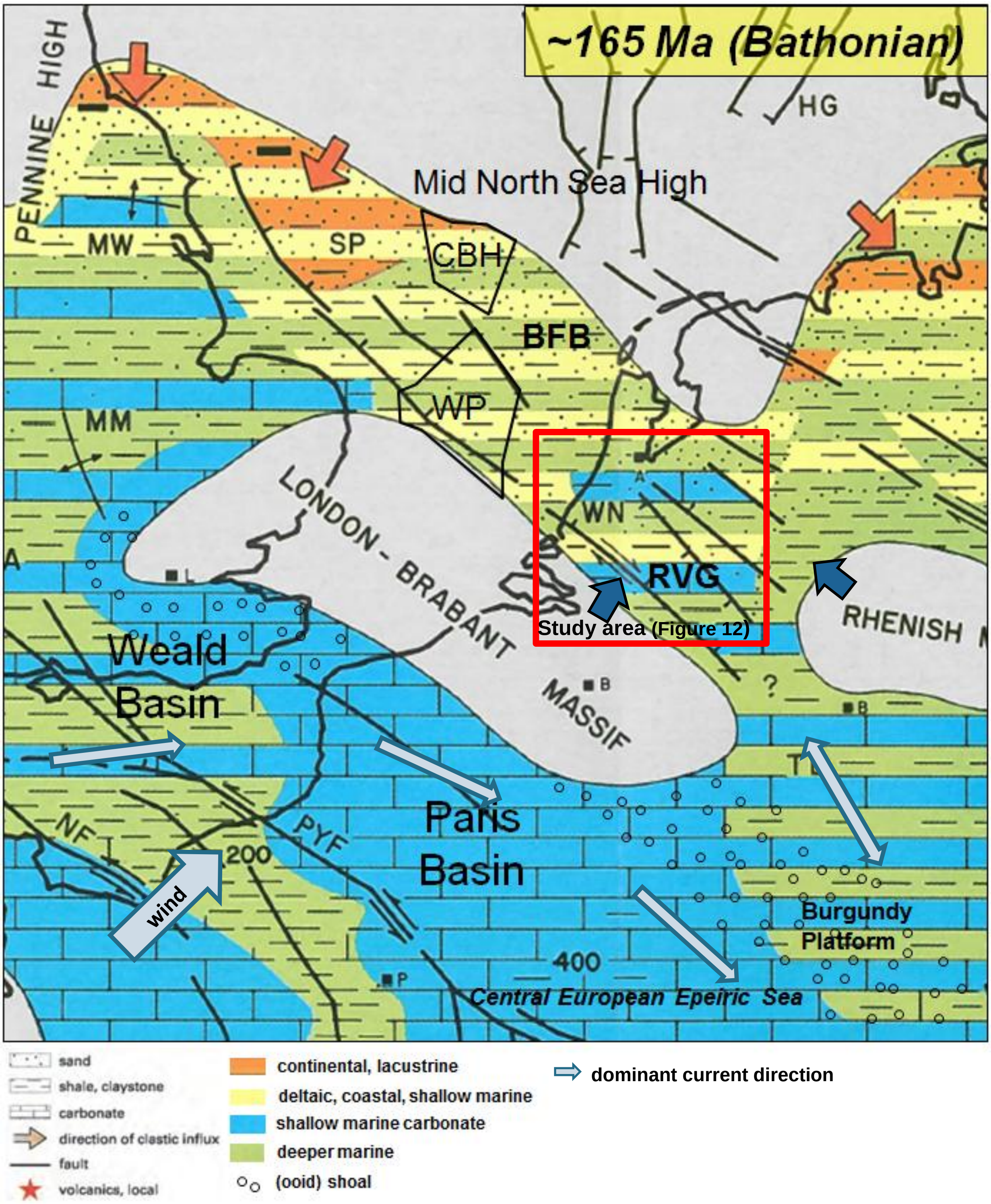


Figure 11. NW European paleogeography during the Middle Jurassic (Latest Bajocian – Bathonian). Carbonate ramps were attached to the London-Brabant Massif in the Weald and Paris Basins in this time. At the same time, Brabant deposition commenced in the Dutch sector. Dominant wind direction was from the southwest. Possibly a marine connection with the Central European Epeiric Sea existed between the LBM and Rhenism Massif. SP = Sole/Silver Pit Basin, CBH = Cleaver Bank High, WP = Winterton Platform, BFB = Broad Fourteens Basin, WN = West Netherlands Basin, RVG = Roer Valley Graben. Modified after Ziegler (1982) and current directions from Wetzel et al. (2013).

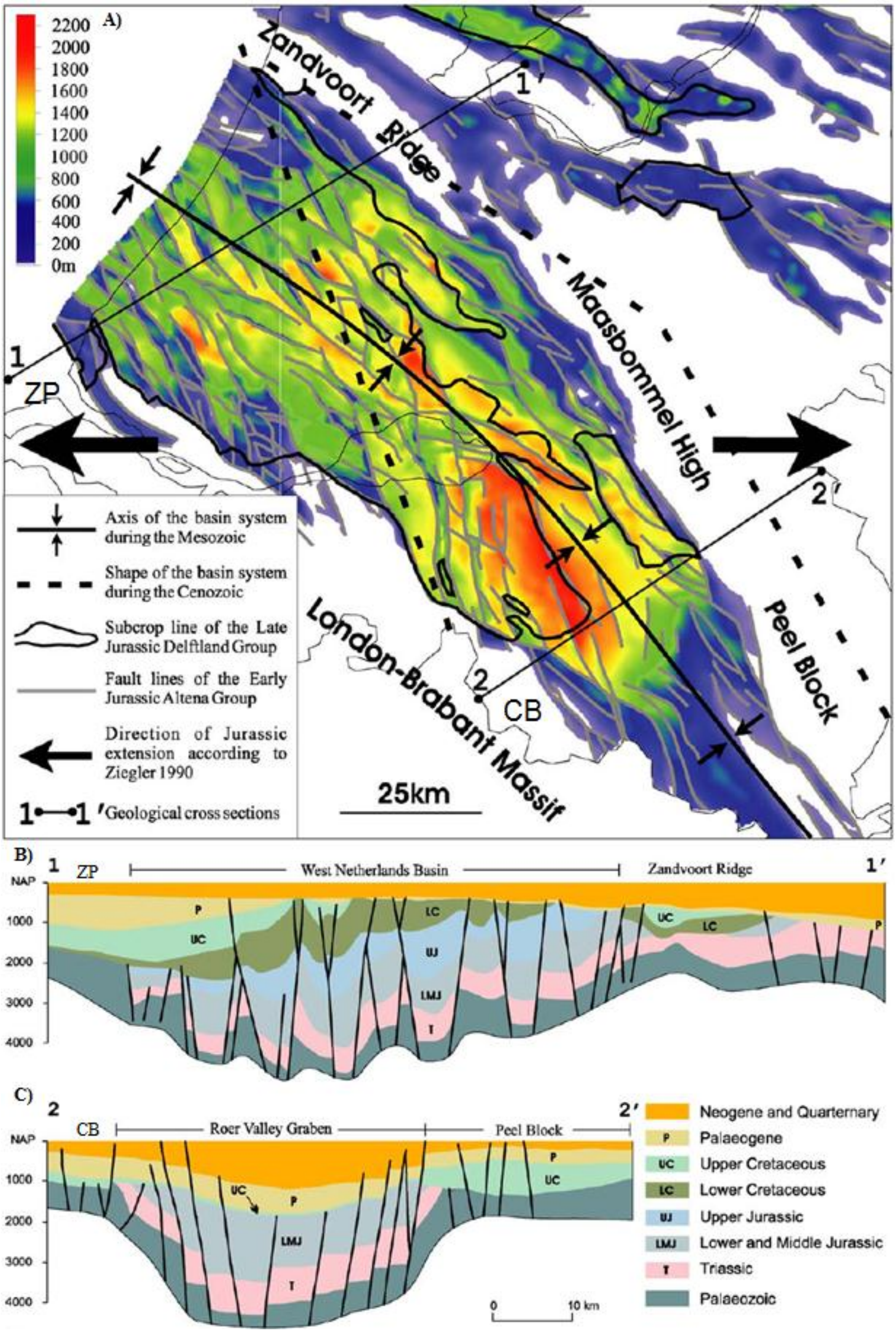


Figure 12. A) Mesozoic outline of the southern Dutch onshore basins indicated by a thickness map of the Lower to Middle Jurassic Altena Group in the West Netherlands Basin and Roer Valley Graben. B and C) SW-NE geological cross section of the West Netherlands Basin and Roer Valley Graben, respectively. ZP = Zeeland Platform. CB = Campine Block. Modified after Worum et al. (2005).

6.1 Geological history Roer Valley Graben

This synthesis focuses on the Jurassic and post-Jurassic sequence in the Roer Valley Graben and West Netherlands Basin. It is mainly based on previous work from Winstanley (1993), Herngreen et al. (2003), Worum et al., (2005), Wong (2007) and Luijendijk et al. (2011). This is followed by a general lithological description of the Brabant Formation based on Van Adrichem-Boogaert & Kouwe (1993-1997).

Jurassic and Early Cretaceous development

The Jurassic in the southern onshore is characterized by a change from slow, regional subsidence in the Early Jurassic ("Southern Permian Basin-style") to rapid fault-bounded subsidence of fault blocks in the Late Jurassic – Early Cretaceous (Herngreen et al., 2003). This is related to the break-up of Pangea (Ziegler, 1982). In the Jurassic, three important tectonic pulses have been identified – the Early, Mid and Late Kimmerian rifting events. Notably, the Late Kimmerian rifting event had major impact on development of the basins.

The major depocenter in the study area during Triassic and Lower Jurassic times was the east – west trending Southern Permian Basin. In the Late Triassic, the Early Kimmerian rift event took place (Herngreen et al., 2003). The last extensional phase of this event caused a widespread marine transgression occurring all over northwest Europe. Following this, fine-grained low-energy lacustrine and pelitic clays of the Sleen (thickness 20-45m) and Aalburg Formation (thickness up to 700m) were deposited over large parts of the Netherlands. These deposits comprise the lower part of the Altena Group. Thin, intercalated bituminous intervals may have source rock potential in these formations (Lutgert et al., 2013). This depositional regime remained until Toarcian times. During the Toarcian basin circulation became restricted and conditions became anoxic. This caused the deposition of an approximately 30m thick bituminous black shale, the Posidonia Shale Formation. This is the most prolific oil source rock of the Netherlands (De Jager et al., 1996). Basin circulation became normal again during the Late Toarcian. During the Bajocian, up to ~300m thick pyritic, shaly claystones of the Werkendam Formation were deposited in an open-marine environment. This formation is thickest in the axial parts of the proto-Roer Valley Graben and -West Netherlands Basin area and thins towards basin margins, platforms and the London-Brabant Massif. This indicates that already during the Bajocian, depocentres were progressively more shifting towards the Roer Valley Graben and West Netherlands Basin centres. Towards the middle of the succession, a more proximal, reservoir-prone interval is found with a distinctly higher silt and sand content (Middle Werkendam Member).

Latest Bajocian – Early Bathonian marks the change to distinctly more shallow-marine depositional environments. The regional paleogeography at this time is shown in Figure 11. The shallower depositional environment was likely caused by large-scale shoaling of these basins. This may be related to uplift of the Central North Sea rift dome towards the north during this time (Van Adrichem-Boogaert & Kouwe, 1993-1997). This uplift event is referred to as the Mid Kimmerian tectonic phase and caused widespread intra-Jurassic truncation in the northern Dutch basins; the Dutch Central Graben, Terschelling Basin and Lower Saxony Basin were deeply truncated (Wong, 2007). Sedimentation continued in the southern Netherlands with deposition of the Brabant Formation. The progressive increase in basin structuration during the Bajocian possibly continued into the Bathonian and Callovian, as recorded in Brabant Formation thickness variations (see chapter "Well log scale"). From the Bathonian to Oxfordian, shallow-marine sandy limestones, marls and oolitic limestones (max. thickness ~350m) were deposited in the southern Netherlands (Broad Fourteens Basin, West Netherlands Basin, Roer Valley Graben, Central Netherlands Basin (inferred) and Achterhoek). The most complete sequences are currently found in the Roer Valley Graben. Brabant deposition terminated in the Late Oxfordian, when the depositional environment changed to upper coastal plain. The Brabant - Delfland transition appears to be relatively conformable in the basin centers, or with a mild hiatus (Burgers & Mulder, 1991; Herngreen et al., 2003), spanning approximately the Mid Oxfordian. Sedimentation continued on rapidly subsiding fault blocks in the axial parts of the basins (Delfland subgroup or Nieuwerkerk Formation of the Alblasserdam Member (Late Jurassic age); Figure 12B). Towards the basin margins and on horst blocks, the Brabant Formation was prone to erosion during this time (Base Delfland Unconformity or 'Mid to Late Kimmerian Unconformity' *sensu* Burgers & Mulder (1991)). The Delfland comprises continental sandstones and shales deposited during the syn-rift basin cycle.

The most rapidly subsiding grabens were uplifted in the Late Kimmeridgian during the Late Kimmerian I tectonic phase (Herngreen et al., 2003; Wong, 2007). This ended the first depositional phase of the Delfland in the Roer Valley Graben and West Netherlands Basin. Rift shoulders became more truncated during this time. The Late Kimmerian I uplift was quickly followed by renewed differential subsidence and deposition in Portlandian times. Progressive depositional onlap towards the basin margins is seen in the Delfland, where the formation is gradually expanding its depositional area to higher basin-fringe fault blocks (Herngreen et al., 2003). The syn-rift basin cycle is terminated in the Hauterivian (Base Cretaceous Unconformity or Base Rijnland Unconformity or Late Kimmerian II Unconformity). Due to absence of Early Cretaceous sediments in the Roer Valley Graben, it is not known whether these sediments were actually deposited (Worum et al., 2005; Jeremiah et al., 2010). In the Early Cretaceous in the West Netherlands Basin, post-rift sedimentation is governed by several marine transgressive episodes and led to the deposition of the sandstones, claystones and greensands of the Vlieland Formation (Rijn, Rijswijk, Berkel, IJsselmonde, Holland Greensand Members).

Post-Early Cretaceous development

Chalk limestones were deposited from the Cenomanian to Coniacian in northwest Europe. Towards the Latest Cretaceous and Early Paleocene (Santonian-Campanian), two important basin inversion events took place, known as the Subhercynian or Late Cretaceous inversion phase and the Laramide phase (Worum et al., 2005; Luijendijk et al., 2011). These important structural events produced a major angular subcrop of Mesozoic strata below the Late Cretaceous unconformity (Figure 12B and C) in the Roer Valley Graben and West Netherlands Basin. The most severe basin inversion in the Roer Valley Graben, up to 1000m, occurred in the northeastern part of the basin, along the Peel Boundary Fault (Luijendijk et al., 2011). Inversion was controlled by local differential movement of fault blocks (reverse reactivation of Kimmerian-age normal faults) (Luijendijk et al., 2011). Much less uplift occurred in the southern and western parts of the basin (0-500m uplift). Chalk sedimentation lasted until the Danian (Paleocene). The Subhercynian and Laramide inversion phases were followed by deposition of marine sediments belonging to the Lower North Sea Group (Landen and Dongen Formations). A third, minor inversion event (Pyrenean phase) in the Late Eocene separates Early Eocene strata (Lower North Sea Group) from Miocene strata (Middle North Sea Group). The Roer Valley Graben was reactivated as a rift basin in the Oligocene with subsidence accelerating in the Plio- and Pleistocene (Michon et al., 2003).

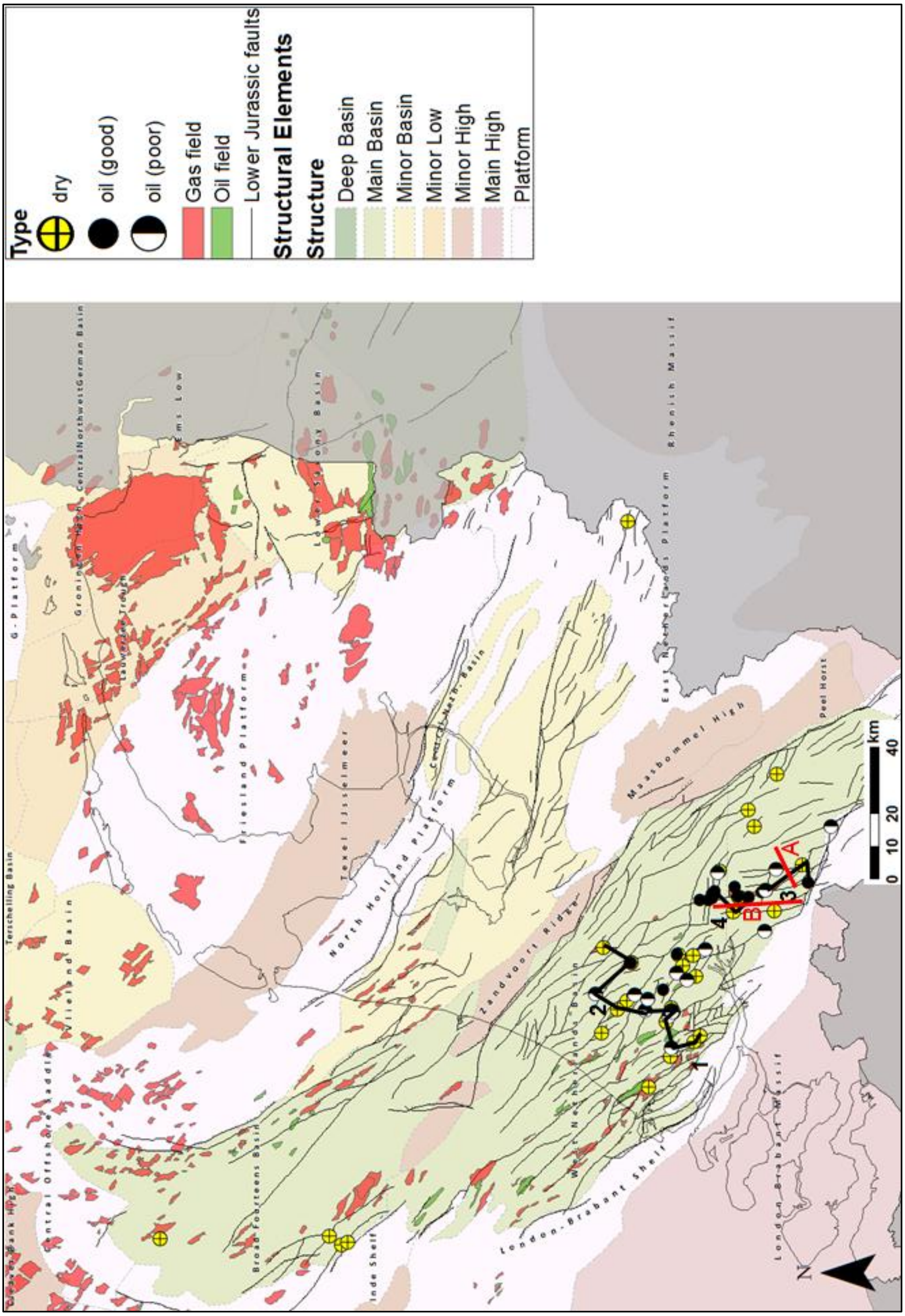


Figure 13. Wells that have encountered the Brabant Formation. Present-day distribution is limited to the BFB, WNB, RVG, Achterhoek (almost? in outcrop) and possibly the Central Netherlands Basin (inferred from seismic). Correlation sections (black; numbered) and seismic sections (red; A & B) also shown.

6.2 Stratigraphy

The Middle Jurassic Brabant Formation forms the top part of the Altena Group (Figure 14). Its lower boundary is formed by the conformable contact with open-marine claystones of the Werkendam Formation. The upper boundary is often an erosional contact with overlying continental sandstones and shales of the Delfland Group. In inverted settings, the upper boundary may be formed by sand-, clay- and carbonate-rich deposits of the Chalk Group (RVG), Lower North Sea Group (RVG/WNB) or Middle North Sea Group (WNB).

Maximum thickness from well data is 367m along hole in OIW-01, but it might be thicker towards the depocenters of that time: it thickens towards axial parts of the Roer Valley Graben, as evidenced on seismic (Chapter 7.1) and Altena Group thickness maps (Figure 12A). The age ranges from the Latest Bajocian to Oxfordian (in most complete sequences). Wells that have encountered the formation are shown in Figure 13. Present-day distribution is restricted to synclinal erosional remnants in the Roer Valley Graben, eastern part of the onshore West Netherlands Basin, parts of the Broad Fourteens Basin, parts of the Central Netherlands Basin (inferred from seismic data) and parts of the Achterhoek area where it is close to the surface (Van Adrichem Boogaert & Kouwe, 1993-1997).

The lithological type wells for the formation are Oisterwijk-01 (RVG) and Werkendam-02 (border RVG/WNB) (Figure 13). The following lithological description from Van Adrichem-Boogaert & Kouwe (1993-1997) is based on these wells.

The Brabant Formation comprises a regressive sequence of shallow marine limestones, marls and oolitic limestones that build out into the Roer Valley Graben from the London-Brabant Massif (Ziegler, 1982; Winstanley, 1993). Van Adrichem-Boogaert & Kouwe (1993-1997) subdivided the formation into seven members in the Roer Valley Graben, on the basis of wireline log signature (gamma ray and sonic) and lithology (Figure 14; Table 2). These members are from oldest to youngest: 1) Lower Brabant Limestone, 2) Lower Brabant Marl, 3) Middle Brabant Limestone, 4) Middle Brabant Marl, 5) Upper Brabant Limestone, 6) Upper Brabant Marl and 7) Oisterwijk Limestone. Maximum regression, i.e. lowest relative sea level, was achieved in the youngest member (Oisterwijk Limestone). Well log data indicates that the Oisterwijk Limestone Member is likely only present in the Roer Valley Graben. The entire succession is generally silty/sandy and fossiliferous. The sandy limestone intervals (Figure 14; Table 2) stand out on logs by their lower gamma ray, higher resistivity and higher sonic velocity response than the marls in between. The age of the Lower Brabant Limestone is biostratigraphically dated as Latest Bajocian – Early/Mid Bathonian, but the biostratigraphic ages of younger units appear to show considerable variation.

The Lower Brabant Limestone (Latest Bajocian – Early-Mid Bathonian) comprises an alternation of marl and limestones, generally fossiliferous, in which the number and thickness of the limestone beds increases towards the top. The unit is clearly recognizable on wireline logs by its characteristic funnel gamma ray log shape (shoaling-upward) (Figure 20 and 21). Thickness of the unit varies from about 30m (basin-margin wells HBV-01, HVB-01) to ~90m (grabens northwest RVG). The Lower Brabant Marl (Late Bathonian) is a marl, locally silty, with locally thin intercalated sandy limestone beds. It may be ferruginous at the top. The Middle Brabant Limestone (Early Callovian) is a very sandy, fossiliferous limestone with intercalated sandy marl or calcareous silt-/sandstone beds. The characteristic log shape (Figure 20 and 21) is shoaling-upward followed by a deepening-upward sequence. The overlying Middle Brabant Marl (Middle Callovian) is a sandy marl interval with a ferruginous section in its lower part. The member may be locally strongly reduced in thickness. The Upper Brabant Limestone (Middle-Late Callovian) is a silty to sandy limestone with occasionally very high sand content (calcareous sandstones). The Upper Brabant Marl (Late Callovian-Early

Oxfordian) comprises a sequence of sandy marls with high sand content, especially in its lower part where distinction with ATBR3 may be hampered. The Oisterwijk Limestone (Oxfordian) is a succession of massive, oolitic/algal limestone beds, sandy at its base.

Van Adrichem-Boogaert & Kouwe (1993-1997) interpret the Brabant Formation to have been deposited in a shallow marine environment, where both clastic input was (periodically) available and carbonate production was possible. The sandy limestone and calcareous sandstone intervals are formed in shallow marine shoal environments during relative sea level lowstands, whereas the marl intervals are formed in relatively moderately deep marine environments during relative sea level highstands

Deposits in the Achterhoek show similarities with the Roer Valley Graben in terms of palynology and lithofacies during the Bathonian (Herngreen & De Boer, 1974). It is thus likely that these areas formed part of a single depositional province, with clastic input in the Achterhoek likely derived from the Rhenish Massif instead of the London-Brabant Massif. However, deposits in the Achterhoek from the Middle – Late Callovian (Klomps Member) do *not* resemble those of the Roer Valley Graben in terms of fossils and lithofacies. It may be that, from this time onwards, the connection between the two basins ceased to exist. The Roer Valley Graben and Achterhoek area were then separated from each other from the Middle Callovian onwards. It may be that the Peel Block proved to be a barrier. However, hard evidence for this is lacking.

Member name	**Code**	**General lithology** *(Van Adrichem-Boogaert & Kouwe, 1993-1997)*
Oisterwijk Limestone	ATBRO	Massive, oolitic/algal limestone
Upper Brabant Marl	ATBRU	Sandy marl
Upper Brabant Limestone	ATBR3	Calcareous sandstone Sandy limestone
Middle Brabant Marl	ATBRM	Silty/fine sandy marl
Middle Brabant Limestone	ATBR2 (1st Cornbrash)	Very sandy limestone Sandy marl/calc. sandstone beds
Lower Brabant Marl	ATBRL	Silty marl Local limestone beds
Lower Brabant Limestone	ATBR1 (2nd Cornbrash)	Marl/limestone alternation Increasing limestone beds to top

Table 2. Subdivision of Brabant Formation members (young at top) and general lithology (Van Adrichem-Boogaert & Kouwe, 1993-1997).

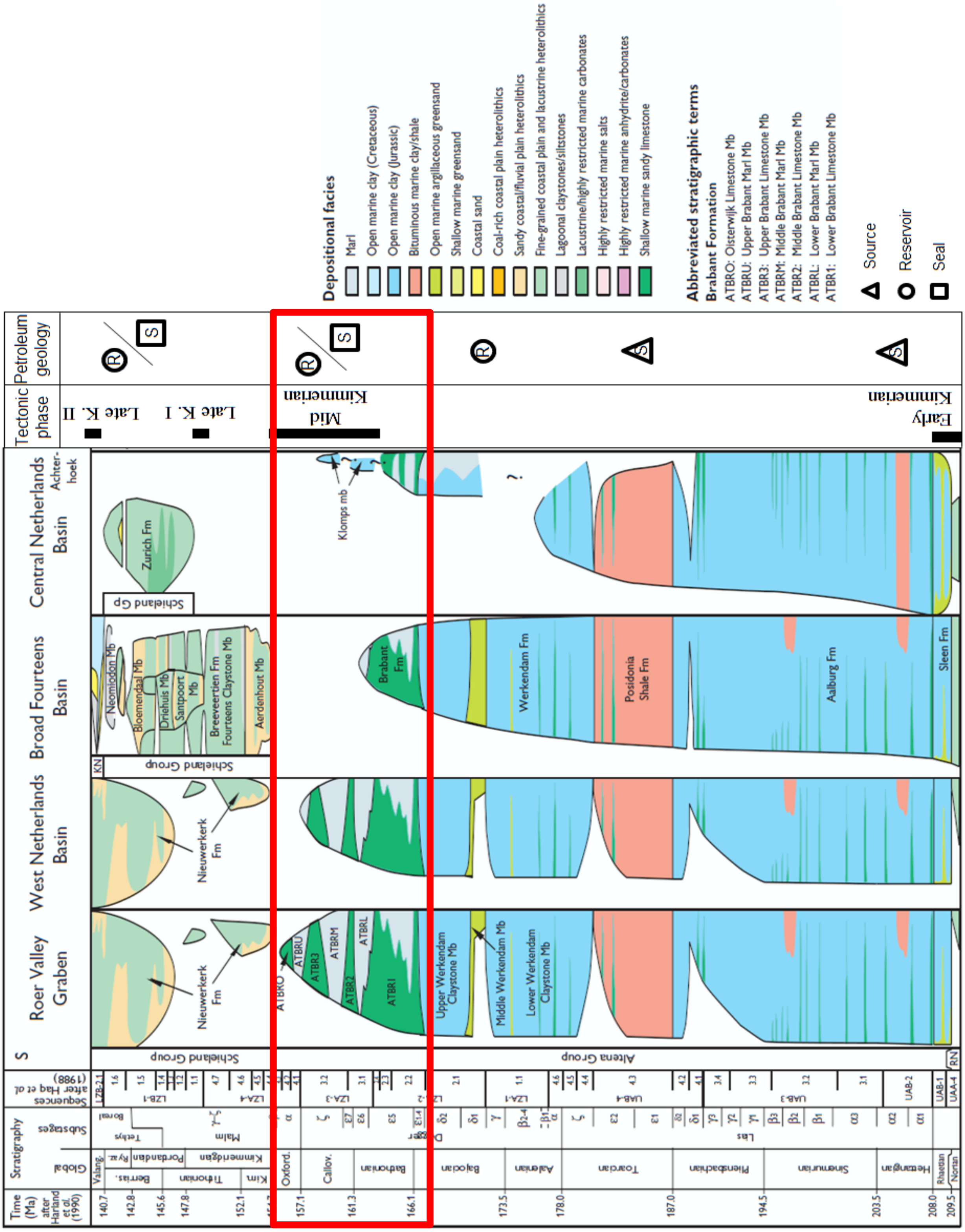


Figure 14. Jurassic lithostratigraphy, main tectonic phases and potential source (triangle), reservoir (circle) and seal (square) rocks in the Roer Valley Graben, West Netherlands Basin, Broad Fourteens Basin and Central Netherlands Basin, compiled from data by Van Adrichem Boogaert & Kouwe (1993-1997), Herngreen et al. (2003) and Winstanley (1993). Red box shows stratigraphy and individual members of the Brabant Formation. Note that only the Werkendam Formation separates the Brabant Fm from the oil-prone Posidonia Shale.

Chapter 7 Observations and interpretations

In order to lay a solid foundation on which an understanding of the conceptual geological model will be based, relevant observations and interpretations will be presented first. This chapter will present and discuss the most important observations and interpretations made during the study. This is approached from three scales: zooming in from the seismic scale (Chapter 7.1), to well log scale (Chapter 7.2) to core scale (Chapter 7.3).

7.1 Seismic scale

Figure 12B and 12C show interpreted regional cross-sections through the West Netherlands Basin and Roer Valley Graben by Worum et al. (2005). The seismic lines clearly show the block-faulted nature of the basins. The Brabant Formation is generally easily identified on seismic in the Waalwijk area.

Seismic character

The individual members of the Brabant Formation are recognizable on 3D and 2D seismic data in the Roer Valley Graben. The transition from acoustically soft marls to acoustically hard limestone beds (positive acoustic impedance contrast) results in a hard-kick, which, in the convention used, corresponds to a trough and red reflector. The reservoir-prone intervals with lowest gamma ray values (Lower, Middle, Upper Brabant Limestone Members) correspond to red reflectors and can be quite confidently picked on seismic across the Waalwijk area.

The seismic character is briefly discussed here with reference to well Waalwijk-01, from where checkshot data is available in combination with good-quality seismic. Unfortunately, no density log is available so synthetics could not be made. Figure 17 shows the Waalwijk-01 well with well tops (in time) and the gamma ray log. The seismic amplitudes are shown in peaks (blue) and troughs (red).

Going down from the ATBRU marls to the ATBR3 limestones (positive acoustic impedance contrast), a high-amplitude red reflector can be seen (note that the ATBR3 well top should have been placed lower: at the top of the rather blocky low gamma ray interval). This high-amplitude red reflector corresponds to the Upper Brabant Limestone (ATBR3). The transition from ATBR3 limestone to ATBRM marls is a negative acoustic impedance contrast and results in a soft-kick and bright blue reflector. An intercalated sandy limestone bed in the ATBRM gives a thin, low-amplitude red reflector in between two blue reflectors. The ATBR2 is characterized by a bright, high-amplitude red reflector formed by a marl-limestone transition (hard-kick). The ATBRL is a relatively thick (~50m), monotonous marl sequence with a strong blue reflector at the top (contact with ATBR2) and vague, transparent reflectors downwards (lack of internal acoustic impedance contrast). The top of the Lower Brabant Limestone is formed by the transition from ATBRL marls to limestone (positive acoustic impedance contrast) which results in a bright red reflector. The ATBR1 reflector is often slightly thicker than the ATBR2 and ATBR3 reflector as a result of its larger thickness. The base of the Brabant Formation is recognized by a blue reflector that marks the transition to the claystones of the Werkendam Formation. The Oisterwijk Member (ATBRO), the youngest member of the Brabant Formation and not present in WWK-01 as a result of erosion, may be present on both sides of the fault block where a fourth, high-amplitude red reflector can be identified at the top of the ATBRU.

Picking the Brabant Formation in the West Netherlands Basin is more problematic due to bad seismic quality and limited areal extent of the formation, as a result of erosional truncation of the formation against the Base Delfland Unconformity.

Layer-cake stratification

In the middle, western and northwestern part of the Roer Valley Graben, the Brabant Formation is characterized by pronounced layer-cake stratification, subtly thickening towards the basin center. Highly parallel and continuous reflectors in both down-dip and along-strike directions are observed (Figure 15 and 16). They generally do not show much lateral variation in seismic amplitude. Subtle thinning of the formation towards the London-Brabant Massif is observed.

These observations suggest lateral continuity of individual sedimentary units, at least on seismic resolution scale (10-40m).

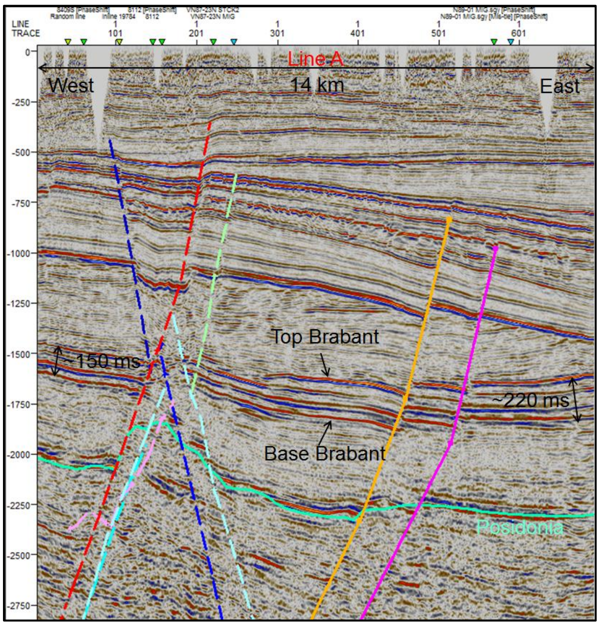


Figure 15. 2D seismic line N87-19 MIG (phaseshifted by Van der Kroef (2014)) downdip, showing the continuous and parallel reflectors and down-dip (eastward) thickening of the formation. Fault framework after Van der Kroef (2014). Figure 13 for location.

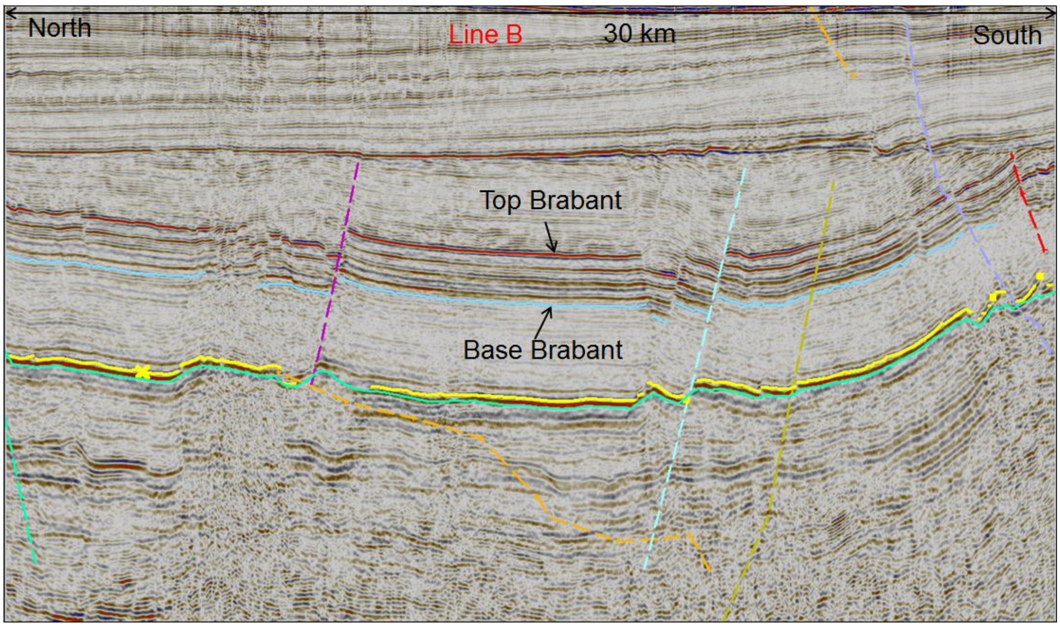


Figure 16. N-S seismic random line (3D TerraCube onshore) along strike, showing parallel, continuous reflectors and northward thickening. Yellow = Posidonia Shale. Figure 13 for location.

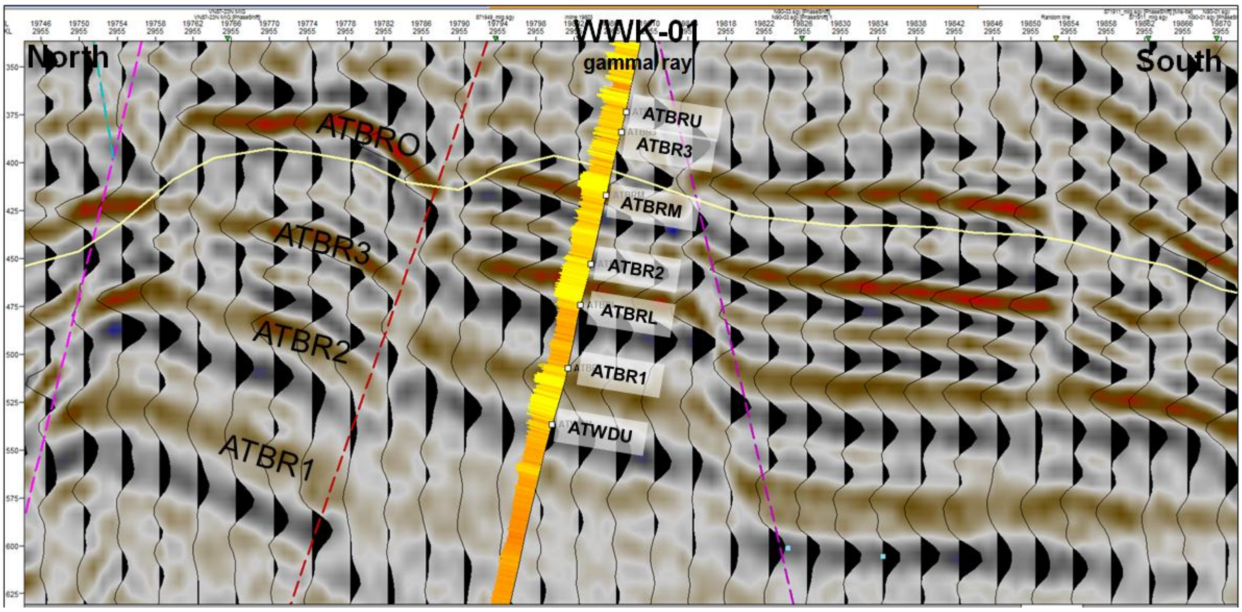


Figure 17. Picking individual Brabant Members, using the WWK-01 gamma ray log and seismic amplitudes with peaks (blue) and troughs (red). On both sides of the penetrated fault block, the Oisterwijk Limestone Member appears to be present. Green line = Base Schieland surface by TNO.

Figure 18. Sharp lithological contact between top ATBR1 (regressive upper shoreface facies) and base ATBRL (transgressive marls, offshore facies), interpreted as a transgressive surface of erosion (TSE). This transgressive surface of erosion marks the top of the ATBR1 formation and represents a sequence boundary.

7.2 Well log scale

Correlation surfaces and lithostratigraphic correlations

Wireline logs of key wells across the area are used for lithostratigraphic correlations. Correlations are shown for two sections in the Roer Valley Graben and West Netherlands Basin (Figure 21; Figure 22; Figure 23). A sequence boundary could be picked at the top of the ATBR1.

The biostratigraphic report of well Haastrecht-01 (RGD rapport 2118-B, 1978) mentions on biostratigraphic grounds the presence of a hiatus at the top of the ATBR1 (816m MD). Below the unconformity, glauconitic, calcareous sandstone beds are found indicating a shallow-marine inner ramp environment (upper shoreface/shoal facies) with high sand input. Above the unconformity, silty marls with lignite particles, shell debris and plant remains are indicative of a middle/outer ramp environment (lower shoreface/offshore facies). This erosional surface is here interpreted to be of purely submarine origin: a transgressive surface of erosion (TSE).

The TSE is also recognized in the AND-04 core (K. Geel, pers. comm.), shown in Figure 18. Here, the surface separates tight upper shoreface limestones below, from silty marls of the offshore facies above. It can be regarded as a sequence boundary and corresponds to the lithostratigraphic top of the ATBR1 (dashed red line in the correlation panels below). Maximum flooding is recorded in the overlying offshore marls (ATBRL) at highest gamma ray values. Other key surfaces could not be confidently picked due to lack of core and biostratigraphic data.

Roer Valley Graben correlation

The correlation in the Roer Valley Graben runs from the basin-margin (HVB-01) towards deeper parts of the basin (BKZ-01; Figure 20) and then further into the basin (SPG-01 to BRAK-01; Figure 21). An important observation in correlation panel 3 (Figure 20) is the thickening of the Lower Brabant Limestone basinward where a thickening of up to a factor 1.5 - 2 can be observed (compare 30m HVB-01 at basin margin vs 60m BKZ-01 towards center). Judging from seismic and logs (compare gamma ray and facies logs in ATBR1 in BKZ-01 and HVB-01), it appears that the same sedimentary units (i.e. the same facies units) thicken in a basinward direction. This has implications for total reservoir thickness as more net pay might be expected in thicker successions. The thinner ATBR1/2/3 in HVB-01 (basin-margin) appears to be a much more amalgamated sequence. This amalgamation may be the result of the depositional setting.

Figure 21 shows a N-S correlation roughly along depositional strike in the northwestern part of the Roer Valley Graben. The Brabant Formation is relatively thick in these wells (gross thickness ATBR1: 60-80m). The gamma ray signature in these wells (~25km apart) is strikingly similar and permits peak to peak correlation over these distances (smaller-scale flooding surfaces shown as thin blue lines in ATBR1 in Figure 21). Each sedimentary unit is easily recognized and correlated on logs. This suggests lateral continuity of individual sedimentary packages in this area. This is in agreement with observations on seismic scale. As a whole, the ATBR1 consists of 1 large-scale regressive, shoaling-upward cycle capped by a transgressive surface of erosion (sequence boundary). It can be subdivided into 3 smaller-scale shoaling-upward cycles, separated by flooding surfaces. All cycles show relatively serrated (but shoaling-upward) gamma ray log character. This may point to frequent marly intercalations; also observed in core. Maximum flooding is located somewhere in the overlying transgressive marls (ATBRL) which are present in predominantly offshore facies. A small-scale regressive episode may occur in this marly unit as indicated by intercalated lower shoreface facies.

The ATBR2 and ATBR3 are generally thinner than the ATBR1. The ATBR2 is characterized by a regressive, shoaling-upward cycle, passing up into a transgressive, deepening-upward cycle that ends in maximum flooding in the ATBRM marls. The overlying, regressive ATBR3 appears to be thinner bedded with up to 4 meter-sized beds of very sandy limestone or, in places, calcareous sandstone in several smaller-scale trans- and regressive cycles. The overlying ATBRU is generally present in relatively proximal, sandy lower shoreface facies, indicating the large-scale regressive nature of the entire Brabant succession. In most complete sequences (not shown in the correlations) an oolitic, algal limestone may be present indicating maximum regression.

Note that there are no wells in the middle of the Roer Valley Graben, where the formation is expected to be thick. Therefore, no proximal – distal trends in the Roer Valley Graben could be confidently established.

West Netherlands Basin correlation

The West Netherlands Basin correlation runs from the southern basin margin (RDK-01) towards the basin center (CAP-01) (Figure 19A), and from CAP-01 towards the northern basin margin (PKP-01) (Figure 19B). The sequence boundary that was picked in HST-01 (biostratigraphy) was transferred to HST-02-S1 and then correlated. It coincides with the lithostratigraphic upper boundary of the ATBR1. Generally, only the ATBR1 and ATBRL are present in the WNB as a result of erosional truncation against Base Delfland Unconformity. The RDK-01 well (basin-margin) and PRW-04 well (horst block) show amalgamated sedimentary units. More basinward, the OBL-01 well shows a thicker, more complete ATBR1 with a larger thickness of reservoir-prone facies. The characteristic GR log character as seen in the Roer Valley Graben is slightly different in this basin. The gamma ray still records a dominantly regressive, shoaling-upward trend in the ATBR1 but sedimentary units appear to be more distal in the basin center (lower shoreface and offshore facies; CAP-01, MKP-13). Towards the northern basin margin, proximal facies re-appear (upper shoreface facies; BSKP-01, PKP-01).

To summarize, the Lower Brabant Limestone is the thickest prospective member of the Brabant Formation (gross thickness up to 80m). It is composed of three small-scale shoaling-upward cycles and 1 large-scale shoaling-upward cycle, formed during relative sea level lowstand. The Middle and Upper Brabant Limestone are thinner, but sandier. The sand content increases towards the top of the formation. The formation is thinner and more amalgamated at the basin margins. Gross reservoir thickness is highest in the basin centre and grabens in west (Waalwijk area) and northwest RVG. Here, thicknesses are highest and facies most proximal (i.e. reservoir-prone). Consequently, in the grabens more metres of net reservoir are expected. Towards the West Netherlands Basin basin centre (area of CAP-01, ZOM-02, MKP-13), facies become slightly more distal. This trend could not be confirmed for the Roer Valley Graben due to a lack of well data.

A)

B)

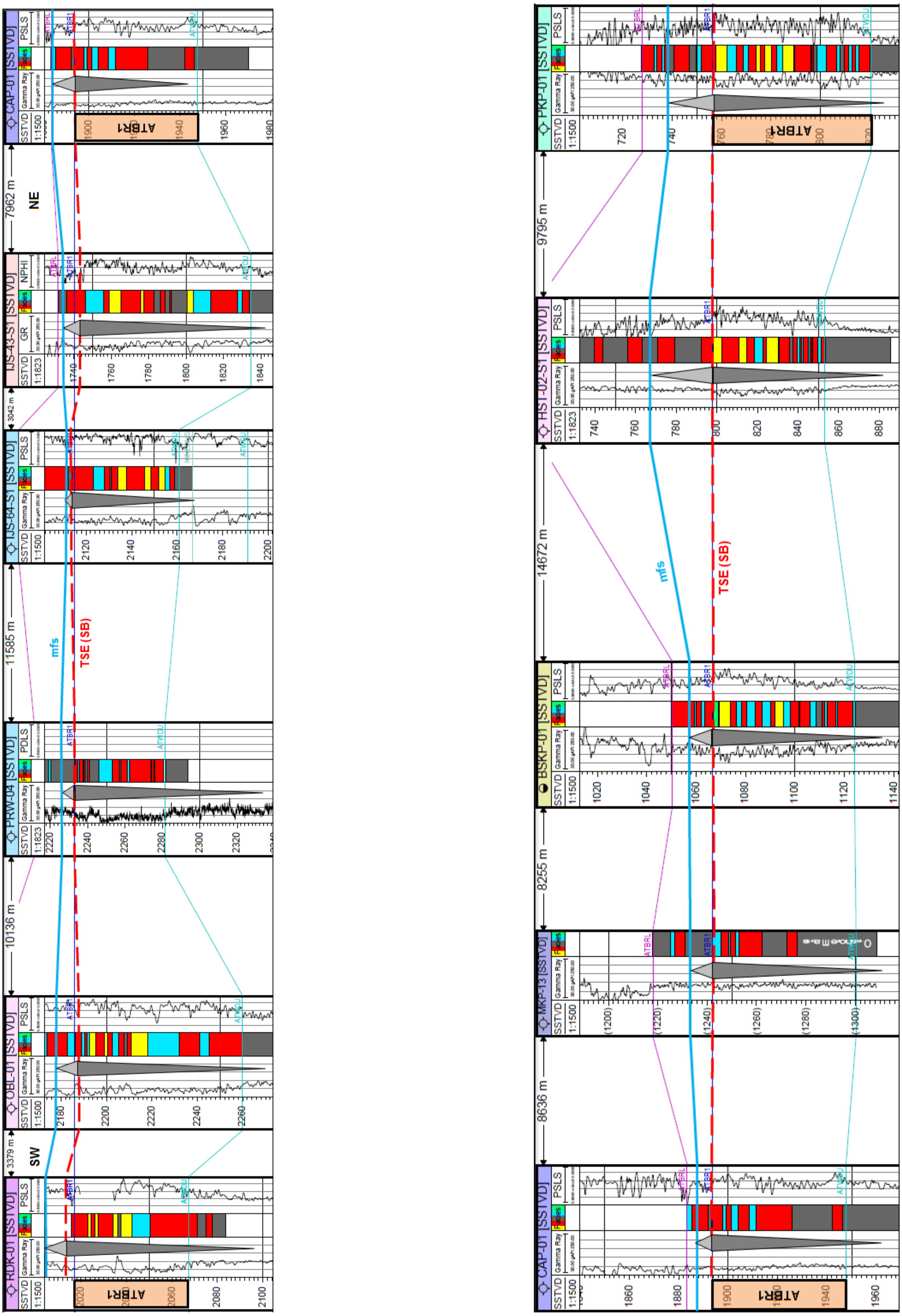


Figure 19. Well log correlation in the WNB from RDK-01 (southern basin margin) to CAP-01 (middle of the WNB) (Figure A; correlation line 1) and from CAP-01 to PKP-01 (northern basin margin WNB; Figure B, correlation line 2). See Figure 13 for location, Figure 28 for facies color coding.

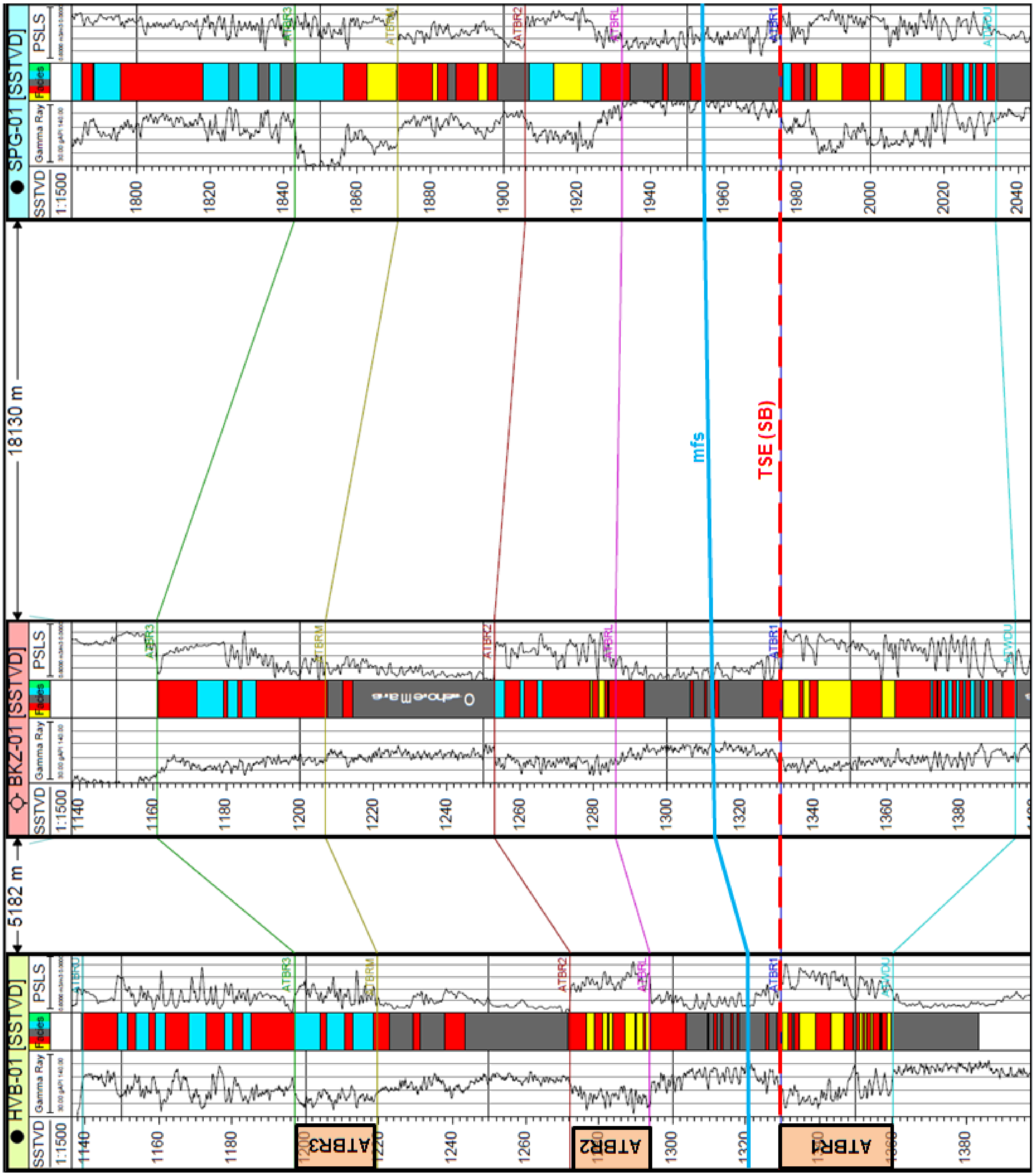


Figure 20. Correlation panel 3 - Well log correlation in the RVG from basin-margin (HVB-01) towards grabens (BKZ-01; SPG-01). Note the thinner and amalgamated basin-margin sequence with lower gross thickness. See Figure 13 for location.

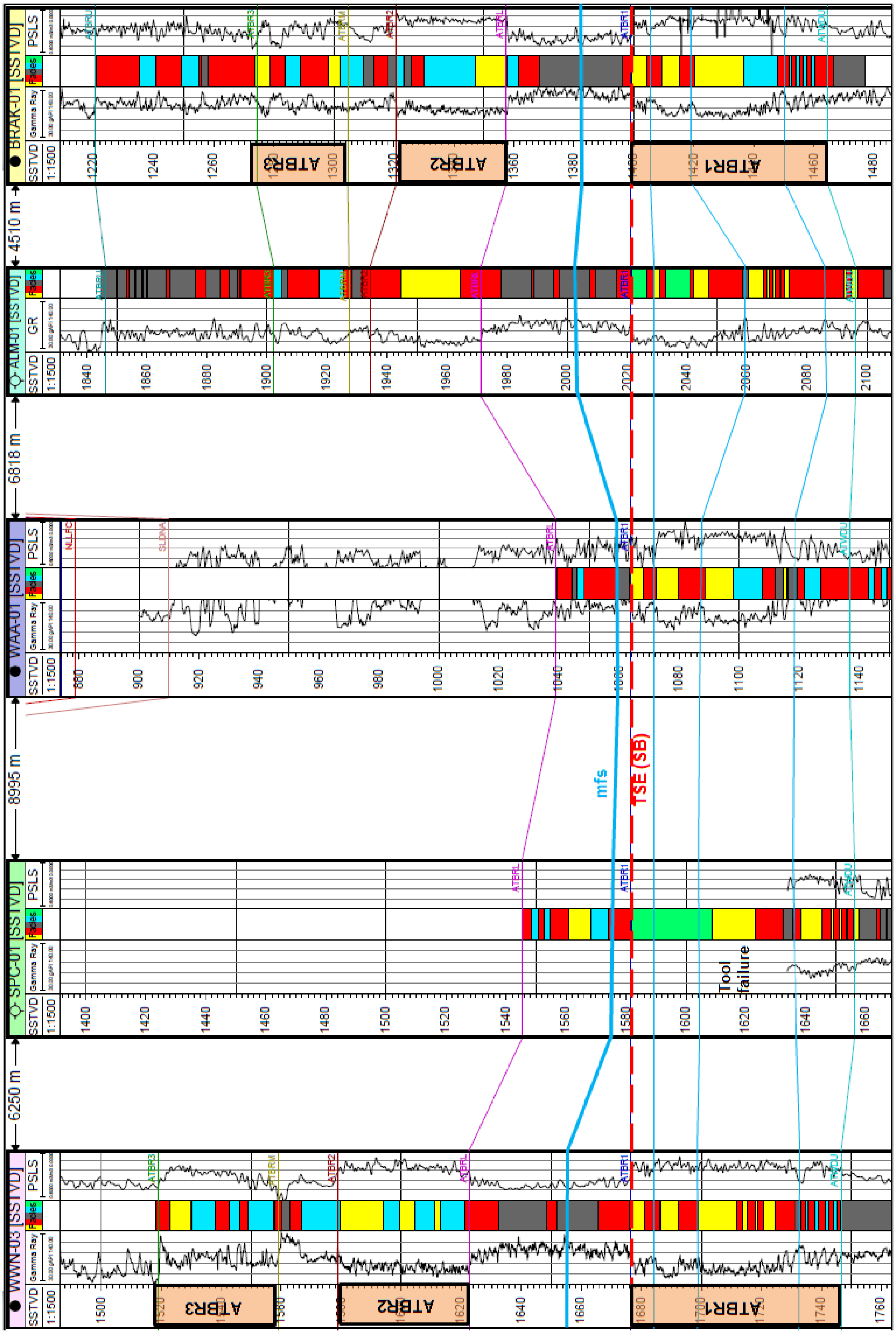


Figure 21. Correlation panel 4 - well log correlation in the northwest RVG where relatively thick Brabant is present in proximal, reservoir-prone facies. Note also the similarity in gamma ray log signature between WWN-03, WAA-01 and BRAK-01 pointing to lateral continuity of individual sedimentary units. Figure 13 for location.

7.3 Core scale

All slabbed cores that are available (Table 3) were studied in the NAM core store. Core quality and recovery is generally low – therefore no detailed core logs have been made. The most continuous cores are AND-03-S2 and AND-04. These cores are used as a basis for facies interpretation. The observed lithofacies are interpreted in terms of depositional environment. Three prominent depositional environments are recognized: offshore (outer ramp), lower shoreface (mid ramp) and upper shoreface/ooid shoal (mid to inner ramp) (Appendix 4; Figure 22). A fourth (foreshore) and fifth (coastal plain/tidal flat) depositional environment is not recognized in cores but inferred from literature (e.g. see Palmer, 1979; Sellwood et al., 1984; Hesselbo, 2008).

Core	Top strat_code	Bottom strat_code	Top (MD)	Bottom (MD)	Total core length (approx.)
AND-04	ATBR3	ATBRM	1399	1408	16m
	ATBRL	ATBR1	1471	1528	42m
AND-03-S2	ATBRL	ATBR1	1195	1251	30m
VEH-01	ATBRM	ATBRM	1582	1588	3m
	ATBR2	ATBR2	1642	1652	5m
	ATBR1	ATBR1	1720	1726	6m
LOZ-01	ATBR2	ATBRL	1989	1995	6m

Table 3. Available slabbed cores for the Brabant Formation. The approximate core lengths are overestimated, as there were many gaps and incomplete/missing sections in the cores.

7.3.1 Sedimentary facies & depositional environments

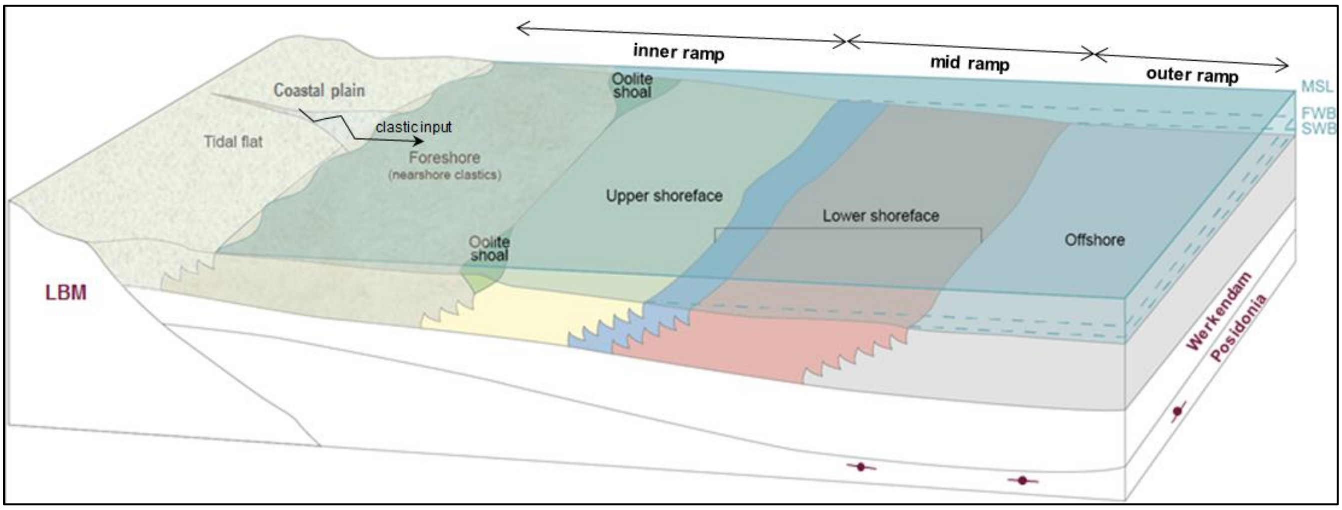


Figure 22. Conceptual depositional model for the Brabant Formation during the Bathonian and Callovian. A gentle dipping, homoclinal carbonate ramp was attached to the London-Brabant Massif. Inner ramp environment hosts foreshore (dominantly clastic), shoal and upper shoreface (both dominantly carbonate) facies, mid ramp environment lower shoreface facies and outer ramp environment offshore facies. The depositional dip of the ramp is here interpreted to have been relatively low as a result of the blanketing effect of underlying Werkendam claystones. See text for details.

Offshore

The offshore facies (Figure 23) is mainly characterized by monotonous, dark grey, brownish to black, marls/claystones or silty marls. It is essentially a micritic mudstone (occasionally wackestone texture). Occasionally, dispersed shell debris or shell debris beds may be present (echinoderms, bivalves, bryozoan, gastropods), which are interpreted to have formed as a result of rare high-energy storm events. Pyrite concretions are not uncommon. A local greenish appearance indicates glauconite presence. In rare cases, dispersed lignite or coal particles are present. Locally, fine to very-fine grained silt beds may be intercalated. The unit is interpreted to have formed in relatively low-energy conditions below storm wave base, in the outer ramp environment. The dominant sedimentary process is suspension settling.

Reservoir potential is very low for this facies. Seal potential is moderate to high, as indicated by poroperm data (see chapter "Reservoir characteristics") and the Lekkerkerk and Andel stranded fields, where these intra-Brabant marls provide top seal.

Lower shoreface

This environment is mainly characterized by two different facies ("Lower shoreface I and II"; Figure 24). Lower shoreface I is most prominent and consists of an intercalation of dark grey, calcareous silty claystone with bands of light grey, calcareous, fine silt- or sandstone (mm to dm-scale). The grey calcareous siltstone bands may increase in frequency and thickness upwards as observed in the AND-04 core (rapid vertical facies changes). The unit has abundant shell debris beds, occasionally in a packstone texture, and abundant dispersed shell debris which are interpreted as storm beds (tempestites). They may be pyritic and/or locally glauconitic and occasionally sandy. Abundant bioturbation characterizes this unit. Faunas consist of planolites, teichichnus, ophiomorpha and serpulids. Rip-up clasts composed of homogeneous clay and/or micrite may be present. The claystone is occasionally silt-size grained. The unit is poorly sorted and often has a chaotic or messy appearance. In the HST-01 core (not slabbed) small-scale hummocky cross stratification is probably identified. The unit is interpreted to have formed between fair-weather wave base and storm wave base, in a low to medium energy, storm-dominated environment on the lower shoreface (mid ramp environment). The abundance of storm beds indicates periodically higher energy conditions.

Lower shoreface II is composed of grey silty/sandy limestone, or when sand content is (very) high, occasionally calcareous silt-/sandstone. It is calcite-cemented, locally glauconitic. Locally the unit may show increased sand content. Rare coal/lignite particles may be present in this facies (AND-06, KDK-01). It may grade into massive, cemented limestone. The unit is interpreted to have formed in a slightly more shallow-marine environment than the Lower shoreface I facies, i.e. where also waves may have had influence, but still in the lower shoreface environment. The relatively high sand content may be the result of phases of foreshore and upper shoreface bypassing and increased terrigenous supply, in a similar manner as observed in the Bathonian Hester's Copse Fm in the Weald Basin in the UK (Sellwood et al., 1984).

The lower shoreface facies has both low reservoir and low seal potential. The coarser silt-graded beds might be potential waste zones with permeabilities up to 4 mD (see "Reservoir characteristics" chapter).

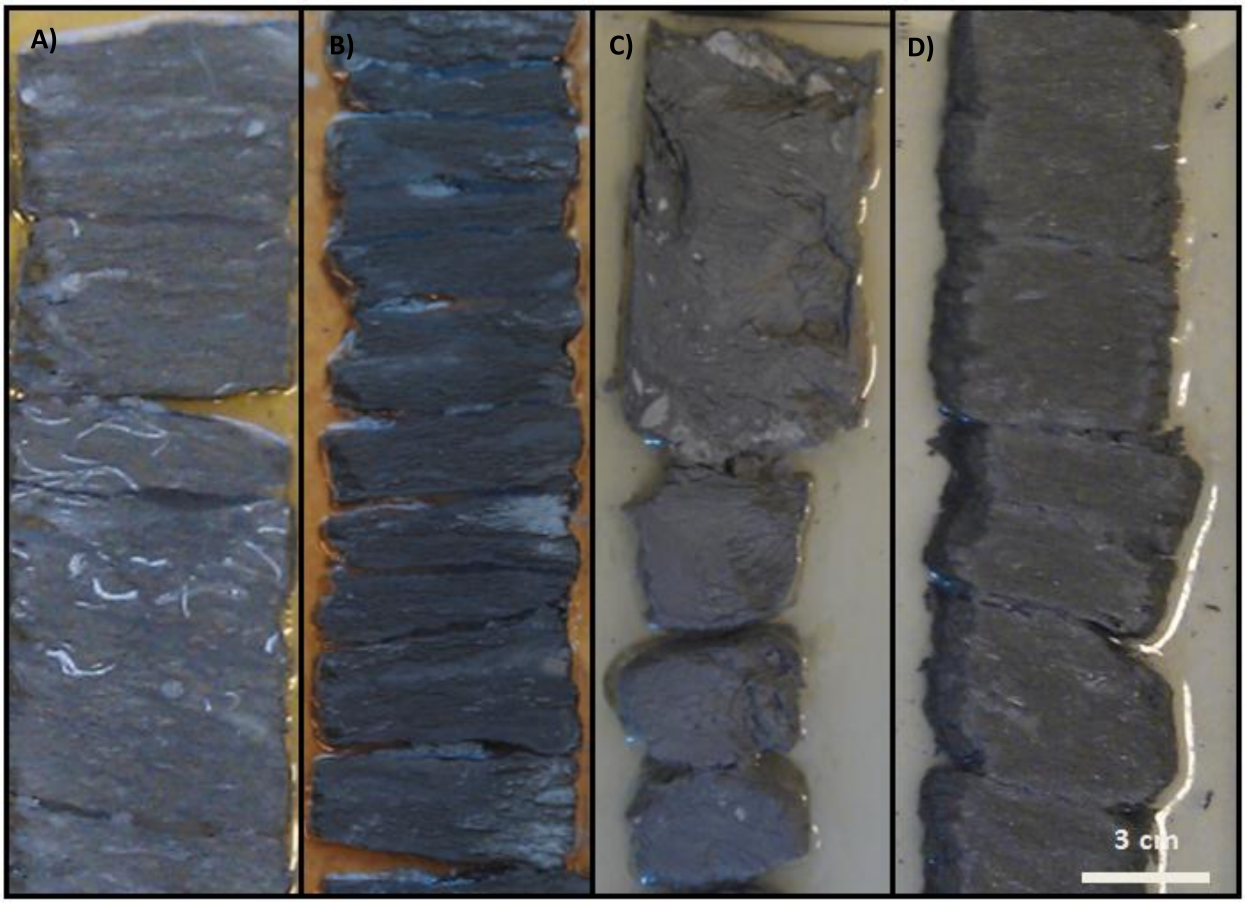
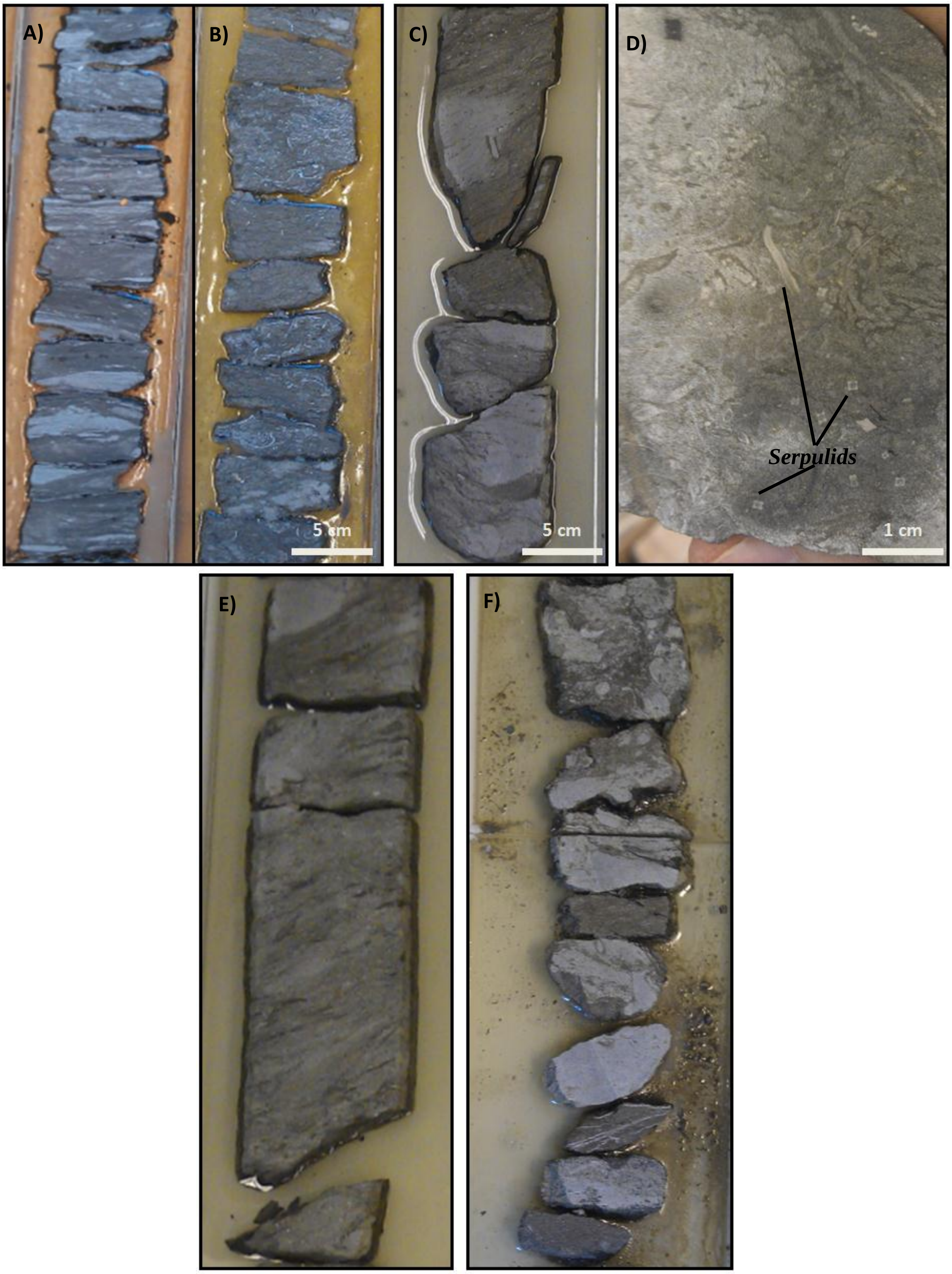


Figure 23 (above). Offshore facies in core. A) **Grey/brown silty marls with shell debris bed and pyrite concretions (AND-04 1496m MD).** B) **Dark grey/brown laminated silty marls (AND-04 1504m MD).** C) **Grey/brown massive marl with calcite concretions/intraclasts (AND-03-S2 1190m MD).** D) **Grey, massive marl, slightly silty (AND-03-S2 1248m MD).**

Figure 24 (below). Lower shoreface facies I (a-c) and II (d-e). A) Alternating dark grey calcareous silty marl with slightly coarser, light grey calcareous siltstone beds and shell debris beds, interpreted as storm-graded beds (Lower shoreface facies I; AND-04 1399m and 1473m MD). B) **Dark grey calcareous siltstone/silty limestone with light grey calcite cemented part. Note the Ophiomorpha burrow (Lower shoreface facies I; AND-03-S2 1212m MD).** C) **Dark grey calcareous siltstone/silty limestone, with light grey calcite cemented part. Note the abundant burrowing organisms (serpulids) (Lower shoreface facies I; AND-04 1519m MD).** D) **Medium/dark grey calcareous siltstone with mud particles and calcite cement (light grey parts), messy appearance (Lower shoreface facies II; AND-03-S2 1211.5m MD).** E) **Light grey, cemented, massive silty limestone with thin dark grey calcareous siltstone (Lower shoreface facies II; AND-03-S2 1198m MD).**


A)
B)
5 cm
C)
5 cm
D)
Serpulids
1 cm
E)
F)

Upper shoreface environment

The upper shoreface (or shoal) environment is characterized by light-coloured (grey/pale grey/offwhite/yellow-brown), well-sorted, fine- to coarse-grained calcarenitic or bioclastic grainstones cemented to various degrees by sparite. The unit may be sandy (quartz-rich). The grainstones are (cross-)laminated with occasionally visible porosity. Occasionally, the unit is massive and cemented (tight). Locally, muddy rip-up clasts are present. Rarely, traces of cryptocrystalline dolomite with sucrosic texture may be present in this facies (not observed in core; WWK-01, WED-01, AND-06). Bioturbation is not common but may be present (Ophiomorpha; Figure 25A). Various 10-30cm thick shoaling-upward cycles can be recognized in the AND-03-S2 core (Figure 25B and C), with at the base massive or slightly laminated, cemented limestones with some muddy particles, grading up into well-laminated, clean (no mud) silty and sandy calcarenites. Another core sample (Figure 25D) shows a slightly erosive base covered by coarse-grained bioclastic calcite grains and micritized shell debris (massive texture), fining upwards into cross-laminated, well-sorted, fine-grained calcite grains. This mass flow event (Bouma A & B sequence) is interpreted as a tempestite sequence (storm bed). Rapid vertical facies changes are observed in the AND-03-S2 core (Figure 25A): the silty/sandy limestone sequences can be abruptly intercalated with marly or silty deposits of the lower shoreface and foreshore. Calcite veins are occasionally observed in core. They seem to occur at lithological contacts that appear to be fractured (fracture network). Timing of this event remains enigmatic. It might be related to fracturing during inversion. The entire upper shoreface facies unit is interpreted to have formed in a high-energy, wave-dominated, upper shoreface environment (inner ramp), where wave action was high and sorted the grains to a high degree.

Overall, the upper shoreface facies unit has moderate to high reservoir potential. The cross-laminated, well-sorted grainstones have occasionally visible porosity in core. Core plug measurements indicate porosities up to 20-29% and permeabilities up to 137 mD (see “Reservoir characteristics” chapter).

Ooid shoal environment

This facies was not encountered in core slabs because it is only sporadically present, and information here comes from well log information. Basically, it can be regarded as a sub-environment of the upper shoreface environment. The facies is characterized by a white/offwhite/light grey, oolitic, algal limestone. It is generally massive and well-sorted, occasionally laminated. The size of the (sub)spherical ooids may vary from fine to coarse. The unit is cemented by micrite and/or sparite. Shell fragments may occur and the unit may have quartz grains. The unit is interpreted to have formed on shoals, in a high-energy, wave-dominated environment in very shallow water depths.

Foreshore and coastal plain environment

Foreshore and coastal plain facies are not convincingly recognized within the study area, but described in literature from formations to the south of the London-Brabant Massif (see below). The possible presence of these facies is inferred from Hesselbo (2008) and Palmer (1979), who describe a proximal siliciclastic facies, grading laterally into carbonate facies (that constitute the carbonate ramp) in the Weald Basin (UK). A similar, gentle-dipping carbonate ramp existed there in the Bathonian. In the study area, these mixed carbonate-siliciclastic facies were likely deposited more towards the London-Brabant Massif during the Bathonian (ATBR1 times). They probably reached the RVG and WNB only during lowest relative sea levels (calcareous sandstones), when regression continued. More evidence in the study area for presence of mixed carbonate-siliciclastic foreshore facies near the

LBM during the Bathonian, comes from basin-margin well DON-01 where a thin, 1m calcareous sandstone bed in the ATBR1 is found (cuttings descriptions).

A proximal coastal plain environment near the LBM is inferred from the rare presence of lignite and dispersed organic material (plant remains) with woody texture in lower shoreface and offshore facies (observed in core and cuttings descriptions). High-energy storm events may have transported these towards the lower shoreface and offshore, where they could settle from suspension after storm surges.

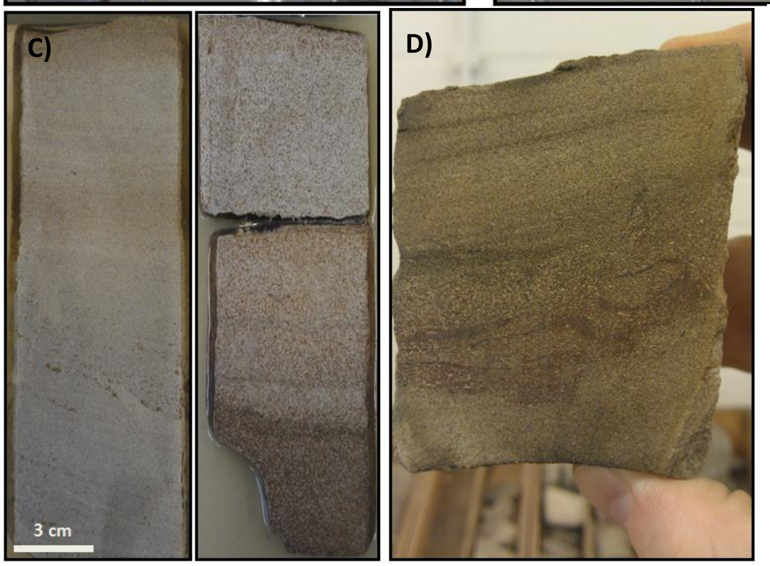


Figure 25. A) AND-03-S2, 1226-1229m MD. Note the large burrow (Ophiomorpha) and rapid vertical facies changes with several intercalated marl and calcareous silt/sandstone beds of the lower shoreface environment (darker colored). B) AND-03-S2, 1219-1224m MD. Relatively clean reservoir section, some shoaling-upward cycles 10-30cm thick can be recognized in this section. C) Insets of B). Left picture shows a shoaling-upward cycle with slightly laminated massive and cemented grainstones with no sand and local muddy particles at the base, cleaning and shoaling up into well-laminated silty and sandy grainstones. Right picture shows very coarse sandy bioclastic grainstone with good visible porosity. D) AND-04: 1523m MD. Tempestite sequence with erosive base and micritized shell debris fining up into well-laminated fine-grained grainstone.

Chapter 8 Analogue formations

This chapter discusses the facies and depositional model of analogue carbonate and non-carbonate successions from the UK and France, as well as the Muschelkalk layer-cake carbonates. Concepts and facies interpretations/depositional environments, used to explain these formations, may be used to understand the depositional model for the Brabant Formation. In addition, it is possible that not all (proximal) facies belts of the Brabant Formation have been drilled in wells in the study area. Knowledge of the possible presence of these facies belts may come from insights into these formations as well.

Analogue and time-equivalent formations for the Brabant Formation exist in the Weald Basin (UK) and Paris Basin (France). These were deposited at the other side of the London-Brabant Massif, coeval with Brabant deposition in the study area. The chronostratigraphy of formations in the Weald, Paris and Sole Pit Basin, compared to stratigraphy of the Brabant Formation, is shown in Figure 26.

8.1 Weald Basin carbonate ramp

During the Middle Jurassic (Bathonian - Early Callovian) in the Weald and Wessex Basin in the UK, an epeiric, tide-dominated carbonate ramp was attached to the south and west of the London-Brabant Massif (Figure 11; Sellwood et al., 1984; Burchette & Wright, 1992; Wyatt, 1996; Hesselbo, 2008). The existence of this carbonate ramp is coeval with deposition of the Lower Brabant Limestone and Lower Brabant Marl in the study area. The ramp dipped gently away from the LBM with a depositional slope of ~0.1°. The sedimentary sequence thickens into the basin (Sellwood et al., 1984; Hesselbo, 2008), as is also observed in the Brabant Formation. The strata can be correlated at least 150km from the London-Brabant Massif into the basin, where it thickens from about 50m (basin-fringe Weald Basin) to over 200m (Wessex Basin). The formations are dominantly composed of oolitic pack- and grainstones, calcareous claystones and minor calcareous sandstones that prograded into the basin. The 200m+ sedimentary sequence is composed of four regressive, shoaling-upwards cycles (Wyatt, 1996). Depositional environments range from clastic fringe grading into lagoonal near the London-Brabant Massif, passing into upper shoreface/shoal facies (foreshoal/backshoal and tidal channels) towards lower shoreface/storm-dominated facies, to open-marine shales in the Wessex Basin (Hesselbo, 2008). Carbonate deposition in the Weald Basin terminated in the Callovian, when the ramp drowned. A major marine transgression led to the deposition of basinal marine clays (Upper Cornbrash and Kellaways of the Oxford Clay Fm). The Oxfordian development of this area is not known. The most important rocks in the Weald Basin are the regressive oolitic grainstones of the Great Oolite Group (Bathonian age). These are the reservoir rock of various oil fields in southern England (Sellwood et al., 1984).

8.2 Paris Basin carbonate ramp

The epeiric carbonate ramp in the Bathonian of the Weald Basin can roughly be correlated towards the more southerly Paris Basin (Figure 11; Brigaud et al., 2014), and probably all the way to southeast France and Switzerland. A large tide-dominated, oolite-rich carbonate platform and ramp (Burgundy Platform) was present during the Middle Jurassic (Wetzel et al., 2013). During the Bathonian – Early Callovian in the Paris Basin, carbonates prograded out into the basin. This stage is coeval with Brabant Fm deposition in the study area and with the Weald Basin carbonate ramp in the UK. An ooid and muddy rimmed carbonate ramp existed in a stable, relatively warm and dry climate (16-24°C) (Brigaud et al., 2014). Depositional environments ranged from protected lagoon to ooid shoal/shoreface to upper and lower offshore (Wetzel et al., 2013; Brigaud et al., 2014). During the

Early Callovian, the carbonate ramp drowned during marine transgression, similar as in the UK (Sellwood et al., 1984).

8.3 Sole Pit Basin

No carbonate ramp existed in the Bathonian in the Sole Pit Basin. Instead, sediments consist of dominantly non- to marginal-marine mudstones and interbedded silt- and sandstones (Hudleston Fm.; Lott & Knox, 1994). The succession accumulated in a fluviodeltaic setting. Sediments were derived from the uplifted Mid North Sea High towards the north (Figure 11; Ziegler, 1982; Lott & Knox, 1994). The overlying 15m-thick Leckenby Formation (Callovian age) comprises glauconitic, carbonate-cemented sandstones deposited in a shallow-marine environment. This formation shows good similarities with coeval calcareous sandstones of the Middle and Upper Brabant Limestone. The overlying Corallian Formation (Early-Mid Oxfordian) is composed of calcareous sandstones that pass upwards into oolitic limestones. This formation is coeval with and lithologically very similar to the Oisterwijk Limestone Member of the Brabant Formation (ATBRO). The oolitic limestones are formed as a series of high-energy shoals with low clastic input. Towards the London-Brabant Massif and onshore England, the oolitic limestones may grade rapidly into fine sand-, silt- and mudstone lithologies (Seeley Fm.; Lott & Knox, 1994). This may have also been the case in the study area but due to sparse well data this cannot be confirmed.

8.4 Muschelkalk

Characteristic features of the Brabant Formation are its “layer-cake”-like appearance on seismic and relatively consistent gamma ray response (at least in the Roer Valley Graben), which suggest lateral continuity of sedimentary units. Typical “layer-cake”-type carbonate successions are described in literature from the Lower Keuper, Lower and Upper Muschelkalk in the German and Dutch sector of the Southern Permian Basin (Pöppelreiter & Aigner, 2003; Borkhataria et al., 2005; Borkhataria et al., 2006). These carbonates were deposited as layer-cakes on epeiric storm-dominated carbonate ramps in the Late Triassic. These epeiric ramps had extremely low depositional slopes on the order of 0.02 - 0.002° and were attached to the London-Brabant Massif. The Lower and Upper Muschelkalk show a basinward-thickening sequence, both on a large (10’s to 100’s of km) and small (1 to 10’s of km) scale. The sequences thin towards the London-Brabant Massif. These thickening and thinning trends are thought to be related to minor differential subsidence, on both a regional and local scale. The differential subsidence patterns coincide with reactivation of crystalline basement lineaments. Thicker sequences may develop in areas that subside slightly faster as a result of minor slip along these deeply-rooted faults. This differential subsidence may influence energy zonation and diagenetic processes on the ramp (Pöppelreiter & Aigner, 2003). Moreover, as described in Pöppelreiter & Aigner (2003), slowly subsiding epeiric ramps undergo continuous reworking and redeposition of supplied sediment. Waves and storms effectively shave off sediment and transport this towards areas of higher accommodation (i.e. areas of stronger subsidence). The interplay between such depositional processes and differential subsidence results in accumulation of maximum sediment volumes in zones of stronger subsidence (Pöppelreiter & Aigner, 2003). This processes is called by the authors ‘sediment volume funneling’. These “layer-cake” successions have a more aggradational than progradational facies architecture as a result of the low depositional dip and low accommodation space on the ramp. This leads to the development of ‘facies sheets’ that extend over rather large areas. Proximally, such facies sheets are amalgamated due to the continuous existence of the area within wave base. Similar type of processes as mentioned above, especially sediment volume funneling, may have played a role in the study area as well during Brabant deposition.

8.5 Conclusions

The Brabant Formation is lithologically comparable to coeval carbonate successions in the UK and France: the lower part of the Brabant Fm (ATBR1, ATBRL, ATBR2) is very comparable to carbonate ramp successions in the Weald and Paris Basin, whereas the upper part (ATBR3, ATBRO) is more comparable to the succession in the Sole Pit Basin.

The carbonate successions in the Weald and Paris Basin were deposited on epeiric carbonate ramps attached to the London-Brabant Massif, from the Bathonian to Early Callovian. Depositional environments in the Weald and Paris Basin are comparable. They consisted of: proximally, clastic fringe grading into lagoonal near the London-Brabant Massif (foreshore), passing distally into upper shoreface and/or ooid shoal facies, lower shoreface facies and finally to offshore facies (open-marine shales). The ramps are generally characterized by gentle depositional slopes (< 0.1°). Strata thicken basinward and thin towards the London-Brabant Massif. Both ramps drowned during the Early Callovian as a result of marine transgression. Such ramp system and depositional environments probably prevailed in the study area as well.

The Callovian and Oxfordian of the Sole Pit Basin show similarities in lithology with the Middle Brabant Limestone, Upper Brabant Limestone (Callovian calcareous sandstones) and Oisterwijk Limestone Member (Oxfordian oolitic limestones). The calcareous sandstones were deposited in a shallow-marine shelf setting; the oolitic limestones were deposited on high-energy shoals when clastic supply ceased. Such depositional settings probably prevailed in the study area as well.

The Brabant Formation is comparable to other "layer-cake"-like carbonate successions in the geologic record, such as the Muschelkalk. These were all deposited on gentle dipping carbonate ramps producing parallel layer-cake stratification. Concepts and processes such as sediment volume funneling used to describe and understand those successions are applicable to the Brabant Formation.

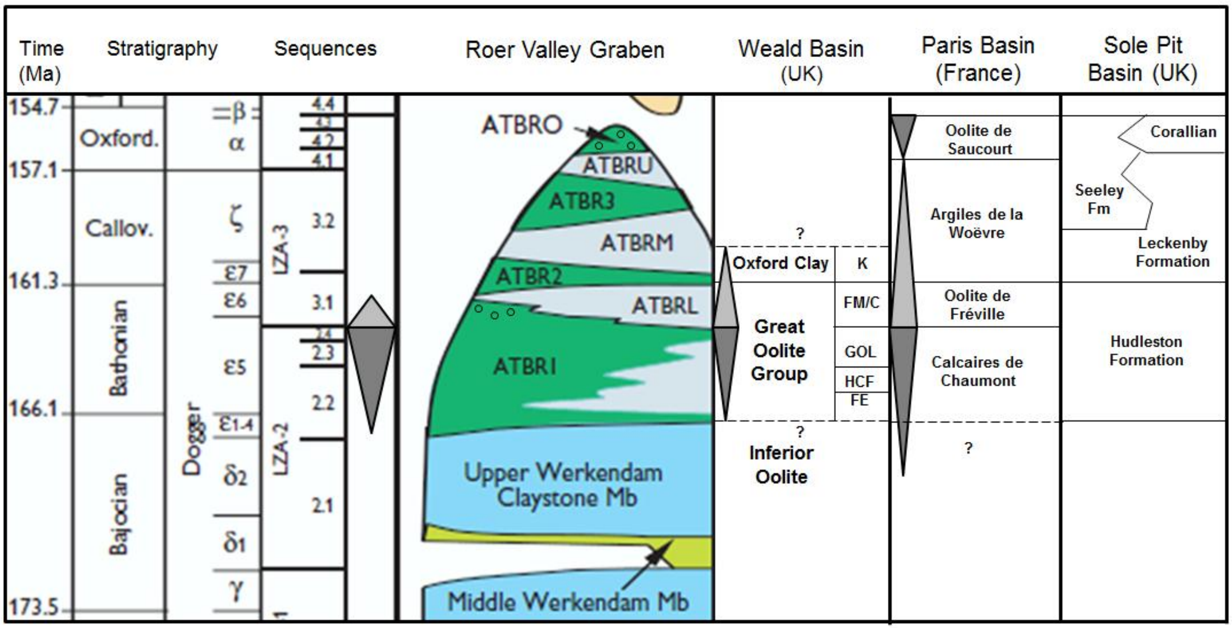


Figure 26. Correlation of the Brabant Formation with coeval formations in southern England (Weald Basin, UK; after Sellwood et al., 1984 and Hesselbo, 2008), in northeast France (Paris Basin, after Brigaud et al., 2014) and in the offshore Sole Pit Basin (UK; after Lott & Knox, 1994). Light-grey shading indicates a dominantly transgressive systems tract, dark-grey shading the regressive systems tract. K = Kellaways Fm., FM/C = Forest Marble & Cornbrash Fm., GOL = Great Oolite Limestone Fm., HCF = Hester's Copse Fm., FE = Fuller's Earth Fm. For details, see text and references.

Chapter 9 Facies interpretation

A facies interpretation has been made by calibrating core facies to logs using *k*-Means Clustering (Chapter 9.1). Facies maps are presented for the Lower Brabant Limestone Member, Lower Brabant Marl Member, Middle Brabant Limestone Member and Upper Brabant Limestone Member (Chapter 9.2). These maps have been combined to form an interpreted 'Brabant Formation sweetspot' map (Chapter 9.3), showing the most prospective area in terms of reservoir presence, thickness and quality.

9.1 Core – log calibration

Wireline log data of the AND-04 and AND-03-S2 wells is limited and consists of spontaneous potential and resistivity – no gamma ray or sonic is available. To calibrate the interpreted core facies to conventional log data (gamma ray, resistivity and sonic), a cluster analysis was carried out (*k*-Means Clustering). Log data are clustered into 4 electrofacies groups (*k*). This gives statistically the best fit to the data. The HBV-01 well has been used for calibration. The four electrofacies groups are correlated with the AND-04 log. Figure 27 shows there is good agreement in the Lower Brabant Limestone (bottom part). Dark green electrofacies corresponds to upper shoreface facies interpreted from core. Upper shoreface facies (predominantly sandy calcarenites; see above) is generally associated with high resistivity, low sonic and low gamma ray values. Light green electrofacies corresponds to offshore facies (marls). These are characterized by low resistivity, high sonic and high gamma ray. Grey and sky blue electrofacies correspond to lower shoreface facies I and II and have intermediate log responses, between the upper shoreface and offshore facies (Table 4).

Facies	Gamma ray	Resistivity	Sonic
Upper shoreface	Low	High	Low
Lower shoreface II	Low	Low-medium	Medium-high
Lower shoreface I	Medium	Medium-high	Low-medium
Offshore	High	Low	High

Table 4. Characteristic log response for each facies, from core-log calibration with *k*-Means Clustering.

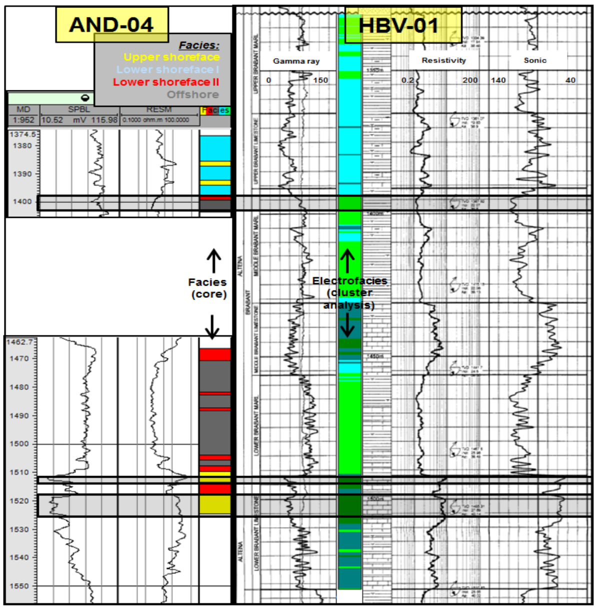


Figure 27. Core-log calibration using *k*-Means Clustering. Interpreted core facies (left) are calibrated to gamma ray, resistivity and sonic log data of HBV-01 (right). The best fit was obtained for 4 clusters.

9.2 Facies distribution maps

The characteristic log responses (Table 4) were used as guidelines for facies interpretation. A tentative facies interpretation was made in wells holding sufficient log data. The fraction of each facies per lithostratigraphic unit was plotted on a map as pie charts. The size of the pie chart indicates the thickness of the member along hole. These facies distribution maps have been constructed for the Lower Brabant Limestone (Early-Mid Bathonian; Appendix 5), Lower Brabant Marl (Late Bathonian; Appendix 6), Middle Brabant Limestone (Early Callovian; Appendix 7) and Upper Brabant Limestone (Mid-Late Callovian; Appendix 8). On these maps, areas with higher fractions of reservoir-prone vs. seal-prone facies can be delineated.

The Lower Brabant Limestone has most well data available, as this unit is best preserved. It can be seen that reservoir-prone facies are predominantly present in the west and northwest Roer Valley Graben. Especially well SPC-01 has relatively thick ooid shoal facies. The formation is thickest in this area as well. Towards the WNB, facies appear to become slightly sandier and more distal (Appendix 5; CAP-01 in Figure 19). To confirm the distal facies trend in the WNB, it was attempted to look for lateral changes in reflector amplitudes. Truncation and bad seismic quality hampered this.

The distal facies trend could also not be confirmed in the Roer Valley Graben due to a lack of well and log data in the basin center. Instead, it appears that the characteristic layer-cake Brabant reflectors (see "Basin and seismic scale" chapter) are present all over the Roer Valley Graben. The consistent amplitude and continuity of the reflectors does not give strong evidence for distal facies presence. It is likely that, as a result of low depositional dip, the facies change was very subtle.

The Lower Brabant Marl generally shows offshore facies in the entire area with only locally some thin intercalated lower shoreface facies. It appears that more proximal facies occur at the RVG/WNB border. This may pose a seal risk in this area.

The Middle Brabant Limestone is overall sandier and has a higher fraction of reservoir-prone facies. There might be a slight increase in distal facies towards the Roer Valley Graben basin center as evidenced by the HVB-01 – BKZ-01 correlation in the southwest (Figure 20). The distribution and thickness of the formation shows clustering in the west and northwest Roer Valley Graben and east West Netherlands Basin area. The Upper Brabant Limestone is the sandiest of the three prospective intervals (calcareous sandstones). The formation thickens towards the Roer Valley Graben basin center. A weak proximal – distal trend in HVB-01 – BKZ-01 (Figure 20) shows evidence for a slight increase in distal facies towards the Roer Valley Graben basin center.

9.3 Sweetspots

The above-mentioned observations were combined in an interpreted “reservoir sweetspot map” that integrates the three prospective limestone members (Figure 28). The most prospective area is found in the northwest and west Roer Valley Graben (Waalwijk area) and at the border with the West Netherlands Basin, where in grabens, all three prospective limestone members are present. They are here thickest developed and present in proximal facies. This gives stacked reservoir potential, more metres of net reservoir and possibly also the highest net-to-gross ratios due to abundant proximal facies. This area can likely be extended towards the Roer Valley Graben basin center as evidenced by seismic, but net-to-gross ratios possibly decrease in this direction as a result of possible distal facies. Towards the (center of the) West Netherlands Basin, the formation is progressively more truncated by the Base Delfland Unconformity. In addition, reservoir quality deteriorates in this direction as indicated by distal facies.

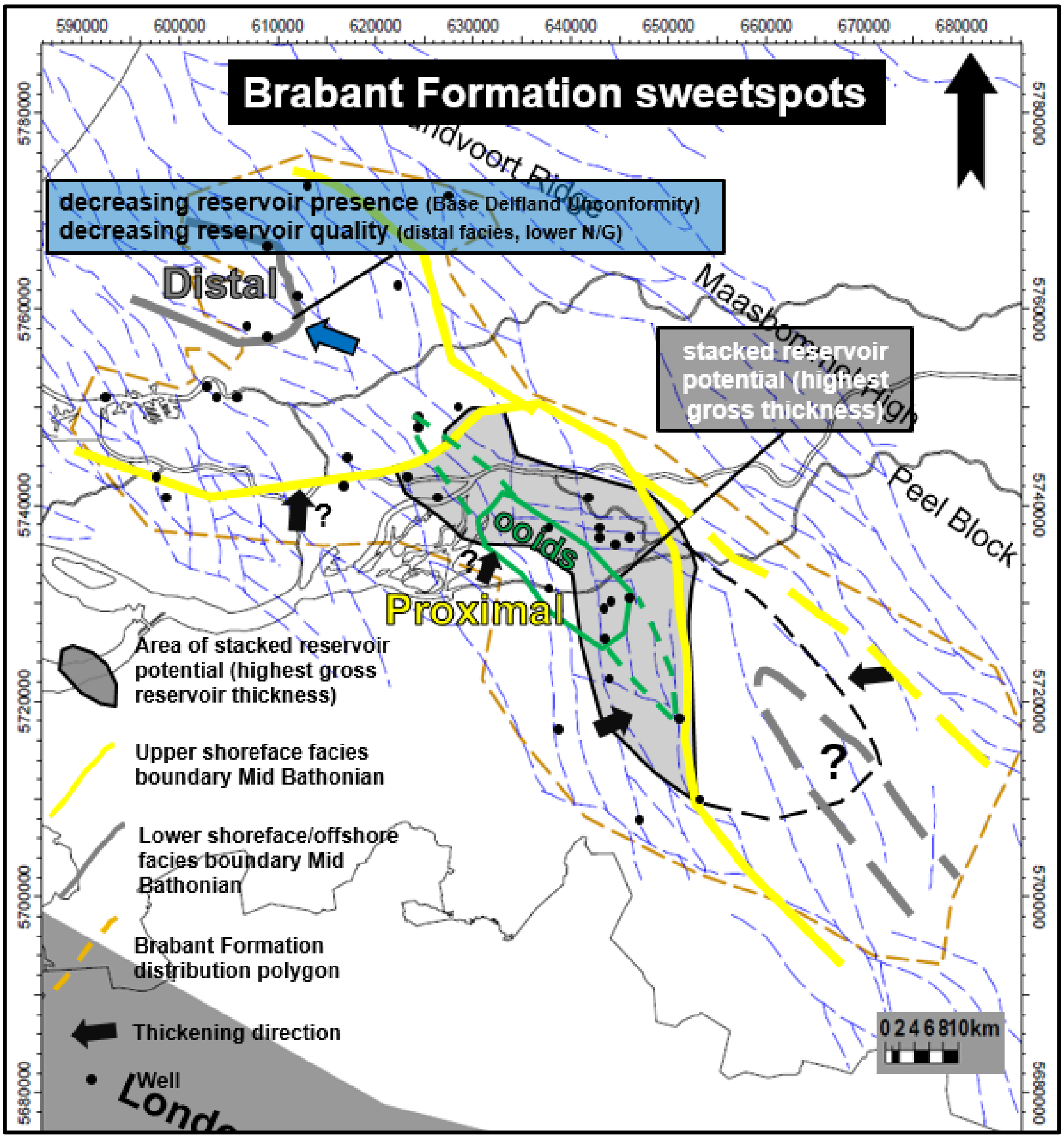


Figure 28. Brabant Formation sweetspot map, constructed from the separate facies distribution maps. Area of stacked reservoir potential and most metres of net reservoir are indicated, as well as possible proximal-distal facies trends. The northwest Roer Valley Graben and border with West Netherlands Basin are considered most prospective. Towards the West Netherlands Basin, truncation and deteriorating reservoir quality decrease prospectivity.

Chapter 10 Conceptual geological model

In this chapter, an attempt is made to place above-mentioned observations and interpretations in a conceptual geological model. The most important observations are summarized in the table below. The conceptual geological model is discussed from several points of view: the depositional, tectonic, climatic and diagenetic setting.

Basin scale (seismic)	Well log scale	Core scale
Layer-cake stratification (down dip and along strike)	Dominantly regressive, shoaling-upward sequences separated by transgressive events	3 dominant sedimentary facies (upper shoreface/shoal, lower shoreface, offshore)
Basinward thickening, thins to LBM	Similar, serrated GR response in sandy calcarenites	Rapid vertical facies changes in upper and lower shoreface facies

The seismic, well log and core observations described above fit in a model of deposition on a carbonate ramp (Figure 22 and 29). This ramp is comparable to carbonate ramps that existed in the Weald and Paris Basin in the Bathonian and Callovian. The ramp, that was attached to the northern edge of the London-Brabant Massif from the Bathonian to Oxfordian, has relatively low depositional dip of ~0.05-0.1° (although not “epeiric”-type dip as seen in the Muschelkalk). Consequently, facies belts are wide and progradational sequences are relatively thin. The ramp is dominated by sedimentary transport processes (Figure 29). The leeward wind position of the ramp with respect to the London-Brabant Massif favors high sediment transport rates. High sediment transport fluxes towards the depocenters of that time (Roer Valley Graben, West and Central Netherlands Basin, Broad Fourteens Basin), in combination with low depositional dip, cause rapid infilling of accommodation space in these basins and thickening of sedimentary sequences in a basinward direction in a roughly aggradational facies architecture. Sediment volume funneling, as described by Pöppelreiter & Aigner (2003), plays a dominant role on the ramp. Thickest sequences are deposited in fastest subsiding grabens.

10.1 Depositional setting

The most important elements of the depositional model are summarized in Figure 22 and 29. The most proximal environments are characterized by coastal plain and foreshore facies. Evidence for such environments comes from Sole Pit Basin analogues (Lott & Knox, 1994), from proximal carbonate ramp facies in the Weald Basin (Sellwood et al., 1986) and from basin margin well DON-01. Foreshore facies are deposited below sea level on the carbonate’s inner ramp. These are thought to be composed of a predominantly clastic lithology, grading laterally into a mixed siliciclastic-carbonate lithology where influence of the carbonate factory becomes progressively stronger. Eventually, the foreshore passes laterally into carbonate-dominated lithologies: upper shoreface facies. Carbonate production is here at a maximum albeit at low to moderate rates when compared to typical platform carbonates formed in hot climates. High-energy, wave-dominated sandy calcarenitic and bioclastic grainstones are deposited in this upper shoreface/shoal environment within fair weather wave base. At the proximal side of this facies belt, ooid shoals may develop. The upper shoreface and ooid shoal facies belt is clearly the most reservoir-prone. Distally, this facies passes into the mid ramp environment where lower shoreface facies are found. These consist of intercalated marl/silt-graded beds with frequent shell debris beds or calcareous silt/sandstone beds. This environment is under the frequent influence of storm events. Storm reworking is the dominant sedimentary process in combination with bioturbation. Distally, the outer ramp environment, offshore facies are deposited. Here, predominantly marls are deposited, occasionally silty with dispersed shell debris beds. This environment is under the influence of suspension settling. However, rare anomalously high-energy storm events cause influxes of coarser sediment.

Low depositional dip

Relatively consistent gamma ray patterns, in combination with rapid vertical facies changes as observed in core in predominantly upper and lower shoreface facies, point to a carbonate ramp with low depositional dip. On such a ramp, small variations in sea level result in large shoreline and facies belt shifts. This results in rapid vertical facies changes. Also, increases in silt and marl content (marly intercalations) in regressive limestones of the ATBR1/2/3 indicate rapid shifting of facies belts back and forth on the ramp. In contrast to rapid vertical facies changes, lateral facies changes appear to be subtle and consequently, facies belts are relatively wide. This is evidenced by well log correlations down-dip and along-strike in the Roer Valley Graben that show individual sedimentary sequences that can be correlated over relatively large distances (10-30km) without major change in facies. Moreover, layer-cake stratification on the seismic-scale is also evidence for lateral continuity. As a consequence of wide facies belts, progradational rates are relatively low. Instead, a more aggradational facies architecture is assumed.

The low depositional dip of the ramp was likely the result of regional subsidence that prevailed in northwest Europe during the Lower and Middle Jurassic, in combination with the draping effect of the underlying claystones of the Werkendam Formation. These open-marine claystones were draped over large areas in the Netherlands and likely leveled out any pre-existing topographic relief. These processes have favored creating a low depositional profile for the Brabant Fm. A depositional slope of ~0.05-0.1° is calculated, based on distance to the London-Brabant Massif (assumed to be 5-10km (low sea levels) and 20-40km (high sea levels)) and depositional water depth (~5-10m for upper shoreface facies and 20-40m for offshore facies). Locally, subsidence rates may have been higher (minor fault activity); accommodation space was rapidly filled in by sediments.

High sediment transport rates

The dominant role that sediment transport processes play on the carbonate ramp is documented in the rock record. An important observation is the frequent influx of slightly coarser-grained clastics (silt-graded storm beds in lower shoreface; calcareous sandstone beds in upper shoreface) and bioclastic carbonate grains (shell debris beds) in predominantly lower and upper shoreface facies. Other evidence comes from the thickness of sedimentary units. The thinner sedimentary sequence in basin-margin wells (for example in HVB-01 and HBV-01) can be explained by their more proximal location, where accommodation space is more limited. Here, constant wave reworking led to amalgamation of sedimentary units and net sediment transport basinward. Distally, there is more accommodation space available and as a consequence of the high sediment transport rates, the sedimentary succession is thicker and more complete here. These thicker successions appear to be present in similar facies. The thickest sedimentary successions are found in the western, northwestern and axial parts of the Roer Valley Graben and eastern West Netherlands Basin.

From cuttings descriptions from well logs, it is concluded that the Brabant Formation in the West Netherlands Basin is sandier than in the Roer Valley Graben. This is in agreement with a calcareous sandstone lithology below the TSE in HST-01. At the same time in the Andel area, calcarenitic grainstones are deposited. This indicates that during deposition of the upper shoreface facies, sand influx varied laterally along the depositional profile. A possible explanation is that tidal channel inlets may have been present on the ramp in the West Netherlands Basin that favored sand accumulation.

10.2 Tectonic setting

Structural complexity increased gradually during the Middle Jurassic (Herngreen et al., 2007). Differential subsidence between basin center (grabens RVG, WNB) and basin margin has played a role, although it is not exactly known how much differential subsidence actually has occurred during Brabant deposition. The subsidence created extra accommodation space in the basins. Sediments rapidly filled the extra accommodation space created by the differential subsidence. The process of sediment volume funneling effectively traps the sediment in areas where most accommodation space is available. This leads to higher gross reservoir thicknesses, and ultimately may lead to more metres of net reservoir in these areas of highest subsidence. Thus, the interplay between sediment transport processes and differential subsidence on the carbonate ramp ('sediment volume funneling' *sensu* Pöppelreiter & Aigner (2003)) is thought to ultimately lead to thickest sedimentary successions in the fastest subsiding grabens, without showing a distal facies trend in the grabens in the west and northwest Roer Valley Graben.

10.3 Climatic setting

The study area was located around 30-35° N during the Bathonian with a relatively large distance to open oceanic gateways (Tethys to far south). The climate in the southerly Paris Basin during the Middle Jurassic was moderately warm and dry (Brigaud et al., 2014). It is assumed that a similar climate existed in the study area. This, in combination with clastic input from the LBM, does not favor high carbonate production rates. So, carbonate production rates were probably low to moderate.

The dominant wind direction in the study area was from the southwest (westerlies and/or tropical cyclones), so the transport-dominated carbonate ramp occupied a leeward wind position relative to the London-Brabant Massif. This leeward position of the ramp favors net sediment transport away from the London-Brabant Massif. Additionally, the relatively large distance to open oceanic gateways may have favored the development of laterally extensive, wide, grainy shoal facies on the ramp (upper shoreface facies), because ocean currents could not 'disturb' or 'disrupt' this shoal belt.

10.4 Diagenetic setting

Diagenesis in carbonates is of major importance to reservoir quality. Understanding the post-depositional and diagenetic evolution of the Brabant Formation involves detailed petrographical and mineralogical analyses and is not the main scope of this study. However, first-order estimates on diagenetic and post-depositional processes with effect on reservoir development can be made. These are briefly mentioned. They can be roughly divided into five diagenetic phases:

1) Base Delfland Unconformity exposure phase (early Late Jurassic)

2) Rapid burial phase (late Late Jurassic-Early Cretaceous)

3) Oil charge phase (mid to Late Cretaceous)

4) Inversion phase (Late Cretaceous – Early Tertiary)

5) Tertiary burial phase (Oligocene – recent)

Early burial of the Brabant Formation caused porosity – permeability reduction due to compaction. The Brabant Formation is overlain unconformably by continental deposits of the Delfland Group. Below the Base Delfland Unconformity, pyrite, hematite, siderite (iron carbonate) and siderite spherules, that have formed due to subaerial exposure and meteoric water influx, are frequently found indicating its subaerial nature (e.g. WAA-01; see below). This early diagenetic phase may have reduced porosity and permeability below the unconformity. On the other side, these leaching fluids may have dissolved carbonate material (freshwater dissolution), leading to increased porosity and permeability. No indications for karstification or extensive secondary porosity generation have been observed, however.

The rapid burial that followed during Delfland deposition may have quickly reduced porosity and permeability due to compaction.

During the mid and Late Cretaceous, the Posidonia Formation reached its maximum oil generation and expulsion phase. This led to oil charge and migration through the Brabant reservoir, as it is stratigraphically located just above the Posidonia. This early oil charge and fill phase may have prevented further cementation and thus retaining porosity and permeability.

During Late Cretaceous inversion, major uplift took place in the basins. Faulting and folding caused extensive fracturing of the Brabant Formation in inverted areas. Calcite vein crystallization may have occurred during this phase as well (core data). In areas where the formation subcrops the Late Cretaceous Unconformity, porosity and permeability may be enhanced as a result of influx of leaching fluids and possible karstification.

Oligocene to recent burial likely further reduced porosity and permeability due to compaction.

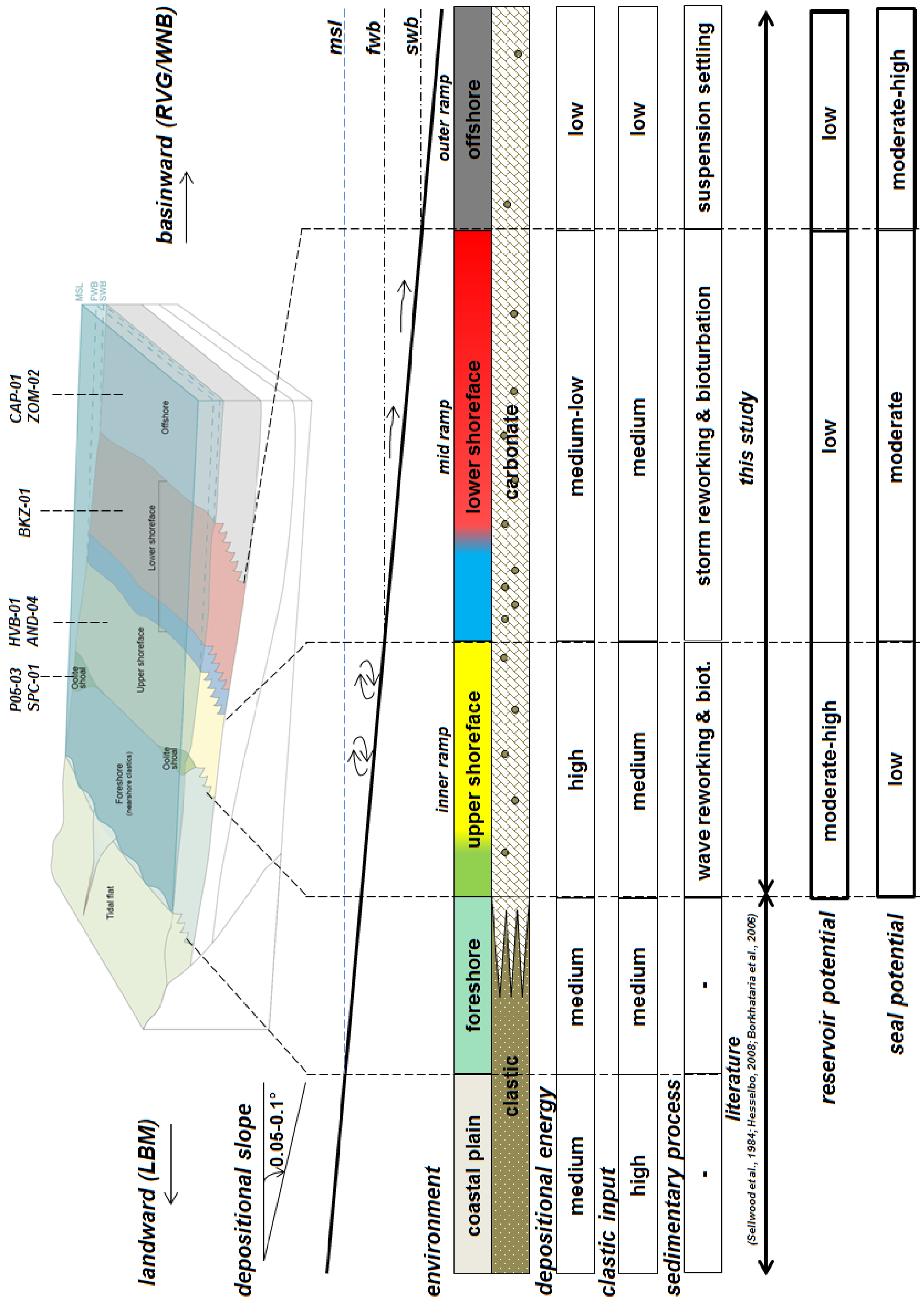


Figure 29. Conceptual depositional model for the Brabant Formation summarizing the main depositional elements of the model as well as reservoir/seal characteristics.

Chapter 11 Reservoir properties

This chapter briefly addresses the reservoir and seal properties of the facies units identified in the Brabant Formation, based on core plug measurements (Chapter 11.1) and NuTech petrophysical well log interpretations (Chapter 11.2).

11.1 Core plug based properties

Core plug-based porosity and permeability measurements were obtained from NLOG. All data comes from vintage wells drilled before 1960. The (relatively limited) data were plotted in porosity vs depth and porosity vs permeability crossplots (Figure 30). A facies interpretation for the porosity-depth plots could not be made because of the limited log data available.

The ATBR1 porosity vs depth plot shows that porosity is decreasing with depth, as expected. A wide range of porosities are found (3-20%). An anomalously high porosity of 31% is reported at 1363m AH in well DON-01 in a calcareous sandstone bed interbedded in sandy limestones. Porosity data for the ATBR2 and ATBR3 (only 2 different wells) is very limited. Maximum porosities of 27% and 29% for respectively ATBR2 and ATBR3 are found.

A poroperm crossplot for the Brabant Formation is shown in Figure 30C. A facies interpretation was made for each plug measurement, based on the facies interpretation made in Petrel. This was cross-checked with well log information (cuttings descriptions) and, when possible, calibrated to core (most samples come from the AND-03-S2 core). Average poroperm data per facies are summarized in Table 5.

Upper shoreface facies rocks (ϕ = 3 - 20%; K = 0.2 - 137 mD) are clearly the most reservoir-prone with average porosity and permeability of 11.3% and 9.8 mD, respectively. A maximum porosity and permeability of a single measurement of 20% and 137 mD is found. Several samples with low porosity and permeability are also present which may be related to tight zones. Such tight zones are observed in core where occasionally calcarenitic grainstones are severely cemented. The reservoir-prone upper shoreface grainstones show comparable porosity and permeability trends with Upper Muschelkalk ooid dolo-pack-/grainstones (Borkhataria et al., 2005). These ooid grainstones are thought to have formed on shoreline-detached shoals on an epeiric carbonate ramp, possibly in the same way as Brabant calcarenites.

Lower shoreface facies samples (ϕ = 6 - 14%; K = 0.1 - 4 mD) show lower porosity and permeability values compared to upper shoreface facies. The average permeability of 1.2 mD indicates low reservoir potential. A maximum porosity of 14% and 4 mD permeability however may indicate moderate reservoir quality in places. Thus, this facies may be a potential thief or waste zone.

The offshore facies (ϕ = 6 - 11%; K = 0.5 - 1 mD) shows an average porosity and permeability of 8.2% and 0.7 mD. The low permeability confirms the sealing potential for oil for this facies. The offshore facies (ATBRU) is the proven top seal in the Lekkerkerk stranded oil field.

11.2 Well log based properties (NuTech)

The average NuTech porosity and permeability are 12% and 2.4 mD in the ATBR1 (used as an analog for upper shoreface facies) which is in agreement with core data (Table 5). Average NuTech porosity and permeability in ATBRL (used as analog for offshore facies) is 13% and 0.6 mD. Permeability is in good agreement with core data; NuTech porosity differs from core porosity. There is relatively small variation in average porosity between upper shoreface, lower shoreface and offshore facies. Average permeability values, however, may be more than 10 times higher in upper shoreface facies compared to offshore facies (Table 5). The well logs by NuTech (Figure 31) clearly show the reservoir potential of the sandy limestone intervals. Highest porosities and permeabilities are calculated for the upper part of the Lower Brabant Limestone (i.e. most regressive part) with permeabilities up to ~20 mD (WWN-03). Porosity and permeability in the WAA-01 well is much lower. This may be related to proximity to the Base Delfland Unconformity that caused influx of meteoric fluids and subsequent cementation, as evidenced by presence of pyrite and siderite minerals in the ATBRL and ATBR1 in this well.

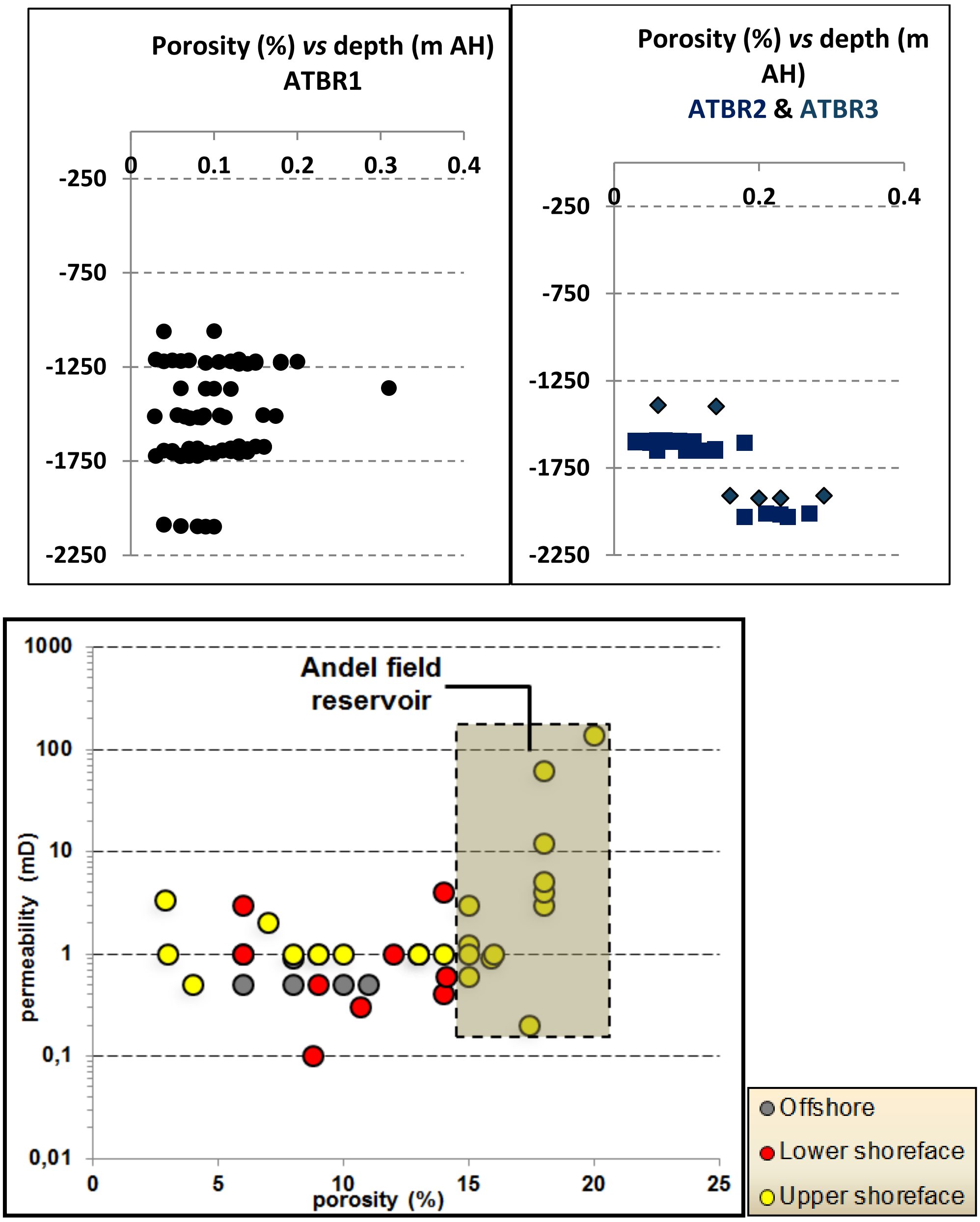
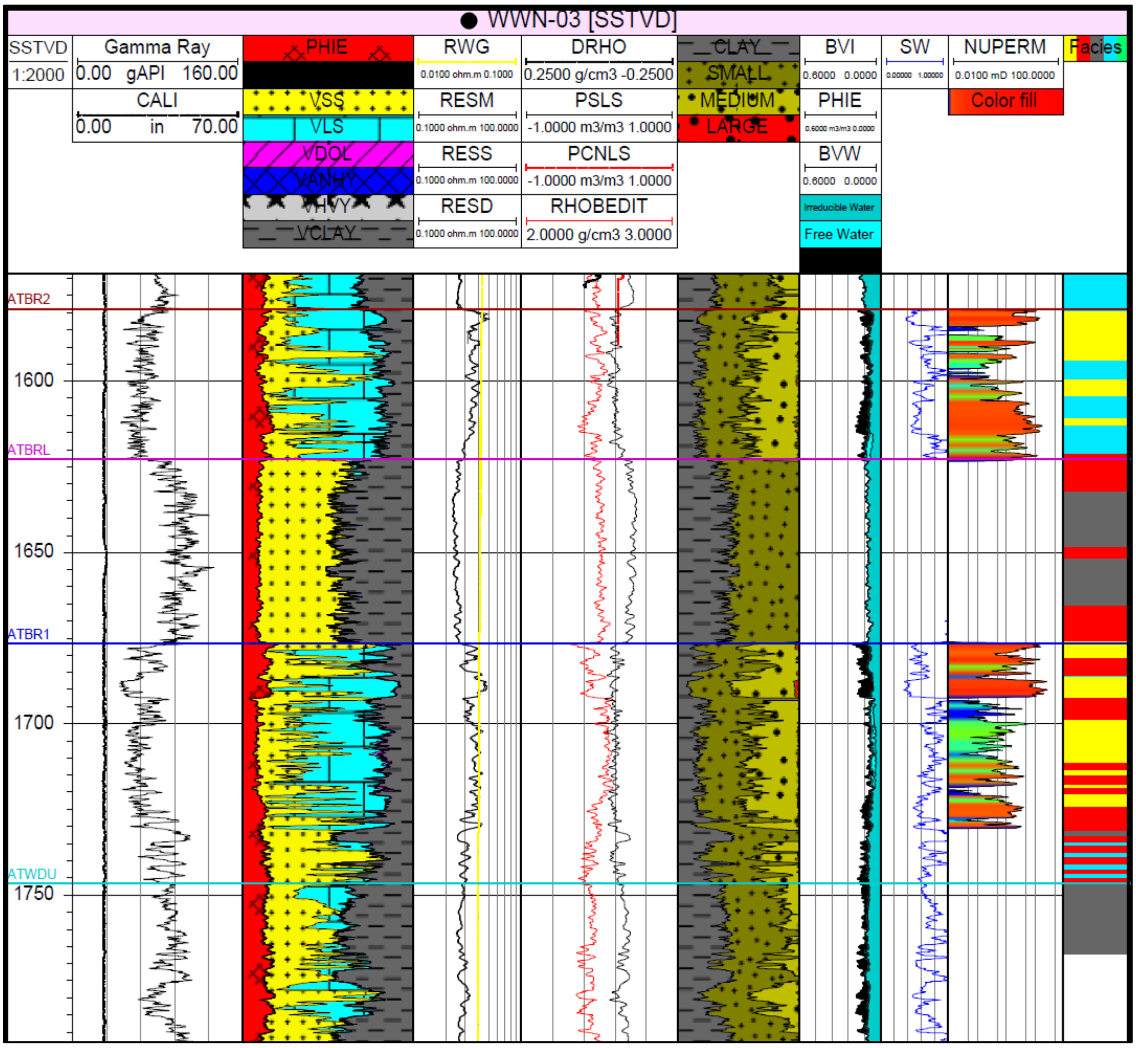


Figure 30. A) Porosity vs depth for the ATBR1. B) Porosity vs depth for the ATBR2 (blue) and ATBR3 (red). C) Poroperm crossplot for those porosity measurements that also had permeability measurements.

Table 5. Average poroperm characteristics per facies, based on core-plug measurements and NuTech petrophysics.

POROPERM **Facies**	***n***	**Average ϕ (%)**	**Average K (mD)**	**NuTech ϕ (%)**	**NuTech K (mD)**
Upper shoreface	25	11.3	9.8	12 *(ATBR1)*	2.4 *(ATBR1)*
Lower shoreface	9	10.5	1.2	-	-
Offshore	6	8.2	0.7	13 *(ATBRL)*	0.6 *(ATBRL)*

A)



B)

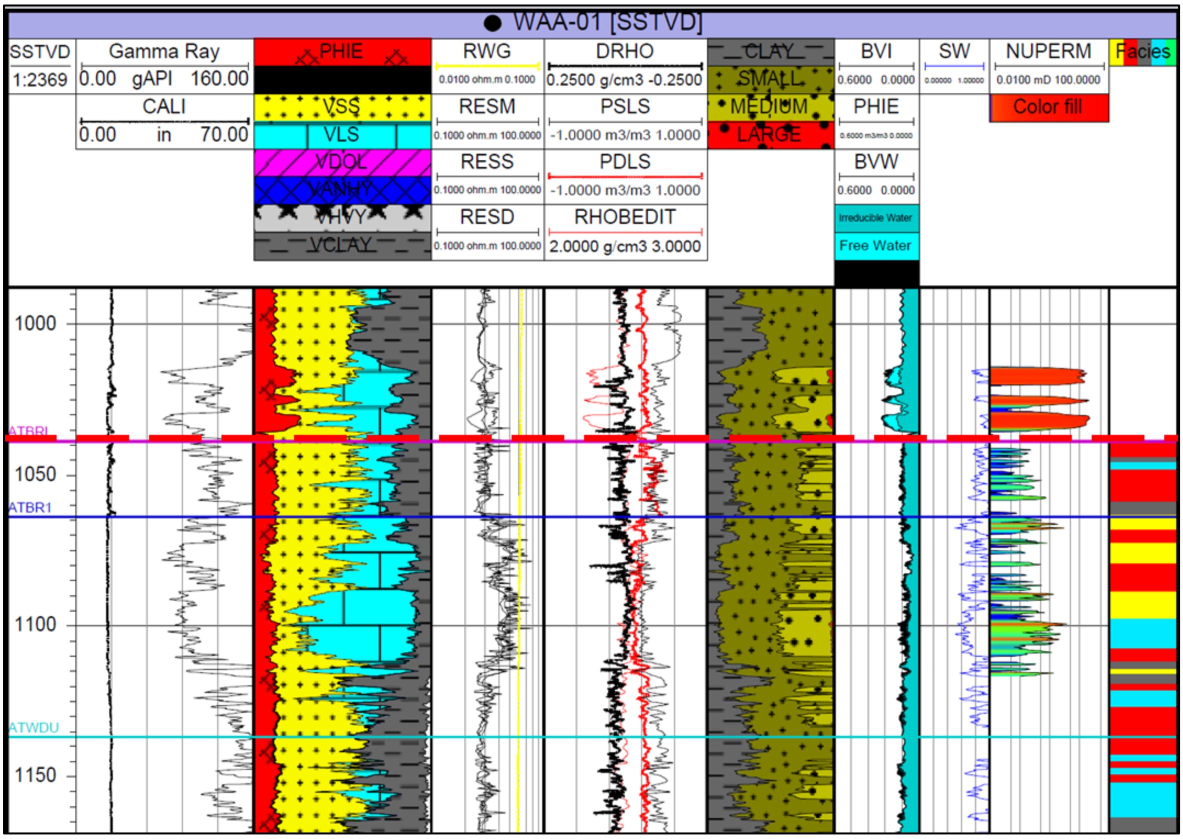


Figure 31. A) NuTech well log for the Brabant section in WWN-03, where the most regressive part of the sequence of ATBR1 and ATBR2 has best reservoir properties. B) NuTech well log for the Brabant in WAA-01, where proximity to the Base Delfland Unconformity likely caused cementation of the carbonates, resulting in lower permeabilities.

Chapter 12 Prospectivity & trap concepts

The previous chapters have presented evidence for and discussed the conceptual geological model, as well as the reservoir and seal properties of the facies units identified in the Brabant Formation. This chapter discusses the prospectivity and potentially prospective trap concepts in the study area, in which the Brabant Formation may occur.

The source and reservoir rocks are first discussed: the oil-prone Posidonia Shale is the source rock and upper shoreface deposits of the Brabant Formation form the reservoir rock. Four trap concepts have been identified in the study area: fault-dip closures, sub-unconformity traps, inversion anticlines and downfaulted traps. The sub-unconformity traps (Chapter 12.1) and downfaulted traps (Chapter 12.2) appear to be yet undrilled.

Source rock

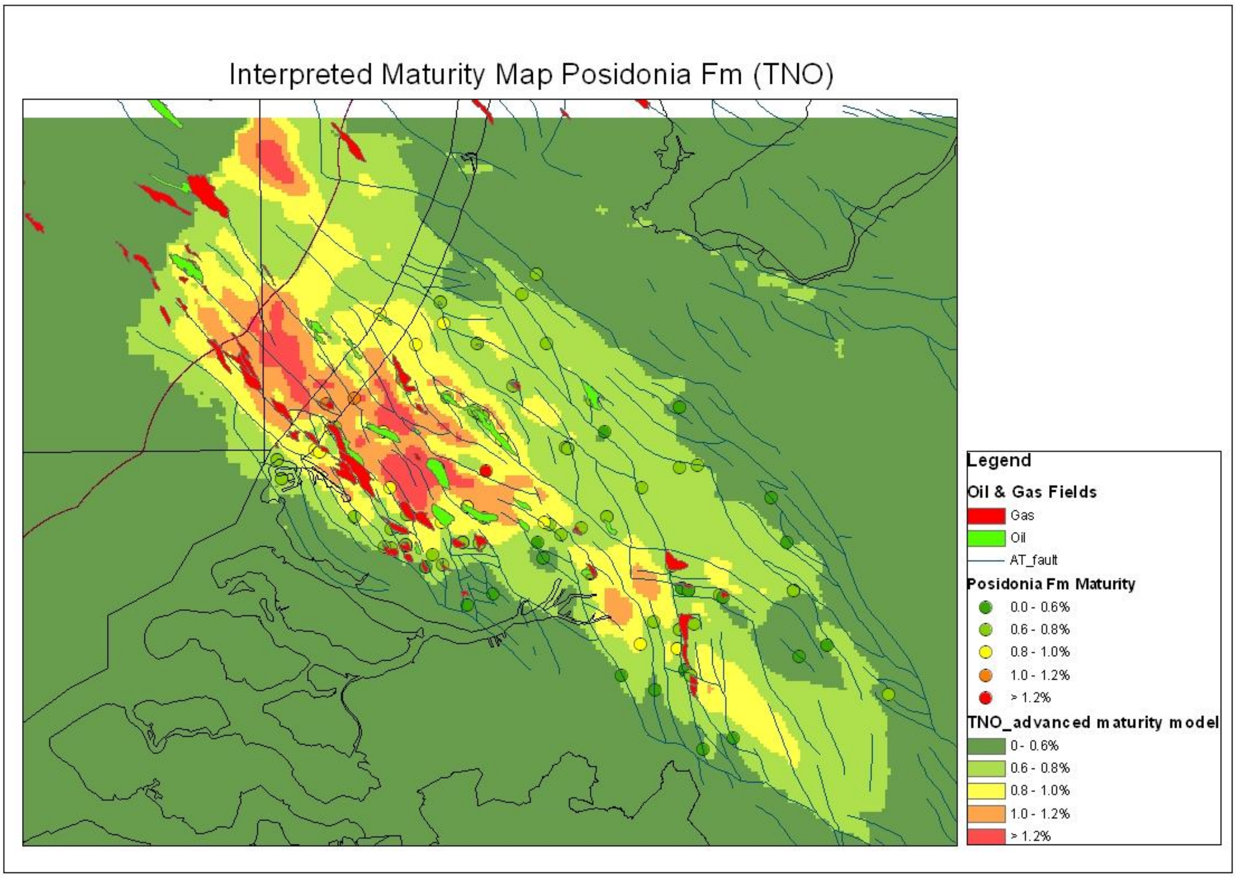
The most likely source rock would be the Toarcian oil-prone (type II) Posidonia Shale. This source rock is a known, prolific source rock in the area. All of the onshore oil fields in the Rijswijk concession appear to have been charged by this source rock (De Jager et al., 1996). Figure 32A shows an interpreted maturity map of this formation by TNO; Figure 32B shows charge modeling results by De Jager et al. (1996). It is currently immature outside the Mesozoic basins. The formation is early oil mature (R_0 = 0.6 - 0.8) in most inverted parts of the basins (northern parts). It is thought, however, that inversion has brought the Posidonia to much shallower levels thereby effectively shutting off the kitchen. Tertiary burial was insufficient to switch the kitchen back on. So, the Posidonia is not an active source rock in these areas. This is confirmed by charge modeling (De Jager et al., 1996) and abundant dry structures in these areas. The formation is currently oil mature (R_0 = 0.8 - 1.2) towards the west of the Andel area (between the Andel and Werkendam wells), in the southwestern part of the West Netherlands Basin and in the middle of the Roer Valley Graben. According to charge modeling, it is actively charging at the moment because the source rock is currently at its maximum burial depth there. Charge is however at a much reduced rate compared to pre-inversion times.

Another potential source rock could be the gas-prone Westphalian coal measures. The long migration path from the Carboniferous is however considered unlikely. Other source rocks could be Namurian hot shales and/or organic-rich intervals in the Aalburg or Sleen Formation (Lutgert et al., 2013). These are however not considered as potential source rocks when assessing the play concepts below, as their source rock potential is speculative.

Reservoir rock

Obviously, the reservoir rock comprises upper shoreface or shoal deposits of the Brabant Formation. The presence of stacked reservoir-prone intervals (ATBR1, ATBR2, ATBR3) in the border area Roer Valley Graben – West Netherlands Basin increases the chances of finding more metres of net reservoir in this area.

A)



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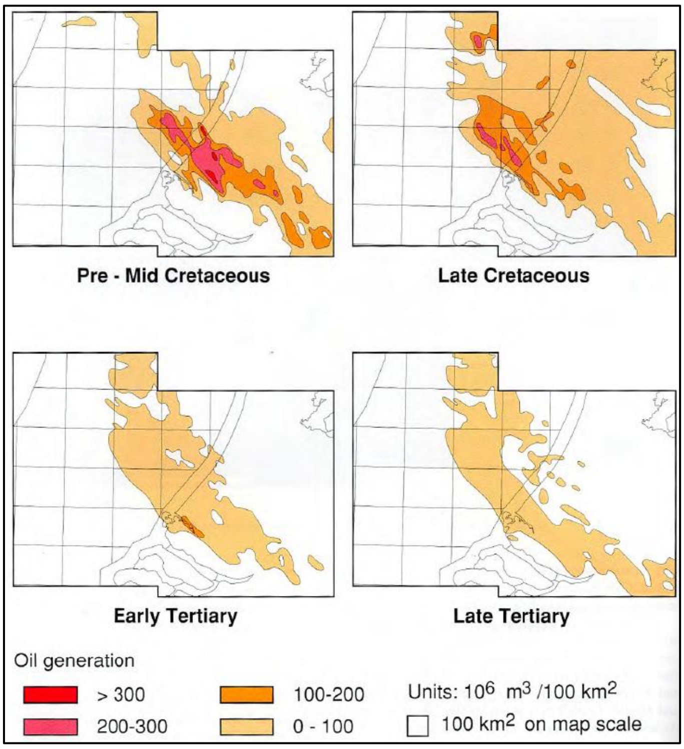

Figure 32. Interpreted, present-day maturity map of the Posidonia Fm (A) by TNO (from Van der Kroef, 2014), and oil charge through time of the Posidonia (B), as reconstructed using charge modeling (De Jager et al., 1996). The charge modeling shows that the kitchen is presently shut off in inverted areas and that charge continuous to present-day in the Roer Valley Graben, albeit at a reduced rate.

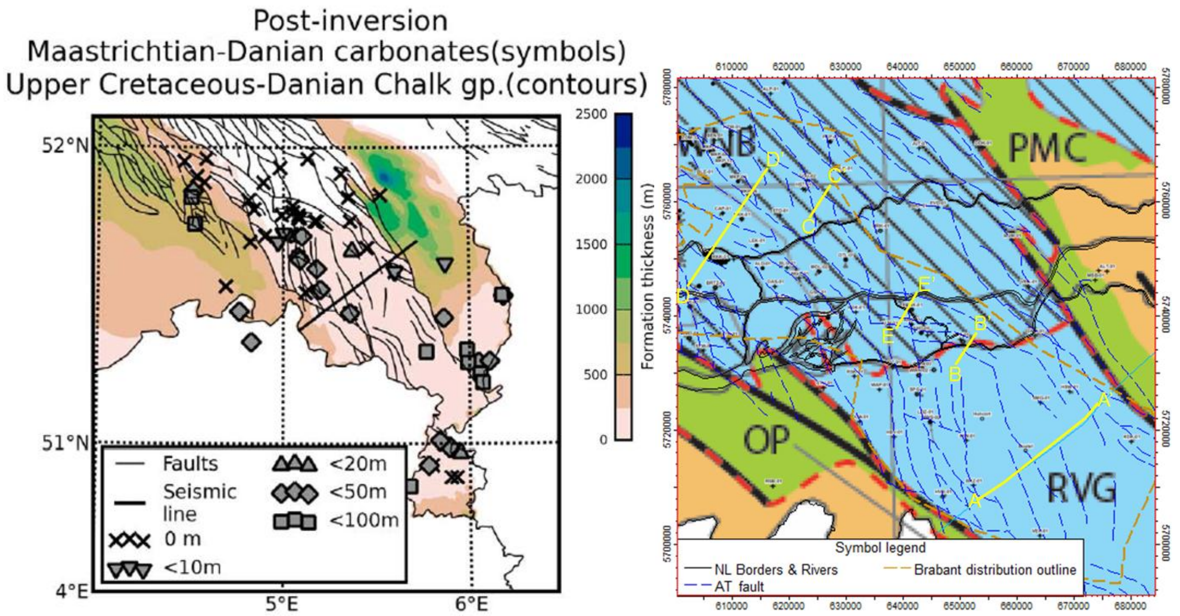

Figure 33. A) Thickness map of the Maastrichtian - Danian chalk (after Luijendijk et al., 2011), showing the presence of chalk deposits in the Roer Valley Graben. The chalk can be up to 50m thick in the basin and may provide top seal. Note also the absence of the Chalk in the northern part of the study area. B) Locations of the seismic lines shown below. In orange, the approximate present-day distribution of the Brabant Formation is shown. In blue, faults at Altena level are shown (TNO).

12.1 Trap concept I: sub-unconformity traps

This trap concept relies on truncation of the formation below the Late Cretaceous Unconformity. Examples of such truncation trap are shown in figures below. Late Cretaceous inversion-related uplift resulted in major erosion in the Roer Valley Graben and northern part of the West Netherlands Basin. Upper Jurassic Delfland and Middle Jurassic strata of the Altena Group (including the Brabant Fm) are severely truncated. This resulted in a large-scale, spectacular low-angle subcrop of the Brabant Formation against this unconformity, which can be clearly identified on seismic in the Roer Valley Graben (Figure 34).

Top seal

In the Roer Valley Graben, the Brabant Formation is unconformably overlain by 10 - 50m thick chalk deposits of the Ommelanden and Houthem Formation (Figure 33A). These may provide a top seal in areas where the formation is truncated by the unconformity. Examples of such trap are shown in Figures 34 and 35. A major low-angle unconformity can be seen on seismic. On top of this unconformity, chalk is found as indicated by wells SMG-01 and BKZ-01. In the northern part of the Roer Valley Graben, and in the northeastern part of the West Netherlands Basin, chalk is absent. There, at the Late Cretaceous Unconformity the formation is overlain by clastics of the Lower or Middle North Sea Group. The Lower North Sea Group may consist of the Heers Member or Landen Clay Member. The latter unit is generally clayey and may provide top seal if present; the first however (Heers Mbr) is a very fine-grained glauconitic sandstone with intercalated clay beds and may pose seal risk if present. The Middle North Sea Group (Rupel Fm) may overlie the Late Cretaceous Unconformity in the West Netherlands Basin. It is composed of either clays (OTL-01 and PKP-01) or sandstones (HST-02) and poses in places a seal risk.

Lateral seal

Lateral seal would be provided by intra-Brabant marls (ATBRL, ATBRM, ATBRU) deposited in offshore facies. These marls are typically up to 40-60m thick. The ATBRU marls, the most sandy of the three marl intervals, are proven to be sealing for oil as evidenced in the Lekkerkerk stranded field. Additional evidence for sealing potential of the marls comes from core plug measurements that document on average low permeabilities (0.6 mD; see Reservoir characteristics). In addition, NuTech petrophysical logs show low permeabilities in marl sections (Figure 31). Moreover, in well HVB-01, an oil show is reported in the ATBR2 but not in overlying ATBRM marls, where only a minor gas show is reported. This indicates that the marls are sealing for oil and not for gas. Thief zones in lower shoreface facies may however exist (see "Reservoir characteristics" chapter) and may pose seal risk.

Timing

Trap development was completed after the main inversion event that ended in the Late Cretaceous (RVG) or Early Tertiary (WNB) as evidenced by Late Cretaceous Chalk overlying the unconformity in the RVG and North Sea Group sediments overlying it in the WNB. Overburden started to develop during the Tertiary when the entire area was under the influence of rapid burial associated with prograding Tertiary clastics coming from the east. Especially since the Oligocene the Roer Valley Graben subsided rapidly. More than 600m of subsidence occurred in this area (Michon et al., 2003), which is generally much more than the estimated amount of inversion of 250-500m (Luijendijk et al., 2011). From burial graphs, this indicates that the Posidonia was pushed back into the oil window during the Miocene (~20 Ma ago). So, from the Miocene onwards the Posidonia may be actively charging in the Roer Valley Graben. Thus the trap must currently have access to this late charge phase. The fact that only the Werkendam shales separate the source rock from the reservoir may increase the likelihood that charge is actually able to reach the trap. However, Late Tertiary - recent charge may have been insufficient to fill a trap full to spill and therefore structures may be underfilled.

Risks

Risks are primarily prospect-dependent. In all cases, a major risk is the access to Late Tertiary - recent charge. An effective migration path from the Posidonia Shale to the trap must be present. The trap in the Roer Valley Graben (Figure 34) sits right above the area where the Posidonia is currently buried deepest. This means that migration must be purely (sub)vertical towards the center of the basin. This might be unlikely as generated oil is more likely to migrate more in an updip way, along the flanks. Charge is also a major risk in the northern part of the West Netherlands Basin. In these areas, the Posidonia is currently mature but not actively charging (De Jager et al. (1996); Figure 32b).

Another risk is seal presence and quality. The 28m thick Ommelanden chalk that has been found in well SMG-01 may function as a seal if it is tight. Towards the north of the Roer Valley Graben, and in the West Netherlands Basin, Lower/Middle Tertiary clastics may be sandy and pose a top seal risk. Moreover, as a result of the folding during inversion, the side seal (intra-Brabant marls of ATBRL, ATBRM and ATBRU) may have been fractured, and therefore leaky (this fracturing would increase reservoir quality however). It may be that if intra-Brabant marls are sufficiently thick, as is the case in the basin center in the middle and northwest Roer Valley Graben, they can still be sealing as fractures might not propagate upwards but instead terminate intra-marl. In places, Tertiary fault reactivation may have breached top seals.

12.2 Trap concept II: downfaulted traps

The trap concept relies on the downfaulting of the formation against claystones of the Werkendam Formation (Figures 35B, 36, 37). This juxtaposes reservoir-prone Brabant intervals against these claystones. Trap configuration should be such that Brabant strata are dipping upwards into and terminate against the fault (as seen on the seismic sections), so that oil could have accumulated in the trap.

This trap type is in general relatively underexplored, since most wells have been drilled on horst blocks instead of grabens. Moreover, in this scenario the reservoir section is located in the graben, so gross reservoir thickness is expected to be higher than on horst blocks, since grabens accumulated thicker Brabant sequences (see “Conceptual geological model” chapter).

Seal

Top seal will be provided by intra-Brabant marls (ATBRL, ATBRM, ATBRU) present in offshore or lower shoreface facies. They are proven to have sealing potential (Lekkerkerk stranded field) but thief zones may exist (lower shoreface facies; see “Reservoir characteristics” chapter). Lateral seal will be provided by favorable juxtaposition against Werkendam claystones. These claystones are a well-known proven side seal for the mature Bunter play in the area. Another requirement is that the prospect-bounding fault should be sealing. The bounding fault has probably had a history of activation (normal faulting) and reactivation (inversion). Therefore, the fault may in fact be a wider fault zone (as seen on seismic in Figure 40 for example), is more prone to leaking and hence pose a seal risk. However, since the juxtaposed Altena (Aalburg, Werkendam) and Delfland sequences are very clay-rich, it can be expected that enough clay has smeared into the fault zone (high shale gouge ratio). This would increase sealing potential of the fault. Again, all these factors are prospect-dependent.

Timing

Maximum oil generation of the Posidonia occurred prior to inversion (Figure 32b). The precise timing of actual trap formation, i.e. when are the strata updip truncated by the fault, is not entirely known. Two scenarios are possible:

1) The trap geometry formed as a result of normal faulting during rifting. This scenario would mean that the trap was already in place in the mid Cretaceous, i.e. during the maximum generation phase of the source rock. This would significantly decrease charge risk as the trap could be filled prior to inversion.

2) The trap geometry formed as a result of inversion along the fault. This means that the trap was in place after the inversion event. This would significantly increase charge risk as the trap should have access to Late Tertiary – recent charge.

Risks

Main risk for both scenarios is seal integrity of the fault and juxtaposition. The bounding fault may have lost its seal integrity during Tertiary reactivation, and caused hydrocarbons to escape (seal breaching). However, not all faults in the area were reactivated in the Tertiary, so this risk is prospect-dependent. Another risk may be unfavorable juxtaposition against silt- or sandstones of the Middle Werkendam Member. This may have caused hydrocarbons to leak cross-fault into this formation. Main risk in the second scenario is charge, because the trap must have access to recent charge.

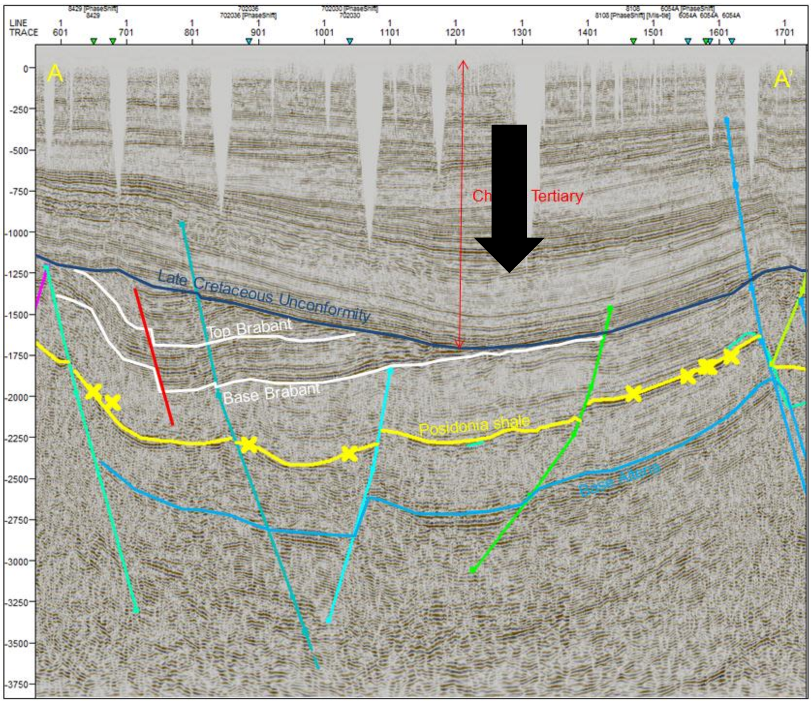

Figure 34. 2D seismic line 8117 showing major low-angle subcrop of the Brabant Fm against the Late Cretaceous Unconformity in the RVG. 25-50m thick Chalk overlies the unconformity and may provide top seal. For location see figure 33B.

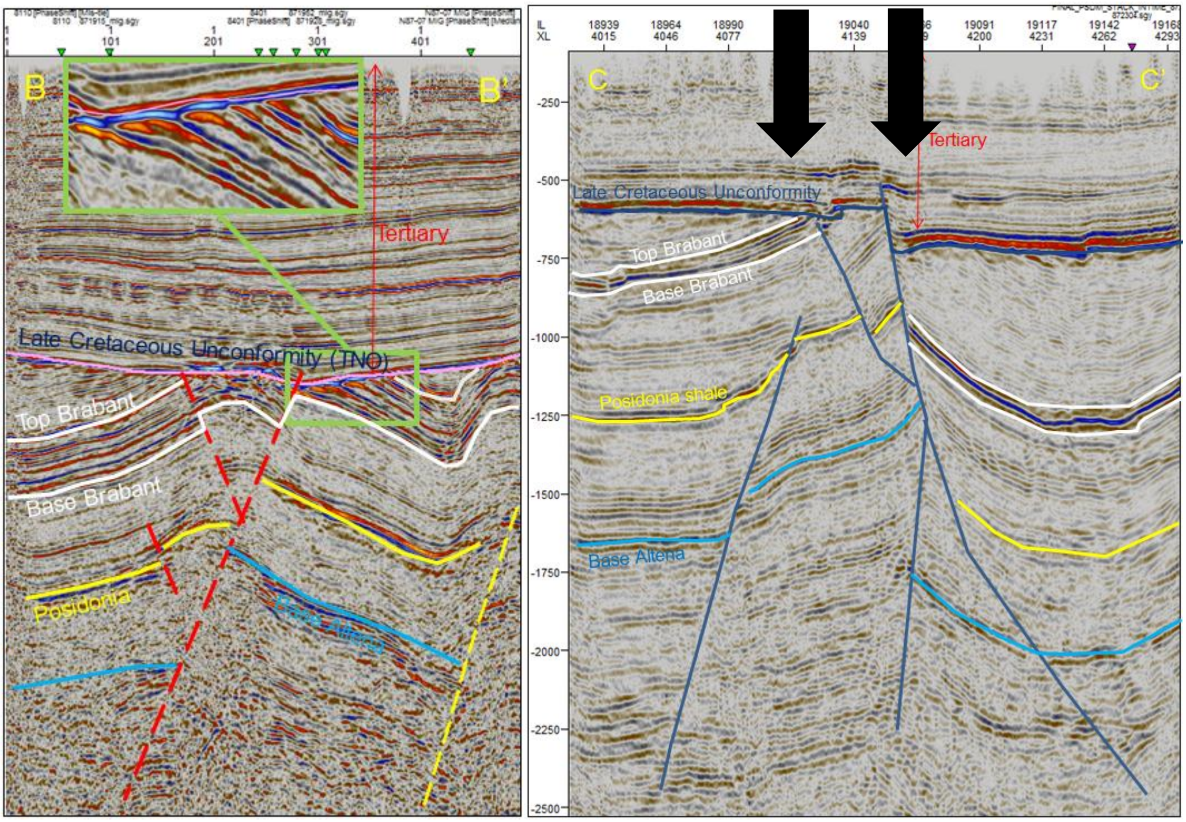

Figure 35. A) 2D seismic line near Kerkwijk, showing truncation against Late Cretaceous Unconformity. Brightening of red reflectors towards the unconformity is seen. These red reflectors are associated with reservoir-prone intervals ("Seismic scale" chapter). Note also the truncated anticline at Brabant level. This anticline is the regional continuation of the nearby Andel inversion anticline which contains oil in the Brabant. B) SW – NE random line in the WNB: truncation below Late Cretaceous Unconformity (left) and the downfaulted trap type (right). For location see figure 33B.

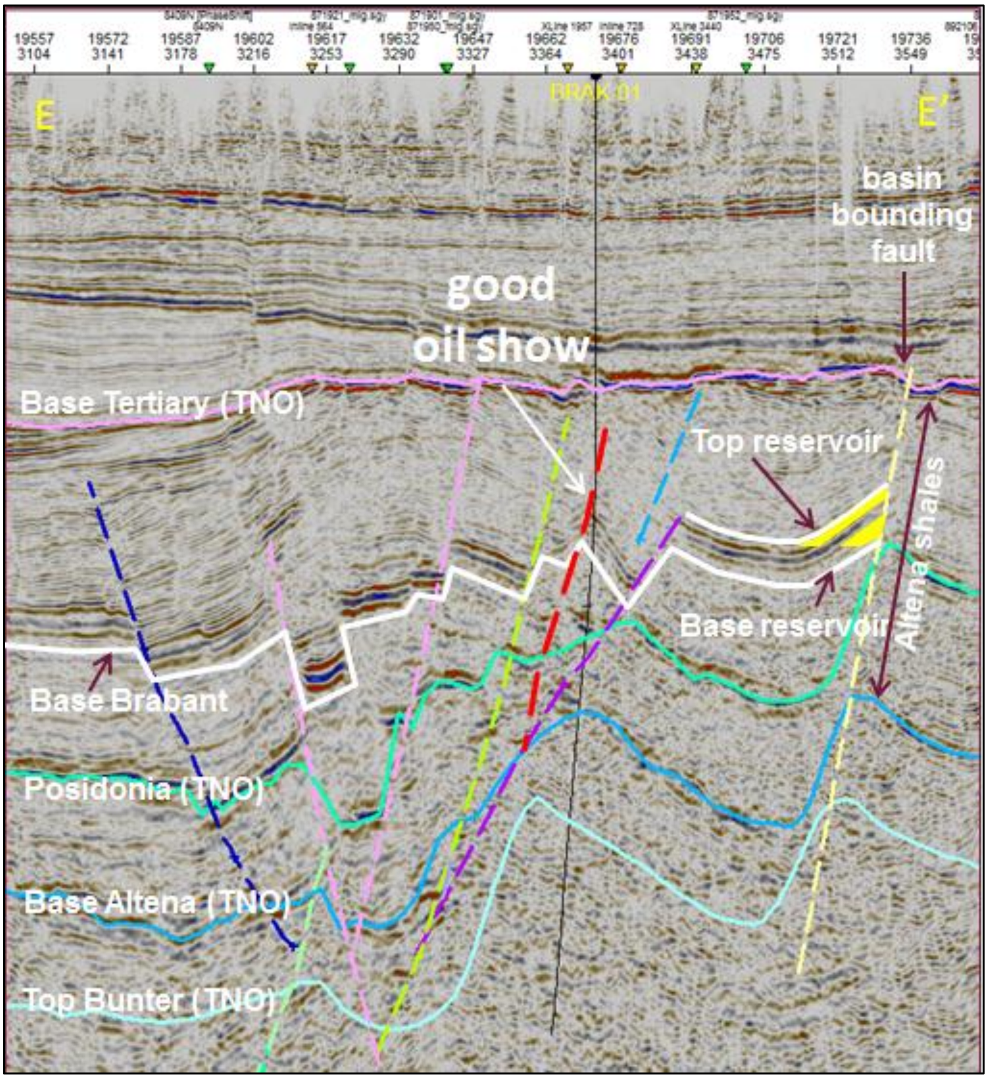

Figure 36. SW-NE random line in the NW Roer Valley Graben, showing downfaulting and juxtaposition of the formation against Altena Group claystones. The shales are a proven lateral side seal in the region for the Bunter play. Note also the abundant fault-dip closures at Brabant level, and the good oil show in offset well Brakel-01. For location see figure 33B.

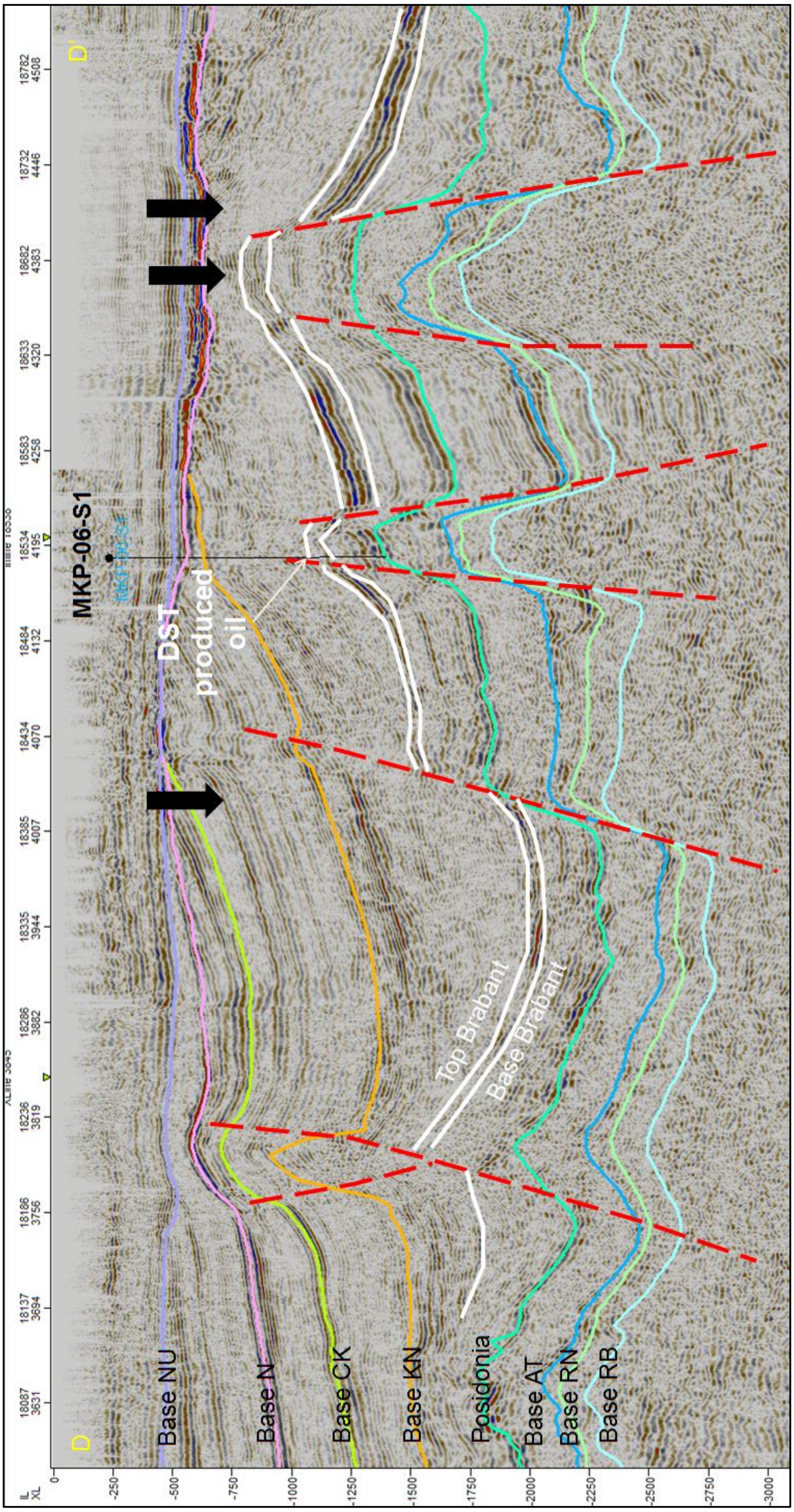

Figure 37. SW – NE random line (3D Terracube onshore) in the WNB showing two examples of a downfaulted trap (first and third arrow) and an inversion anticline trap (inverted horst block; middle arrow). Note that the DST at MKP-06-S1 (P&A) tested 421m oil. This indicates that there may be oil in place in these areas in the Brabant. For location see figure 33B.

12.3 Additional prospectivity

Fault-dip closures (proven play)

In fault-dip closures at Brabant level, the Brabant would be juxtaposed against interbedded sands and shales of the Delfland Group. This implies a juxtaposition seal risk and potential leaking into this formation. However, the Lekkerkerk stranded oil discovery (fault-dip closure; see above) proves that fault-dip closures at Brabant level may hold oil accumulations, probably when they are favorably juxtaposed against Delfland shales. The play is thus proven.

As a result of the intensely block-faulted nature of the Roer Valley Graben and West Netherlands Basin, several potential fault-dip closures can be recognized on seismic across the area (Figure 36). When commerciality of this play can be proven in the near future (development Lekkerkerk field?), the prospectivity of the area will be significantly upgraded. Mapping of these traps was not within the scope of this study. This will be addressed in a follow-up study.

Inversion anticline (proven play)

This play is proven at Brabant level with the Andel field that contains oil in Brabant reservoirs in an inversion anticline. Several of such trap structures have already been drilled in the area: Andel (stranded oil discovery), MKP-06-S1 (DST tested oil) and HST-01 (dry but fair oil show). It appears that not much undrilled structures of this trap type are still left in the subsurface. However, towards the north of Moerkapelle (middle black arrow; Figure 37), a major undrilled combined inversion anticline – sub-unconformity trap was identified on seismic at Brabant level. It appears that the structure is relatively large and potentially holds significant volumes. Prospectivity is demonstrated in this area by a 6.5-hour DST taken to the south in offset well MKP-06-S1 (1959; P&A), that tested an unknown quantity of oil at Brabant level (ATBR2). The undrilled structure is located structurally shallower, so may have trapped oil. Further study should map this prospect.

Broad Fourteens Basin

The prospectivity of the Brabant Formation in the Broad Fourteens Basin has not been studied and is speculative at the moment. Presence of the formation in this basin is known from seismic data and 4 wells (P05-06, P05-04, P05-03 and K14-07). None of these wells have oil or gas shows in the Brabant Formation. At least the Lower Brabant Limestone and Lower Brabant Marl, and possibly even younger members, are (locally) present in synclinal erosional remnants. These grabens were likely deeply buried and were not entirely uplifted and eroded during inversion. It may be that there are trap possibilities in areas where the Brabant Formation is erosionally truncated against Vlieland claystones (Jeremiah et al., 2010), acting as a seal. Moreover, in P05-03, ~30m thick ooid shoal facies were encountered in the ATBR1. This facies may have high reservoir potential as ooids dissolve relatively easily under influence of leaching fluids (secondary porosity creation). Such decameter-thick oolitic limestone sequences are well-known from the Weald Basin (UK) where they are prolific oil reservoirs (Great Oolite Group; Sellwood et al., 1984).

Chapter 13 Discussion

This chapter briefly discusses remarks on NuTech's modeling results, the conceptual geological model and evidence for the conceptual model from carbonate ramp forward modeling, as well as a discussion of the geological development of the Brabant Formation and discussion of important factors that may influence reservoir quality.

13.1 Reflection on NuTech's modeling

Considering supporting evidence from hydrocarbon shows and mud and composite logs, presented in Chapter 5 and Appendix 9, NuTech's model is reasonably reliable in sandstone lithologies. In "complex" lithologies such as carbonates and anhydrite-carbonate formations, NuTech's model is relatively unreliable. NuTech uses the same (constant) input parameters in all wells and model runs. The cementation factor from Archie's equation, for example, is almost always constant in the modeling (2). This need not always be the case. Especially in carbonates, the cementation factor of the rock is very important and may strongly vary as a result of diagenetic effects and complex pore structures. Such subtle differences may have influenced modeling results in especially carbonates. For best modeling results, such input parameters should be calibrated to local geology and knowledge of the formation under study. Calibration is crucial!

13.2 Conceptual geological model and modeling results

The open-marine claystones of the Werkendam Formation (Bajocian age) established a low topographic relief at the onset of Brabant deposition because they were draped as a "layer-cake" over any large pre-existing topographic relief in the study area. As a whole, the Brabant Formation can also be regarded as a "layer-cake", that was draped over the underlying topography.

In the Latest Bajocian, Brabant deposition commenced when the entire study area shoaled. A carbonate depositional environment with a gently dipping ramp geometry established in the area north of the London-Brabant Massif. This environment was predominantly clastic in proximal locations (coastal plain/tidal flat and foreshore) and graded basinward into a predominantly carbonate environment (upper shoreface/lower shoreface/offshore). Climate was moderately warm (16 – 24 °C) and dry. *In situ* carbonate production rates were low to moderate. Sediment transport processes played a dominant role on the ramp. As a result of the gentle depositional slope, small sea level fluctuations caused large facies belt shifts. Individual sedimentary units appear to be laterally continuous and stacked in a more aggradational instead of progradational facies architecture. Basin margin sequences are thinner and more amalgamated. Thicker sedimentary units were deposited in individual grabens in the west and northwest Roer Valley Graben and eastern West Netherlands Basin. It appears that this occurred in similar facies in this area. Towards the centers of the WNB and possibly RVG, slightly more distal facies occur. The thickening/thinning trend is the result of the interplay between differential subsidence and high sediment transport rates on the ramp: maximum sediment volumes accumulated in areas of most accommodation space. This led to higher gross reservoir thicknesses in these areas and more metres of net reservoir are here expected.

Modeling results confirm that parameters as sediment transport rate and carbonate production rate are important in order to maintain a carbonate ramp profile. Carbonate ramp geometries have been modeled by Williams et al. (2011). Results show that the most important factor in maintaining a carbonate ramp profile is the rate of sediment transport relative to the rate of carbonate production. All ramps will eventually evolve into flat-topped platforms if the *in situ* carbonate production rate is higher than the rate of sediment transport. This is not seen in the Roer Valley Graben and West

Netherlands Basin, where a ramp profile is continuously maintained (at least during the Bathonian and Early Callovian). The modeling results thus confirm that high sediment transport rates and low-moderate in situ carbonate production rates have played a dominant role in the study area throughout the Bathonian and Callovian in order to maintain the carbonate ramp profile. Modeling results also show the importance of sediment volume funneling. The interplay between differential subsidence and high sediment transport rates on the gentle dipping ramp resulted in accumulation of maximum sediment volumes in areas of highest subsidence (Figure 9B in Williams et al., 2011).

13.3 Geological development of the Brabant Formation

During the Early and Middle Bathonian, sandy calcarenitic and bioclastic grainstones (upper shoreface/shoal facies), intercalated with lower shoreface/offshore silty marls, were deposited in a predominantly aggradational facies architecture on the gentle dipping carbonate ramp (ATBR1; 30-80m thick). During this regressive event, vast areas of the basin were within fair weather wave base and accumulated upper shoreface facies. Basin centers, however, accumulated a slightly more distal sedimentary sequence. These areas were probably most of this time in between fair-weather wave base and storm wave base. A continuously back-and-forth shifting sea level caused the intercalation of storm-graded silty marls within the proximal regressive sandy limestone sequence. The shallowest and most reservoir-prone environment on the ramp was located at the boundary between the Roer Valley Graben and West Netherlands Basin and northwest Roer Valley Graben (Waalwijk area). This large-scale shoal area also accumulated thickest Brabant deposits – it thus appears that subsidence here did not influence facies patterns.

During the Late Bathonian, the carbonate ramp was flooded by a large-scale transgressive event as evidenced by the transgressive surface of erosion recognized at the top of the ATBR1. This transgressive event can probably be correlated with major transgression and drowning of coeval carbonate ramps in the Weald Basin (Cornbrash and Oxford Clay Formations; Sellwood et al., 1984; Hesselbo, 2008) and Paris Basin (Argiles de la Woëvre; Brigaud et al., 2014). The study area now constituted the mid and outer ramp environment of the carbonate ramp – offshore and lower shoreface facies sediments were deposited during this transgressive event (ATBRL; ~40-60m thick).

In the Early Callovian, regressive conditions returned on the ramp as evidenced by the deposition of sandy calcarenites and calcareous sandstones of the ATBR2 (~20-40m thick). The sediments are sandier in nature (mixed siliciclastic – carbonate) indicating progressive regression of the Brabant Formation as a whole. The sedimentary stacking pattern appears to be again in an aggradational facies architecture. Basin centers may have accumulated more distal facies, but the border area Roer Valley Graben – West Netherlands Basin again accumulated thick sediments in proximal facies.

During the Middle Callovian, transgressive conditions gradually returned with deposition of the ATBRM. This unit shows strong thickness variations and is thin developed in the area border Roer Valley Graben / West Netherlands Basin, and thicker in the south of the Roer Valley Graben (cf. Figures 20 and 21). The boundary area Roer Valley Graben / West Netherlands Basin may have accumulated more proximal facies (foreshore and upper shoreface) whereas towards the south, more distal facies accumulated. Alternatively, some areas may have experienced increased uplift. During the Callovian, the Peel Block and Maasbommel High to the northeast probably uplifted and may have shut off connection with the Achterhoek/Central Netherlands Basin (Van Adrichem-Boogaert & Kouwe, 1993-1997). This also reflects the progressively increasing basin structuration that took place during this time.

The Late Callovian marks the change to regressive mixed carbonate – siliciclastic deposition of the ATBR3 (~20-40m thick); calcareous sandstones and sandy calcarenites were deposited (foreshore/upper shoreface facies) intercalated with lower shoreface facies. The ATBR3 shows strong lithological similarities with the Leckenby Formation in the Sole Pit Basin. Unfortunately, West Netherlands Basin sediments are missing for this member as a result of erosion. The stacking pattern is not exactly known as correlations cannot be accurately made. The Latest Callovian – Early Oxfordian sandy marls of the ATBRU were deposited during a transgressive event. These marls can be very sandy locally.

Brabant sedimentation continuous in the Early – Middle - Late? Oxfordian with deposition of massive algal and oolitic limestones of the ATBRO (Oisterwijk Member). The entire Sole Pit Basin – West Netherlands Basin - Roer Valley Graben area had shoaled to such a degree, that these ooid shoal deposits probably accumulated over vast areas in the basin centres, as indicated by coeval oolitic limestone deposits of the Corallian Formation in the basin centres of the Sole Pit Basin.

The general upward increase in sand content in the Brabant succession, to the extent that almost the entire ATBR3 consists of calcareous sandstones, is interpreted to be the result of continued regression and progressive uplift of the London-Brabant Massif during the late Middle Jurassic. The uplift increased clastic supply from the hinterland.

13.4 Factors influencing reservoir quality

The major factors controlling reservoir quality are thought to be initial depositional facies and diagenesis (including burial history).

Initial distribution of depositional facies is, of course, a major factor on reservoir quality. During the regressive episodes, vast areas where under the influence of the same proximal facies belt at the same time. Grabens and basin centers have thicker Brabant successions developed as a result of differential subsidence, in comparison to horst blocks and basin-margins. The gross reservoir thickness is thus higher in grabens; this may lead to more metres of net reservoir in these areas. Most potential net pay is expected in the border area West Netherlands Basin – Roer Valley Graben and Waalwijk area, because thick, proximal upper shoreface/ooid shoal facies have been deposited here during relative sea level lows. In addition, erosion of Brabant strata (Base Delfland Unconformity) appears to have been minimal here.

Reservoir quality in carbonates is generally strongly controlled by diagenesis. Burial history has influenced porosity negatively and deeper-buried Brabant samples generally show lower porosities as shown in Figure 30A, but confident porosity-depth relationships could not be established due to a lack of porosity data. The diagenetic setting of the Brabant Limestone was not thoroughly studied and remains speculative. Low permeabilities in the ATBR1 in WAA-01 (Figure 31) may be related to siderite/hematite/pyrite cementation due to proximity to Base Delfland Unconformity. Thus, grabens - areas where this unconformity is less pronounced – have possibly better porosities and permeabilities than horst blocks and areas in the West Netherlands Basin.

In the Paris and Weald Basin, Late Kimmerian uplift of the London-Brabant Massif caused denudation of carbonate rocks near the basin margin. This caused lateral recharging of the carbonate reservoirs with meteoric fluids and led to strong cementation and loss of porosity and permeability in these carbonates (Vincent et al., 2007). A similar scenario may have occurred in the study area and would have lead to increased cementation and tight zones in southern basin-margin Brabant sequences (southern Roer Valley Graben). This remains speculative, however.

Chapter 14 Conclusions

Analysis of the Lutgert et al. (2013) petrophysical database resulted in a ranked list of several overlooked exploration opportunities in the Broad Fourteens Basin, West Netherlands Basin and Roer Valley Graben. Untested hydrocarbon potential is recognized in the Chalk, Holland Greensand, Delfland, Brabant Formation, Lower Muschelkalk, Zechstein Fringe Sandstones, Zechstein 1 Fringe Carbonate and Westphalian C/D. With respect to the opportunities identified, the prospectivity of the Brabant Formation has been studied into more detail, because of 1) fair to good modeled reservoir properties by NuTech, 2) presence of two stranded oil discoveries, 3) 10+ untested good-quality oil shows, and 4) no producing fields in the study area. This resulted in 1) the construction of a conceptual geological model, 2) a first-order understanding of reservoir properties and spatial variability, and 3) identification of two new trap concepts.

The Bathonian – Oxfordian Brabant Formation comprises three re- and transgressive cycles of sandy limestone – marl deposition, with an oolitic limestone on top. The formation is thought to have been deposited on a transport-dominated carbonate ramp with relatively low depositional slope (0.05 - 0.1°). Consequently, facies belts are wide, lateral facies changes relatively subtle and vertical facies changes rapid. Clastic input from the hinterland (London-Brabant Massif) was able to reach the ramp. This, in combination with low to moderate *in situ* carbonate production rates and the leeward position of the ramp, favored high basinward sediment transport rates. Three dominant depositional environments are recognized from core data: upper shoreface or shoal (inner ramp), lower shoreface (mid ramp) and offshore facies (outer ramp). Calcarenitic and bioclastic grainstones of upper shoreface facies are clearly the most reservoir-prone (Φ_{Avg} = 11%, K_{Avg} = 10 mD). Lower shoreface storm deposits (interbedded marls and siltstones) may be a potential waste or thief zone. Offshore silty marls and claystones have sealing potential (Φ_{Avg} = 8%, K_{Avg} = 0.7 mD).

Structural complexity increased gradually during the Middle Jurassic, and the slightly faster subsiding grabens accumulated thicker sequences, still in similar facies, than adjacent horst blocks and basin margins. As a consequence, gross reservoir thickness increases towards these former depocenters and is likely at a maximum in the fastest subsiding grabens. This is in contrast to basin margin sequences where the formation is thinner and much more amalgamated. Most net pay can be expected in areas of highest subsidence (grabens) because of stacked reservoir potential and larger gross reservoir thicknesses. This area can be found at the border Roer Valley Graben / West Netherlands Basin and in the (north)west Roer Valley Graben. Throughout the Middle Jurassic, this area was probably a large-scale shoal area that was notably shallower than the basin centers of the West Netherlands Basin and Roer Valley Graben. Towards the basin centers of the West Netherlands Basin and Roer Valley Graben, reservoir quality slightly deteriorates as a result of subtle facies change.

Prospectivity of the formation is demonstrated on several representative seismic sections. These show that the Brabant Formation may be present in four prospective trap configurations: fault-dip closures, inverted horst blocks, downfaulted against Altena Group shales and truncated against the Late Cretaceous Unconformity. The latter two are new trap concepts. Risks are primarily prospect-dependent and mainly related to charge and seal. The prospectivity in the Broad Fourteens Basin was not studied and remains speculative, but it is recognized that the formation might be locally truncated here below claystones of the Vlieland Formation. Future mapping of the formation will likely upgrade the prospectivity in the Roer Valley Graben, the (north)eastern West Netherlands Basin and, potentially, the Broad Fourteens Basin.

Chapter 15 Recommendations

The availability of petrophysical log interpretation results, such as derived from NuTech's petrophysical modeling, has proven to be of great value in recognizing source rock potential (Lutgert et al., 2013) and conventional bypassed pay potential (this study) in the study area. In a similar way as the exploration opportunities identified in the study area, other geographical areas in the hydrocarbon provinces of the Netherlands may equally benefit from a similar petrophysical evaluation approach. It is therefore recommended to extend the petrophysical evaluation approach, followed by NuTech or other specialized consulting companies, to include more vintage wells in the Netherlands, in order to maximize capturing all potential bypassed pay.

The next step in the prospectivity assessment of the Dutch southern on- and offshore basins should be to study the prospectivity of the other overlooked exploration opportunities identified in this study into more detail. Untested hydrocarbon potential has been recognized in the Chalk, Holland Greensand, Delfland, Lower Muschelkalk, Zechstein Fringe Sandstones and Carbonates and Westphalian C/D. Each of these formations should be the scope of detailed follow-up studies.

Especially the Delfland subgroup has high priority and appears to have oil potential in the Roer Valley Graben. Exploration for this should focus on understanding reservoir connectivity and seal quality of the shales.

This study is the first attempt to discuss the geological model and prospectivity of the Brabant Formation. It has resulted in a better understanding of the formation in the Dutch subsurface. However, this study is not a complete work and more data is needed. The next steps in the prospectivity assessment of the Brabant Formation should focus on:

1) re-evaluation and detailed core logging of available and requested core data to update the depositional model;

2) study in more detail factors that influence reservoir quality, with focus on diagenesis and depositional facies (trends), using NuTech petrophysical logs, updated core data and concepts taken from analogue carbonate formations in the Paris and Weald Basin (e.g. see Sellwood et al. (1984), Vincent et al. (2007));

3) mapping of Base Brabant and intra-Brabant reflectors in the Roer Valley Graben, West Netherlands Basin and Broad Fourteens Basin to create depth maps, thickness maps, property maps, etc.;

4) identification and mapping of leads/prospects at Brabant level, focusing on fault-dip closures and downfaulted traps.

In light of point 4), most attractive exploration targets appear to be fault-dip closures and downfaulted traps. Fault-dip closures are proven, and several fault-dip closures are present in the study area. Downfaulted traps are attractive as well, because 1) they are underexplored due to preferential drilling on horst blocks, 2) the Brabant Fm is thought to have slightly higher gross reservoir thickness in grabens, increasing potential net pay thickness, and 3) possibly lower charge risk if trap formation pre-dates inversion.

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Chapter 18 Appendices

Appendix 1 - Lutgert et al. (2013) study results

N.B. Ranked according to RQI. First 35 results shown + 'false pay' omitted (= evaporites & Dolomitic Keuper) + overlooked opportunities identified in this study (green)

Formation	Code	RQI	# of samples	Net Pay (m)	Vclay (avg)	ϕ (avg)	K (mD; avg)	Sw (avg)
Rot Fringe Sst	RNROF	3544.9	6374	744.1	0.15	0.12	39.63	0.34
Slochteren Fm	ROSL	3043.9	4947	700.5	0.1	0.11	3.68	0.5
Hardegsen Fm	RBMH	3014.3	5011	648.6	0.14	0.12	26.24	0.42
Alblasserdam (Delfl.)	SLDNA	2923.0	3387	446.3	0.19	0.16	91.38	0.59
L. Volpriehausen Sst	RBMVL	2343.1	4156	534.5	0.12	0.09	4.37	0.41
Main Buntsandstein	RBM	1842.9	3855	385.5	0.16	0.16	71.99	0.37
Westphalian C/D	DCDH	1668.3	2888	371.7	0.2	0.11	11.59	0.41
Volpriehausen Clay	RBMVC	1622.5	2861	366.2	0.18	0.09	2.09	0.46
U. Volpriehausen	RBMVU	1325.9	2546	300.4	0.15	0.1	7.96	0.42
L. Brabant Limestone	ATBR1	1090.8	2083	258.8	0.18	0.12	2.39	0.57
L. Detfurth Sst	RBMDL	1021.2	1814	236.4	0.11	0.11	4.98	0.49
Holland Greensand	KNGLG	982.9	2142	223.5	0.22	0.25	40.15	0.63
Chalk Group	CKGR	**975.0**	1484	222.3	0.15	0.15	1.39	0.69
De Lier Sand/Shale	KNNSL	773.0	1773	185.7	0.19	0.17	34.66	0.58
U. Detfurth Sst	RBMDU	746.7	1604	166.9	0.17	0.1	2.11	0.49
Detfurth Clay	RBMDC	723.2	1263	156.7	0.15	0.11	9.92	0.42
M. Brabant Limestone	ATBR2	679.5	1326	157.4	0.17	0.12	2.55	0.55
Delft Sandstone	SLDND	663.7	1223	147.6	0.16	0.17	1425.68	0.41
Vlieland Clay	KNNCM	555.3	1383	138.3	0.25	0.11	0.96	0.59
Basal Solling Sst	RNSOB	528.7	849	115.8	0.13	0.1	16.21	0.39
U. Rot Fringe Clay	RNROY	513.4	1005	112.0	0.21	0.11	73.59	0.32
L. Rot Sst	RNROL	509.7	1007	115.5	0.22	0.1	3.1	0.44
Rogenstein Mbr	RBSHR	502.8	882	109.6	0.23	0.08	3.26	0.36
L. Muschelkalk	RNMUL	485.5	814	109.2	0.16	0.1	60.4	0.35
U. Muschelkalk	RNMUU	479.5	730	108.6	0.27	0.12	3.56	0.51
Lower Bunter Sst	RBSH	446.8	660	100.6	0.24	0.11	7.28	0.37
Rijswijk Mbr	KNNSR	351.7	617	75.2	0.14	0.18	489.15	0.39
Breeveertien Fm	SLDBA	344.5	494	52.9	0.1	0.15	3.89	0.63
Z2 Fringe Sst	ZEZ2S	276.3	574	57.5	0.05	0.12	7.48	0.4
U. Brabant Limestone	ATBR3	251.9	487	62.3	0.19	0.15	4.13	0.62
Strijen Fm	DCHS	251.7	480	69.1	0.18	0.09	1.82	0.46
Z1 Fringe Sst	ZEZ1S	238.1	465	54.6	0.1	0.07	1.82	0.37
Z1 Fringe Carbonate	ZEZ1F	227.9	356	50.6	0.1	0.06	2.97	0.27
…								
ATWDM	ATWDM	86.2	133	19.1	0.14	0.2	15.12	0.58

Appendix 2 - Hydrocarbon shows database for overlooked opportunities

Well	Formation top	Formation bottom	Top (MD)	Bottom (MD)	Oil	Gas	Quality	NuTech well?
Chalk Group								
P15-01	CKGR		1000.01	1025	y	n	Good	y
P15-01	CKGR		1000	1025	n	y	Good	y
P15-01	CKGR		970	980	n	y	Good	y
Q16-05	CKTXM	CKTXG	1683	1720	n	y	Good	y
Q13-03	CKGR	CKGR	978	1030	n	y	Good	No
Q13-03	CKGR	CKGR	978.01	1030	y	n	Good	No
MSG-02	CKGR	CKGR	1200	1325	n	y	Good	No
PRW-01	CKTXG	CKTXG	1768	1768.01	y	n	Poor	No
Holland Greens.								
BRT-02-S2	KNGLG	KNGLG	1800	1875	n	y	Good	y
BRT-02-S1	KNGLG		1730	1735	n	y	Good	y
BRT-01	KNGLG		1695	1705	n	y	Good	y
P18-01	KNGLG		1928	1970	y	n	Good	y
NKK-01	KNGLG		603	609	y	n	Poor	y
P15-01	KNGLG	KNGLG	1555	1555.01	n	y	Good	y
Q16-05	KNGLG	KNGLG	1955	1955.01	y	n	Good	y
Q16-05	KNGLG	KNGLG	1967	1967.01	y	n	Good	y
Q13-02	KNGLG	KNGLG	1058	1062	n	y	Fair	y
Q13-02	KNGLG	KNGLG	1058.01	1062	y	n	Fair	y
LIR-02-S1	KNGLG	KNGLG	1376.9	1377.9	y	n	Good	n
DEL-07	KNGLG	KNGLG	910	940	y	n	Good	n
IJS-64	KNGLG	KNGLG	717	756	y	n	Poor	n
LED-01	KNGLG	KNGLG	582	595	y	n	Fair	n
LED-03	KNGLG	KNGLG	520	520.01	y	n	Poor	n
LED-03	KNGLG	KNGLG	615	622	y	n	Poor	n
LOD-01	KNGLG	KNGLG	1215	1232	y	n	Poor	n
MON-01	KNGLG	KNGLG	1453	1456	y	n	Good	n
NKK-01	KNGLG	KNGLG	603	609	y	n	Poor	n
PNA-02	KNGLG	KNGLG	930	955	y	n	Poor	n
SCL-01	KNGLG	KNGLG	1145	1160	y	n	Fair	n
SCL-01	KNGLG	KNGLG	1168	1188	y	n	Good	n
SPKW-01	KNGLG	KNGLG	2060	2060.01	y	n	Good	n
Delfland								
AND-06	SLDNA		1012.9	1012.91	y	n	Good	y
AND-06	SLDNA		1040	1040.01	n	y	Good	y
AND-06	SLDNA		1290	1290.01	n	y	Good	y
AND-06	SLDNA		955	955.01	n	y	Good	y

AND-06	SLDNA	973	989.7	y	n	Fair	y
ARV-01	SLDNA	1255	1255.01	y	n	Good	y
ARV-01	SLDNA	1247.8	1247.81	y	n	Good	y
ARV-01	SLDNA	790	850	y	n	Poor	y
BRAK-01	SLDNA	1154	1160	y	n	Good	y
BRT-01	SLDNA	2115	2115.01	n	y	Fair	y
BRT-01	SLDNA	2096	2096.01	y	n	Good	y
BRT-01	SLDNA	2095	2108.5	y	n	Good	y
BRT-01	SLDNA	2083	2095	n	y	Good	y
BRT-01	SLDNA	2375	2380	y	n	Good	y
GAG-01	SLDNA	0	0	y	n	Good	y
GAG-01	SLDNA	2545.01	2615	n	y	Good	y
GAG-01	SLDNA	2510	2620	y	n	Good	y
GAG-01	SLDNA	2390.01	2545	n	y	Good	y
LIR-45	SLDNA	2125	2275	n	y	Good	y
MKP-14	SLDNA	858	875	y	n	Good	y
MSV-01	SLDNA	2420	2435	n	y	Good	y
Q13-04	SLDNA	1528.5	1528.51	y	n	Good	y
Q13-04	SLDNA	1537	1537.01	y	n	Good	y
Q13-04	SLDNA	1542.5	1542.51	y	n	Good	y
Q13-04	SLDNA	2022	2035	y	n	Good	y
Q16-02	SLDNA	2600	2630	y	n	Fair	y
WAA-01	SLDNA	1000	1005	y	n	Fair	y
WED-02	SLDNA	820	950	y	n	Poor	y
WED-02	SLDNA	1425	1470	y	n	Poor	y
WED-02	SLDNA	1225	1395	y	n	Poor	y
WED-02	SLDNA	950	1090	y	n	Fair	y
WED-02	SLDNA	1205	1225	y	n	Fair	y
WED-03	SLDNA	1200	1230	y	n	Poor	y
WED-03	SLDNA	1710	1720	n	y	Good	y
WOB-01	SLDNA	867	872	y	n	Good	y
WOB-01	SLDNA	853.2	855.4	y	n	Good	y
WOB-01	SLDNA	937	939	y	n	Good	y
WOB-01	SLDNA	1055	1065	y	n	Good	y
WOB-01	SLDNA	1040	1090	y	n	Good	y
WOB-01	SLDNA	1000.01	1010	y	n	Good	y
WOB-01	SLDNA	1000	1010	n	y	Good	y
WOB-01	SLDNA	985	1040	y	n	Good	y
WOB-01	SLDNA	945	975	y	n	Good	y
WOB-01	SLDNA	943.5	945	y	n	Good	y
WOB-01	SLDNA	765	780	y	n	Good	y
WWN-03	SLDNA	1405	1589	y	n	Good	y
WWK-01	SLDNA	1681	1681,01	n	y	Fair	y
WWK-01	SLDNA	1347	1347,01	n	y	Good	y
plus more…							

Brabant Formation								
SPG-01	ATBR1		2098	2149	y	n	Good	y
WWN-03	ATBR1		1813	1890	n	y	Poor	y
WWK-01	ATBR1		1985	2013	y	n	Good	y
BRAK-01	ATBR1		1430	1460	y	n	Fair	y
HVB-01	ATBR1		1381	1413	y	n	Good	y
WAA-01	ATBR1		1072	1125	y	n	Fair	y
WED-02	ATBR1		1740	1746	y	n	Fair	y
WED-03	ATBR1		1865	1890	y	n	Good	y
BSKP-01	ATBR1		1065	1075	y	n	Good	y
WWK-01	ATBR2		1880	1890	y	n	Fair	y
WWN-03	ATBR2		1710	1740	y	n	Good	y
BRAK-01	ATBR2		1339	1378	y	n	Fair	y
AND-06	ATBR2		1498	1499	y	n	Good	y
WED-03	ATBR2		1775	1800	y	n	Good	y
HVB-01	ATBR2		1320	1328	y	n	Good	y
HVB-01	ATBR2		1335	1342	y	n	Good	y
WWK-01	ATBR3		1753	1755	y	n	Good	y
AND-06	ATBR3		1470	1471	y	n	Good	y
BRAK-01	ATBR3		1290	1300	y	n	Good	y
BRAK-01	ATBR3		1312	1320	y	n	Poor	y
WED-02	ATBR3		1545	1564	y	n	Poor	y
WWN-03	ATBR3		1624	1624,01	n	y	Good	y
WWN-03	ATBR3		1589	1640	y	n	Good	y
AND-01	ATBR2	ATBR2	1542	1576	y	n	Good	n
AND-02	ATBR1	ATBR1	1200	1232	y	n	Fair	n
AND-04	ATBR1	ATBR1	1500	1522	y	n	Poor	n
AND-05	ATBR3	ATBR3	1347	1348	y	n	Poor	n
AND-05	ATBR1	ATBR1	1506	1509.5	y	n	Poor	n
BLG-01	ATBR1	ATBR1	1153	1160	y	n	Weak	n
EHV-01	ATBR1	ATBR1	2484	2495	y	n	Good	n
HPT-01	ATBR1	ATBR1	1140	1167	y	n	Poor	n
HST-01	ATBR1	ATBR1	816	819	y	n	Poor	n
HST-01	ATBR1	ATBR1	837	837.01	y	n	Good	n
HST-01	ATBR2	ATBR2	690	710	y	n	Fair	n
IJS-03-S1	ATBR1	ATBR1	1865	1905	y	n	Good	n
LEK-01	ATBRU	ATBR3	1393	1435	y	n	Good	n
LEK-01	ATBRM	ATBR2	1435	1475	y	n	Fair	n
LEK-01	ATBR1	ATBR1	1705	1715	y	n	Weak	n
MKP-05	ATBR1	ATBR1	1207	1233	y	n	Good	n
MKP-05	ATBR2	ATBR2	1130	1147	y	n	Fair	n
MKP-06-S1	ATBR1	ATBR1	1272	1280	y	n	Good	n
MKP-06-S1	ATBR1	ATBR2	1295	1355	y	n	Good	n
NKK-01	ATBR1	ATBR1	1988	2015	y	n	Weak	n
OIW-01	ATBR1	ATBR1	2130	2150	y	n	Weak	n

VEH-01	ATBR2	ATBR2	1607	1633	y	n	Weak	n
VEH-01	ATBR1	ATBR1	1715	1720	y	n	Fair	n
WED-01	ATBR2	ATBR2	1616	1616.1	y	n	Good	n
WED-01	ATBR1	ATBR1	1672	1677	y	n	Good	n
WED-01	ATBR1	ATBR1	1677	1679	y	n	Good	n
WED-01	ATBR1	ATBR1	1683	1683.7	y	n	Good	n
RKK-07	SLDNA	ATBR1	1825	1860	y	n	Poor	n
WWS-02	ATBRU	ATBRU	2795	2800	y	n	Fair	n
Middle Werkendam								
WWK-01	ATWDM		2426	2426.01	y	n	Good	y
SPG-01	ATWDM		2454	2462	y	n	Fair	y
AND-06	ATWDM		1780	1780.01	y	n	Good	y
AND-06	ATWDM		1800	1825	y	n	Good	y
Q16-02	ATWDM		2731	2734	n	y	Fair	y
WAA-01	ATWDM		1452	1474	y	n	Good	y
WED-03	ATWDM		2000	2025	y	n	Good	y
MRK-01	ATWDM	ATWDM	944,2	944,21	y	n	Good	y
MRK-01	ATWDM	ATWDM	1015,8	1015,81	y	n	Good	y
MRK-01	ATWDM	ATWDM	1025,5	1025,51	y	n	Good	y
Q04-03	ATWDM	ATWDM	1450	1450,01	y	n	Poor	y
OTL-01	ATWDM	ATWDM	1441.5	1441.51	y	n	Good	y
OTL-01	ATWDM	ATWDM	1440	1440.01	y	n	Good	y
OTL-01	ATWDM	ATWDM	1438	1438.01	y	n	Good	y
OTL-01	ATWDM	ATWDM	1436.5	1436.51	y	n	Good	y
OTL-01	ATWDM	ATWDM	1430	1430.01	y	n	Good	y
OTL-01	ATWDM	ATWDM	1429	1429.01	y	n	Good	y
KWK-01	ATWDM	ATWDM	1500	1525	y	n	Good	y
WLK-01	ATWDM	ATWDM	747	779	y	n	Good	y
MKP-04	ATWDM	ATWDM	1350.7	1352.7	y	n	Good	No
ALM-01	ATWDM	ATWDM	2298	2310	y	n	Good	No
AND-04	ATWDM	ATWDM	1740	1750	y	n	Good	No
AND-04	ATWDM	ATWDM	1795	1800	y	n	Good	No
BRK-01-S1	ATWDM	ATWDM	2735	2742	y	n	Poor	No
HPT-01	ATWDM	ATWDM	1466	1472	y	n	Poor	No
LED-01	ATWDM	ATWDM	1833	1839	y	n	Poor	No
MKP-02	ATWDM	ATWDM	1310	1325	y	n	Poor	No
MKP-04	ATWDM	ATWDM	1345	1345.9	y	n	Good	No
MKP-04	ATWDM	ATWDM	1346.8	1350	y	n	Good	No
MKP-04	ATWDM	ATWDM	1352.7	1354.2	y	n	Good	No
MKP-04	ATWDM	ATWDM	1354.2	1356	y	n	Good	No
MKP-04	ATWDM	ATWDM	1356	1358	y	n	Good	No
MKP-05	ATWDM	ATWDM	1395	1410	y	n	Poor	No
WED-01	ATWDM	ATWDM	1986	1998	y	n	Good	No
WED-01	ATWDM	ATWDM	1990.5	1990.51	y	n	Good	No

MKP-05	ATWDM	ATWDM	1443	1448	y	n	Poor	No
MKP-04	ATWDM	ATWDM	1345.9	1346.8	y	n	Good	No
Lower Muschelkalk								
P14-A-01	RNMUL	RNMUL	2387	2403	n	y	Good	
Q14-02	SLDN	RNMUU	2490	2641	n	y	Good	
BKZ-01	ATRT	RNMUA	2171	2173	y	n	Fair	
LIR-45	RNMUL	RNMUL	2970	2975	n	y	Good	
GWD-01-S1	RNMUU	RNMUU	1845	1850	y	n	Fair	
JUT-01	RNMUE	RNMUL	2560	2650	y	y	Good	
MKP-14	RNMUL	RBMVL	2100	2300	n	y	Poor	
OAS-01	ATWD	RNMUL	1240	1985	y	n	Poor	
OAS-01	RNKPR	RNMUL	1950	2000	y	n	Poor	
PKP-01	RNMUL	RNROL	1945	2076	n	y	Poor	
P06-A-02-S1	RNMU*	RNMU*	-	-	n	y	Poor	
Zechstein Fringe Sandstones								
Q13-07-S2	ZEZ1S		3508	3513	n	y	Weak	y
P18-01	ZEZ2S		3466	3520	y	y	Good	y
Q16-02	ZEZ2S		3838	3850	n	y	Good	y
KDZ-02-S1	ZEZ3S		3583	3591	n	y	Fair	y
P15-02	ZEZ1S	ZEZ1S	3148	3148.01	n	y	Good	n
P15-02	ZEZ1S	ZEZ1S	3178	3178.01	n	y	Good	n
Q10-03	ZEZ2S	ZEZ2S	2828	2831	n	y	Good	n
Q10-03	ZEZ1S	ZEZ1S	2889	2891	n	y	Good	n
Q13-06	ZEZ1S	ZEZ1S	3053.5	3088	n	y	Good	n
Q16-04	ZEZ2S	ZEZ2S	3475	3475.01	n	y	Poor	n
Q11-03	ZEZ3C	ZEZ2S	2700	2730	n	y	Good	n
Q16-FA-101-S1	ZEZ1S	ROSL	3680	3705	n	y	Fair	n
Zechstein 1 Fringe Carbonate								
P15-02	ZEZ1F	ZEZ1F	3180.5	3195	n	y	Good	
Q04-02	ZEZ1F	ZEZ1F	2854	2854.01	n	y	Good	
Q05-02	ZEZ1F	ZEZ1F	2228	2247	n	y	Good	
Q05-02	ZEZ1F	ZEZ1F	2247	2255	n	y	Good	
Q07-04	ZEZ1F	ZEZ1F	2742.4	2742.41	y	n	Good	
Q13-06	ZEZ1F	ZEZ1F	3090	3092	n	y	Good	
Q13-06	ZEZ1F	ZEZ1F	3090.01	3092	y	n	Good	
Q13-07-S2	ZEZ1F	ZEZ1F	3530.7	3530.71	y	n	Fair	
Q13-07-S2	ZEZ1F	ZEZ1F	3532	3536	y	n	Good	
Q14-02	ZEZ1F	ZEZ1F	2857	2863	n	y	Good	

Westphalian C/D								
EVD-01	DCDH	DCDH	1896	1925	y	n	Good	y
EVD-01	DCDH	DCDH	1925	1930	y	n	Good	y
EVD-01	DCDH	DCDH	1930	1942	y	n	Good	y
EVD-01	DCDH	DCDH	1943	1943.4	y	n	Good	y
EVD-01	DCDH	DCDH	1961	1964	y	n	Good	y
EVD-01	DCDH	DCDH	1964	1992	y	n	Good	y
EVD-01	DCDH	DCDH	2009	2010	y	n	Good	y
EVD-01	DCDH	DCDH	2010	2070	y	n	Good	y
EVD-01	DCDH	DCDH	2070	2075	y	n	Good	y
HST-02-S1	DCDH	DCDH	2518	2523	y	n	Good	y
MRK-01	DCDH	DCDH	2750	2800	n	y	Fair	y
OTL-01	DCDH	DCDH	3073.5	3073.51	y	n	Good	y
OTL-01	DCDH	DCDH	3074.3	3074.31	y	n	Good	y
OTL-01	DCDH	DCDH	3059	3059.01	y	n	Good	y
OTL-01	DCDH	DCDH	2993.6	2993.61	y	n	Good	y
OTL-01	DCDH	DCDH	2960.01	3095	n	y	Good	y
OTL-01	DCDH	DCDH	2960	3095	y	n	Good	y
OTL-01	DCDH	DCDH	3088.5	3088.51	y	n	Good	y
PKP-01	DCDH	DCDH	2610	2655	n	y	Good	y
Q16-04	DCDH	DCDH	3555	3630	y	n	Poor	y
Q16-04	DCDH	DCDH	3670	3670.01	y	n	Poor	y
WED-02	DCDH	DCDH	3462	3489	y	n	Good	y
WED-02	DCDH	DCDH	3410.5	3423.5	y	n	Good	y
WED-02	DCDH	DCDH	3434.5	3462	y	n	Good	y
JUT-01	DCDH	DCCR	1825	2100	n	y	Good	y
HST-01	DCDH	DCDH	2490	2504	y	n	Poor	No
HST-01	DCDH	DCDH	2400	2415	y	n	Poor	No
STH-01	DCDH	DCDH	2690	2690.01	n	y	Good	No

Appendix 3 - Hydrocarbon shows database + descriptions for the Brabant Formation

N.B. All shows are oil shows except AND-03-S2 and AND-05 (gas). Yellow = DST that produced oil/gas or interesting oil show for other reason

Well	*Quality*	*Top Fm*	*Bottom Fm*	*Show Description*
AND-01	Good	ATBR2	ATBR2	Chl react pos
AND-01	Good	ATBR1	ATWDU	**DST tested 0.2 m3 oil (inversion anticline, stranded discovery)**
AND-02	Fair	ATBR1	ATBR1	Fluorescentie ppm schnb olie (max. 3200 ppm)
AND-03-S2	Good	ATBR?	ATBR?	**DST produced flammable gas**
AND-04	Poor	ATBR1	ATBR1	Fluorescentie ppm schnb olie (max. 200 ppm)
AND-04	Fair	ATBR1	ATWDU	Fluorescentie ppm schnb olie (max. 1100 ppm)
AND-05	Poor	ATBR3	ATBR3	**DST produced flammable gas**
AND-05	Poor	ATBR1	ATBR1	**DST produced flammable gas**
AND-06	Good	ATBRM	ATBR2	occ Sst fluo, pl-dull gold clear cut m milky wh cf
AND-06	Good	ATBR3	ATBR3	Good traces pale orange fluo (Calc Sst), clear cut, occ slow white cf
BLG-01	Poor	ATBR1	ATBR1	Questionable
BRAK-01	Good	ATBR3	ATBR3	white flu, tr fast white flu cut streaming **(fault-dip closure show)**
BRAK-01	Good	ATBR3	ATBR3	minor white flu
BRAK-01	Fair	ATBRM	ATBR2	minor white flu, no cut
BRAK-01	Good	ATBR1	ATBR1	minor white flu, tr white flu cut
BSKP-01	Fair	ATBR1	ATBR1	Dull yel fluor, pl yel cut, v wk tea stn
BSKP-01	Fair	ATBR1	ATBR1	Dull yel fluor, pl yel cut, v wk tea stn
CAP-01	Poor	ATBRL	ATBRL	Poss weak fluor poss oil staining
EHV-01	Fair	ATBRL	ATBRL	Aceton + Fluorescence
EHV-01	Good	ATBR1	ATBR1	Acet + Fluorescence + Chl
HPT-01	Poor	ATBR1	ATBR1	Fluorimeter metingen, gemiddelde ppm ongeveer 12.
HST-01	Poor	ATBR1	ATBR1	Iets ligniet. Chl reactie positief
HST-01	Good	ATBR1	ATBR1	Iets ligniet. Op splijtvlakken enig olieresidu
HST-01	Fair	ATBR2	ATBR2	Chl reactie positief. **DST: zwak vergaste spoeling en zout water (inversion anticline)**
HVB-01	Fair	ATBRM	ATBRM	Yellowish brown direct fluor, poor yellowish white crush cut fluor with a yellowish white fluor residue.
HVB-01	Fair	ATBR2	ATBR2	Yellowish brown direct fluor, poor yellowish white crush cut fluor with a yellowish white fluor residue.
HVB-01	Fair	ATBR2	ATBR2	Yellowish brown direct fluor, poor yellowish white crush cut fluor with a yellowish white fluor residue.
HVB-01	Fair	ATBRL	ATBRL	Yellowish brown direct fluor, poor yellowish white crush cut fluor with a yellowish white fluor residue.
HVB-01	Good	ATBR1	ATBR1	Bright white to light yellow direct fluor, instant streaming yellowish white cut fluor, bright yellow fluor residue and occasionally light brown stain.
IJS-03-S1	Good	ATBR1	ATBR1	Aceton + Fl + chlr
KWK-01	Fair	ATBR1	ATBR1	Extr. Lt. Chl. Cut (if this means: **extremely light Chlorethene cut, then good-quality sub-unconformity show)**
LEK-01	Good	ATBRU	ATBR3	**Acet, DST produced 10-15% oil (stranded discovery, fault-dip closure)**
LEK-01	Fair	ATBRM	ATBR2	Acet
LEK-01	Weak	ATBR1	ATBR1	Acet
MKP-05	Good	ATBR1	ATBR1	Acet, DST did not produce
MKP-05	Fair	ATBR2	ATBR2	Acet
MKP-06-S1	Good	ATBR2	ATBR2	**Aceton + Fl + chlr. DST: "retrieved 421m oil" (inversion anticline)**
MKP-06-S1	Fair	ATBR1	ATBR1	Fl+Acet.

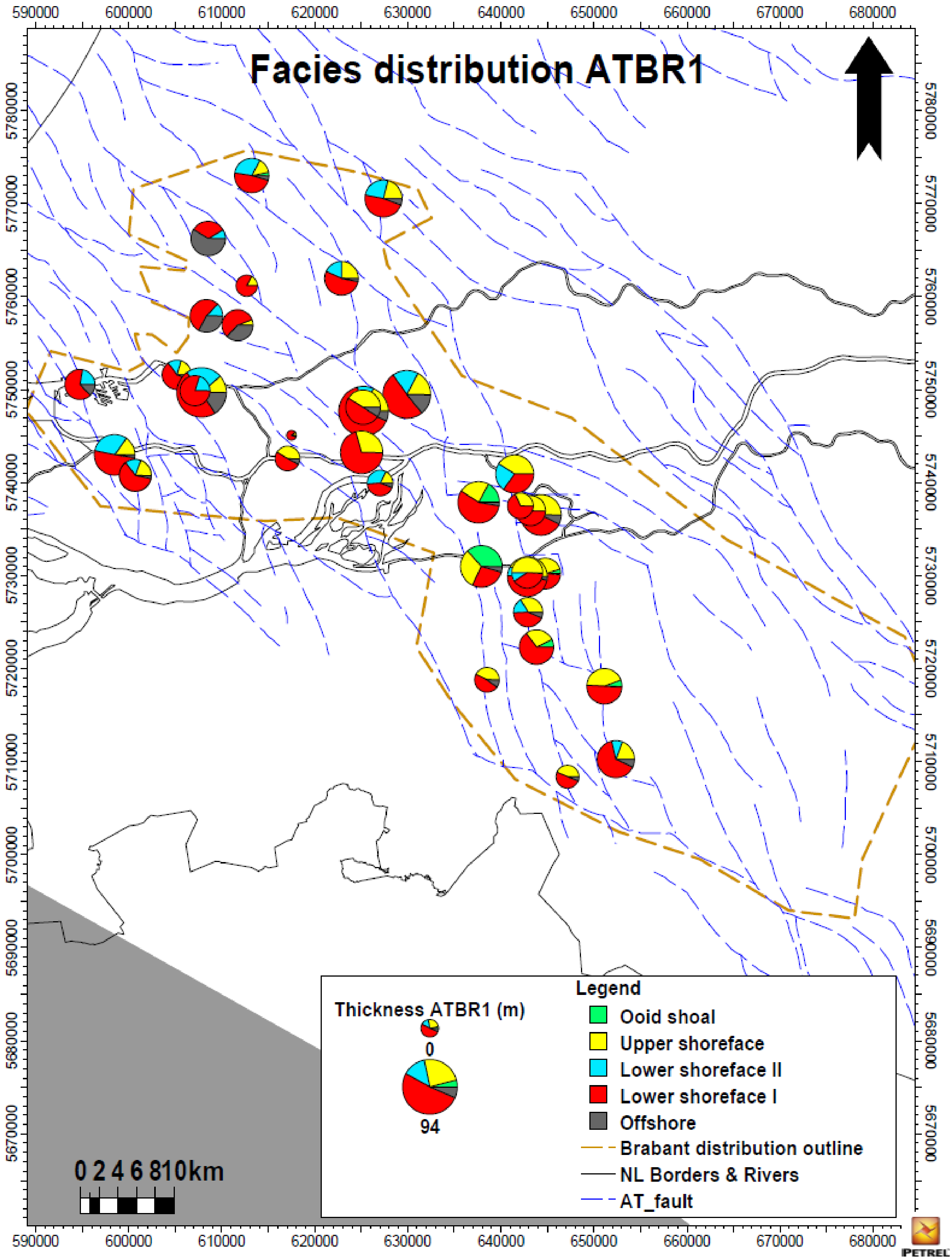
MKP-06-S1	Fair	ATBR1	ATBR1	Fl+Acet.
NKK-01	Weak	ATBR1	ATBR1	Acet
NKK-01	Fair	ATBR1	ATWDU	Aceton
OAS-01	Poor	SLDNA	ATBR1	Acet + Fluo
OIW-01	Weak	ATBR1	ATBR1	Acet
OIW-01	Weak	SLDNA	ATBRL	Acet
RKK-07	Good	SLDNA	ATBR1	Acet+fluo
SPG-01	Good	ATBR1	ATBR1	rr bri yel-org fluor, rr blmg cut
VEH-01	Weak	ATBR2	ATBR2	Acet, Fluo
VEH-01	Fair	ATBR1	ATBR1	Acet, Fluo
VEH-01	Weak	ATBRM	ATBRM	Acet, Fluo
WAA-01	Good	ATBR1	ATBR1	**Chl Ac Fluo good oil show (inv.-anticline/possibly downfaulted show?)**
WED-01	Good	ATBR2	ATBR2	Acet. DST did not produce
WED-01	Good	ATBRL	ATBRL	Acet+Fluo+Chl.
WED-01	Good	ATBR1	ATBR1	Acet+Fluo+Chl.
WED-01	Good	ATBR1	ATBR1	Acet+Fluo+Chl.
WED-01	Good	ATBR1	ATBR1	Acet+Fluo+Chl.
WED-02	Fair	ATBR1	ATWDU	Chl, Acet, Fluo
WED-03	Good	ATBR1	ATBR1	Pin point fluo, bright gold yellow pale cut, sl pl str milky wh cf transl
WED-03	Fair	ATBR2	ATBR2	Pin point fluo, gold yel, no cut, weak milky wh lt ct, trans
WED-03	Fair	SLDNA	ATBR2	Pin point fluo, gold yel, no cut, vlt yel, weak cut fluo, transp
WWK-01	Good	ATBR3	ATBR3	5-10% nat fluor, slow wh-yel crush-cut fluor, residual oil
WWK-01	Good	ATBR2	ATBR2	occ dull wh-bright yel nat fluor, slow cut, mod mlky wh crush-cut fluor.
WWK-01	Good	ATBR1	ATWDU	pa yel fluor, rare wh bloom-stream crush cut fluor
WWN-03	Good	SLDNA	ATBR1	occ fair br yel white direct fluo with slow streaming yellow white fluo cut
WWN-03	Good	ATBR2	ATBRL	occ fair br yel white direct fluo with slow streaming yellow white fluo cut
WWS-02	Poor	ATBRU	ATBRU	Very weak fluorescence, with slow yellow crush cut fluo

Appendix 4 - Facies descriptions and depositional environments for the Brabant Formation

Depositional environment	**Facies**	**Composition/fossils**	**Sedimentary structures**	**Grain size and sorting**	**Depositional environment**
Ooid shoal	White-offwhite-light grey oolitic grainstone	Fine-medium-coarse ooids (spherical to subspherical) rare 1m dolomite bed? (PKP-01, SPG-01), micrite/sparite cmnt, argillaceous laminae (organic-rich intervals?), occ shell fragments, occ sandy (qtz; pack-/wackestone texture when sandy)	Massive, locally laminated	Well-sorted, medium-coarse	High energy, wave-dominated, 1-5m water depth
Upper shoreface	Pale yellow-brown or offwhite/light grey calcarenite	Mud-to grainstone, sparry calcite matrix, locally sandy (grainstone-, occ sandy bioclastic packestone texture), occ bands of shell debris with coarse calcite grains and erosive base fining up to cross-laminated fine calcite grains, occ traces of cryptocrystalline dolomite with sucrosic texture (WWK-01, WED-01, AND-06), traces crinoids	Massive or cross-laminated, local rip-up clasts, locally well-developed tempestite sequence	Well-sorted, fine-medium, occ coarse	Medium-high energy, wave-dominated upper shoreface, 5-10m water depth with occ storm beds
Lower shoreface	Pale grey-light grey silty/sandy limestone, occ calcareous silt-to sandstone	Calcareous, loc very sandy, pyrite, fauna as below + tidal-living organism, loc glauconitic, occ coal in places where sst (AND-06, KDK-01)	Bioturbation?, rip-up clasts?, occ. grading to massive silt/limestone, occ. w/ coal parts (KDK-01, AND-06)	Medium-sorted, silt to fine-grained sand	Low-medium energy, wave-dominated lower shoreface,10-20m water depth below FWB
	Intercalation of dark grey calcareous, silty claystone with bands of grey calcareous silt-/fine sandstone	Frequent bands of shell debris (packstone texture, coral debris in BRAK-01), occ dispersed shell debris (mud- to wackestone texture), occ sandy, pyritic, loc glauconitic, fauna: *Planolites*, *Teichichnus*, *Ophiomorpha*, *Serpulids*,	Abundant bioturbation, abundant rip-up clasts, storm beds, messy/chaotic appearance, possibly HCS in HST-01 core	Poor-medium-sorted, siltstone fine grained to occ fine-grained sand, claystone occ silt-grained	Low-medium energy but frequently high-energy, storm-dominated lower shoreface, 20-60m water depth between FWB and SWB
Offshore	Dark grey calcareous silty claystone (marl)	Mudstone texture, occ dispersed shell debris (mud- to wackestone texture), occ bands of shell debris (rare), pyrite concretions, loc glauconitic, occ ferruginous, occ hematitic, occ tr of coal, micrite matrix, shell debris fossils: echinoderms, brachiopods, bivalves, bryozoan, gastropods	Abundant bioturbation, occ lamination (planar/ draping?)	Poorly sorted, fine/very fine- grained silt, micrite	Low energy, offshore below SWB, >~60m? water depth

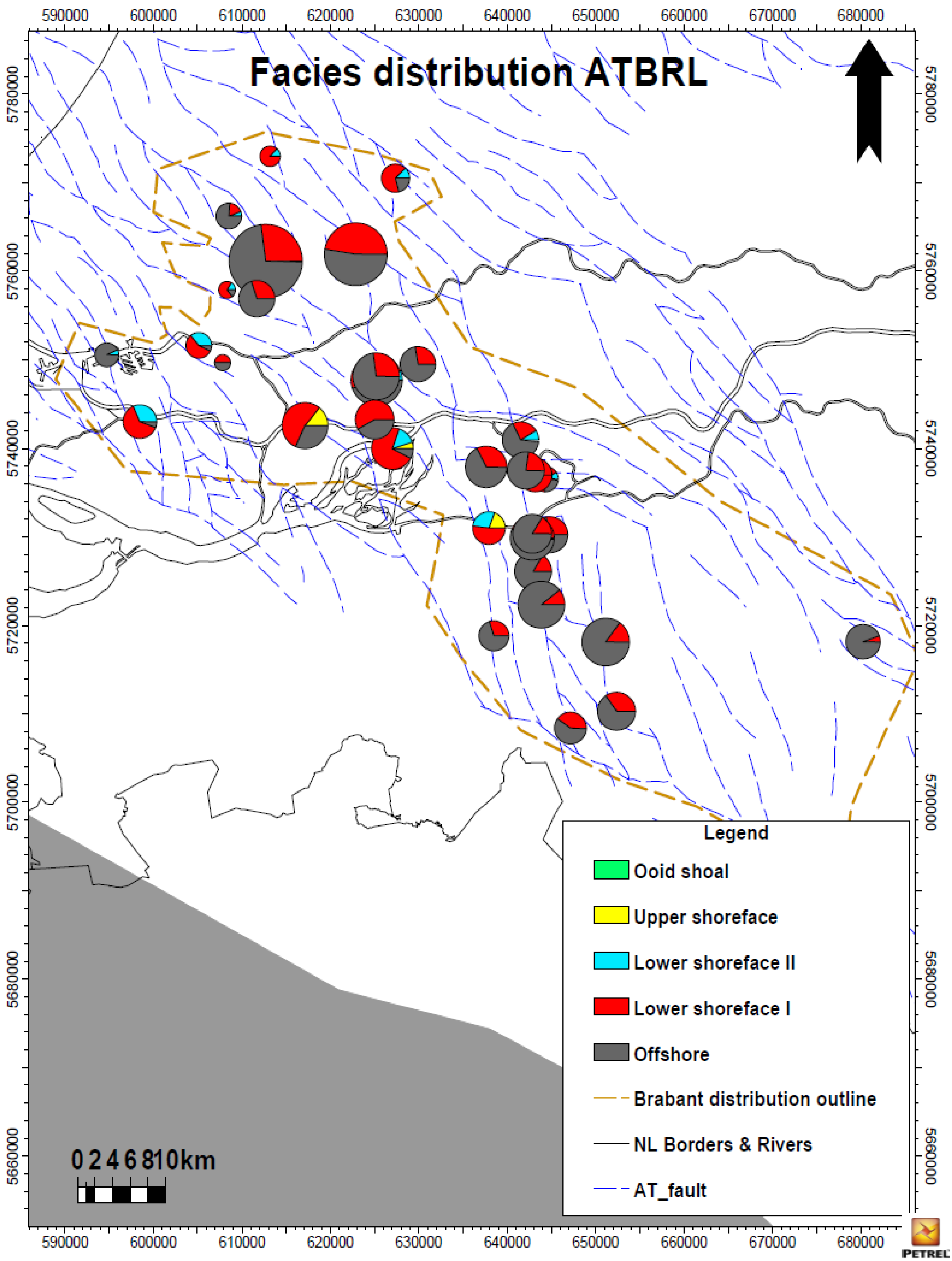
Appendix 5 - Facies distribution map Lower Brabant Limestone

Latest Bajocian – Early/Mid Bathonian



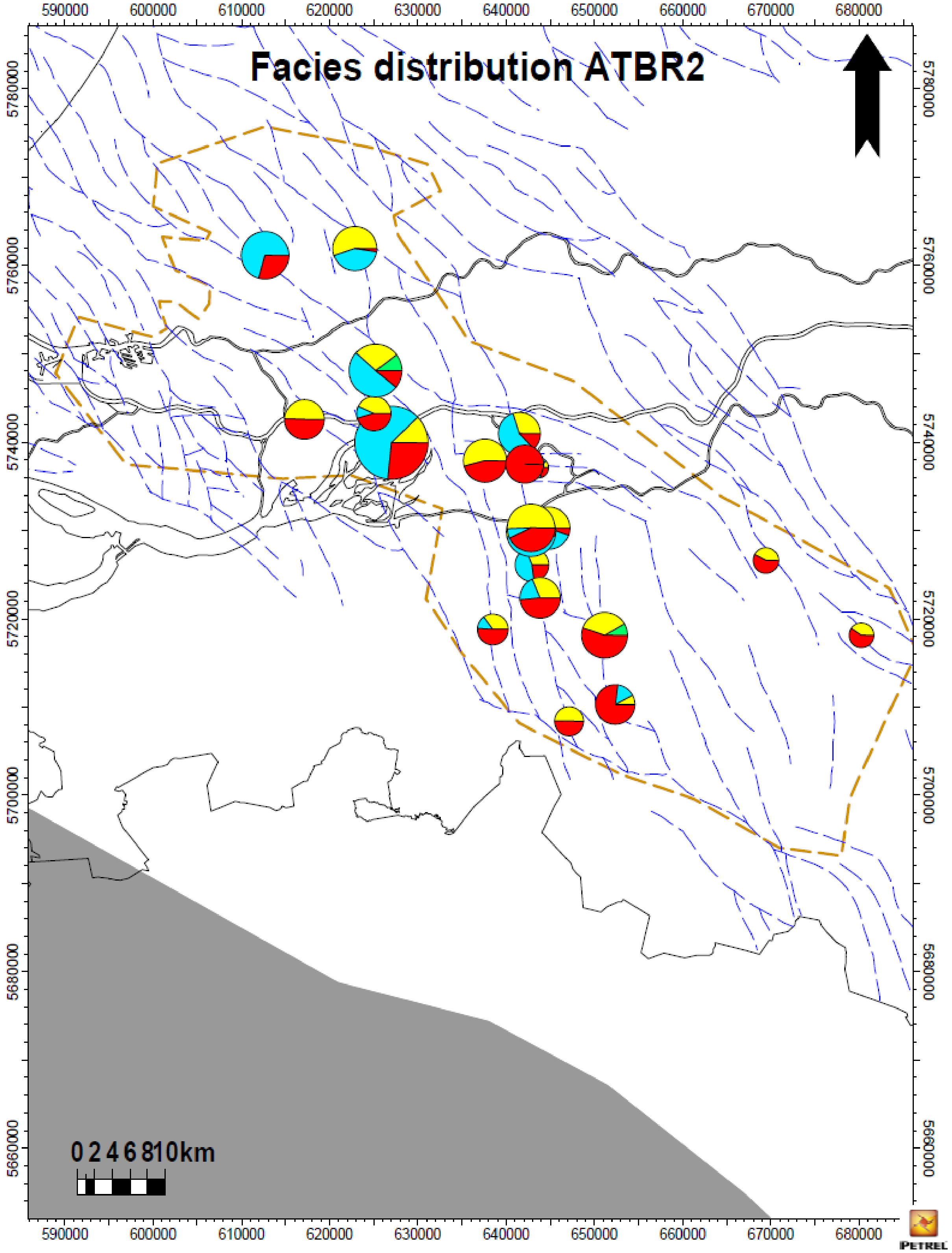
Appendix 6 - Facies distribution map Lower Brabant Marl

Late Bathonian-Early Callovian



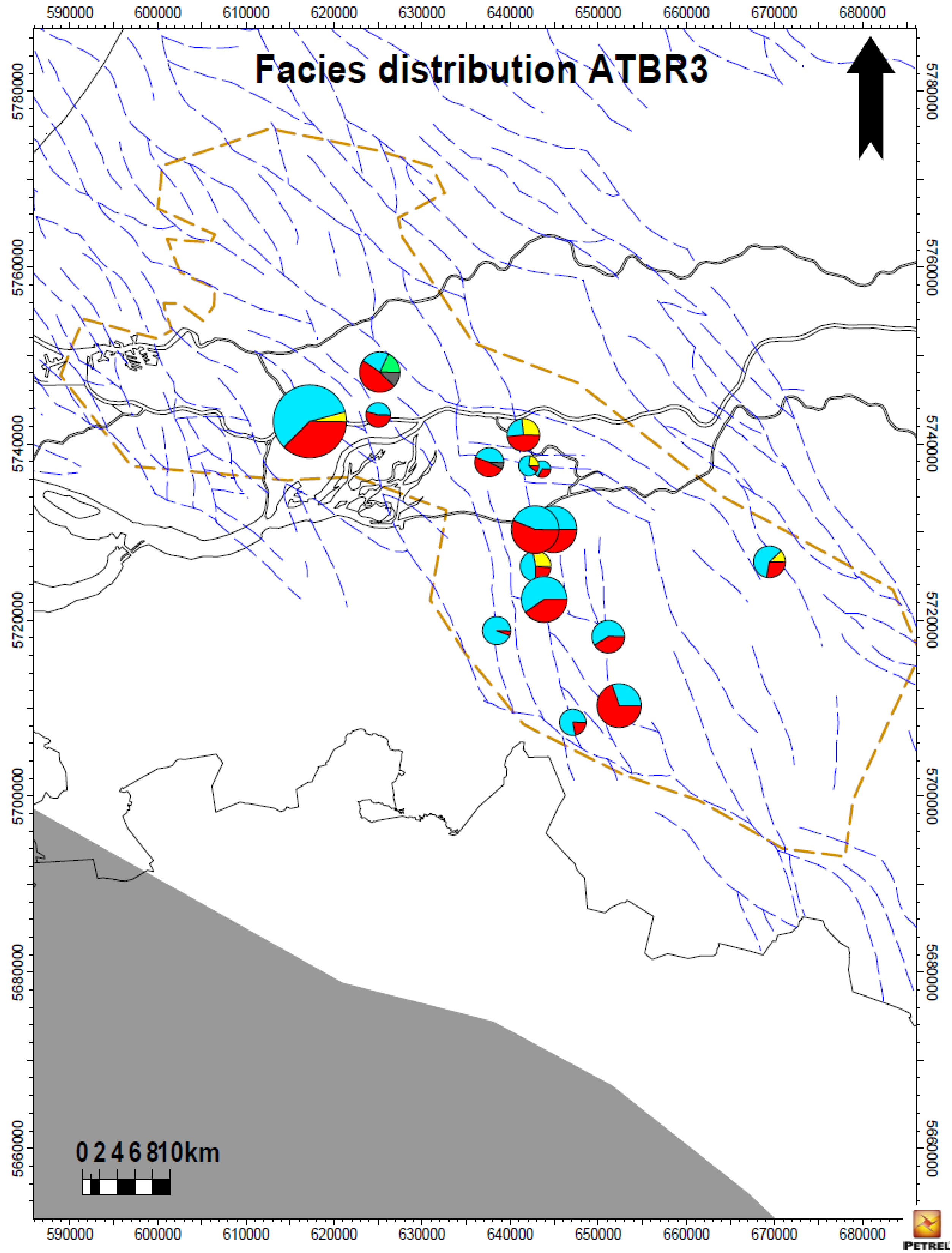
Appendix 7 - Facies distribution map Middle Brabant Limestone

Callovian



Appendix 8 - Facies distribution map Upper Brabant Limestone

Upper Callovian



Appendix 9 - Comprehensive NuTech analysis – details per formation

The QC of the NuTech results focused mainly on two aspects, namely modeled lithology and modeled hydrocarbon show presence (potential net pay). This was primarily done by manually checking and comparing well logs, mud logs, composite logs with NuTech log interpretations, in combination with calibration to the in-house EBN oil and gas shows database. This was done for the opportunities that were identified by Lutgert et al. (2013) and by this study.

Chalk Group

In the show database, several wells have recorded shows, mainly in the offshore F and L blocks. In the study area, P15-01, Q13-03 and MSG-02 have oil and gas shows in the Chalk, as well as PRW-01 and Q16-05 in the Texel Greensand Member (CKTXG).

P15-01 (Figure 1) was analyzed by NuTech (input logs GR, shallow-medium-deep resistivity, sonic, neutron, density). However, for unknown reasons, only the bottom part of the Chalk interval was analyzed by NuTech. The modeled lithology is a sandstone with clay content, which is in strong discordance with the cuttings lithology (soft chalk/chert). Some pay has been calculated, but the mud log shows that *this interval* of the Chalk is dry. However, the upper part of the Chalk (not analyzed by NuTech for unknown reasons) shows a very good oil (oil bleeding from cuttings) and gas show.

The GAG-02-S1 well (input logs GR, shallow-deep resistivity, sonic) has a modeled lithology that is more in accordance with the observed lithology. Pay was calculated with low hydrocarbon saturations, (albeit with a low Rank) but the mud log shows no signs of hydrocarbons. There are several more wells in this category (e.g. HVB-01, P06-S-01).

The mismatch in the Chalk for both wells in terms of both lithology and hydrocarbon show indicates that NuTech's model clearly is not capable of handling this type of formation. NuTech has clearly overestimated this formation.

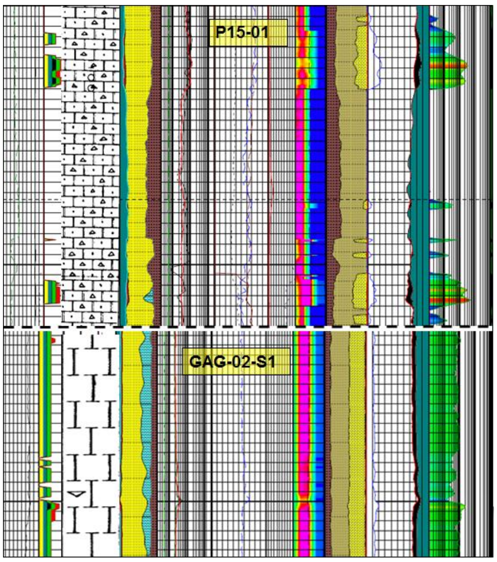


Figure 1. NuTech log interpretation and mud log lithology. Small amounts of potential net pay have been modeled by NuTech, whereas in reality, the formation is completely dry from mud logs.

Holland Greensand Member

The highest ranking well in the NuTech analysis is BRT-02-S2 (Figure 2). Seven input logs were used in the analysis (GR, shallow-deep resistivity, sonic, neutron, density, PEF). The interpreted lithology is a ~50:50 sandstone : limestone with minor clay content and high porosities. The well report, however, describes the formation as a calcite-cemented, glauconitic sandstone, locally pyritic and argillaceous. The NuTech model does not reproduce the observed lithology, even though abundant input logs were available. It may be that the combined presence of calcite, pyrite and glauconite caused misinterpretation. The heavy mineral calcite lowers GR and increases resistivity response. This may have led to misinterpretation for limestone. This is because limestones generally have low GR and high resistivity (when cemented). Pyrite and glauconite however, may suppress resistivity response. Glauconite increases GR response. It is likely that the balance between these three minerals caused erroneous lithology interpretation.

Surprisingly however, the hydrocarbon fill is very well modeled. NuTech calculates a continuous HC column up to 1875m depth at which a hydrocarbon-water contact is located. The mud log shows a high gas concentration (total gas 52,949 ppm) over the interval and a weak oil show. A decrease in gas concentration and disappearance of the oil show at 1875m roughly coincide with the modeled HC-water contact. According to the field database, this well is producing as part of the Barendrecht field. The Holland Greensand forms the gas cap of this oil field.

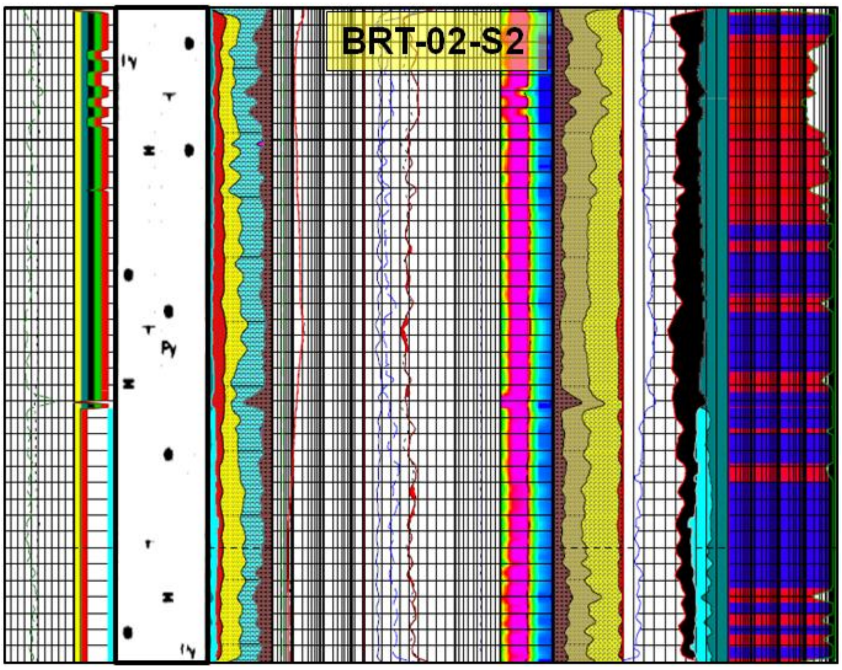


Figure 2. Well BRT-02-S2 for the Holland Greensand interval. Also shown is the conventional well log lithology.

Brabant Formation

In Lutgert et al. (2013), this formation showed high remaining potential - ranking even higher than the Holland Greensand. Overlooked oil shows are reported from 29 wells of predominantly Good quality (some Fair and Poor). However, not all wells are included in this database, and even more wells with shows were found after manually comparing the NuTech shows with well logs. Shows mainly occur in the ATBR1, -2 or -3 (Lower, Middle, Upper Limestone Members, respectively), but occasionally shows in Brabant marls may also occur. Examples of NuTech interpretations are shown here for wells WAA-01, WWK-01 and HVB-01 (Figure 3).

For the Lower Brabant Limestone in WWK-01 (input logs GR, shallow-deep resistivity, sonic), the NuTech interpretation models a limestone with subordinate sand and clay content, with occasional sandy or clay-rich streaks. The observed lithology from cuttings shows a sandy limestone with fossil debris and clay-rich streaks. The NuTech model is in perfect agreement with the observed lithology where also the clay streaks are well modeled. The oil show (occasional dull yellow natural fluorescence, slow white crush-cut) is also quite well modeled, however NuTech overestimates in the upper part of the formation.

The HVB-01 modeled lithology (input logs GR, deep resistivity, sonic) for the Middle Brabant Limestone is in strong disagreement with the observed lithology (argillaceous limestone with some clay streaks). The NuTech model shows a 80 : 20 sandstone : clay lithology. Moreover, NuTech models no hydrocarbon shows, whereas the mud log indicates a good show (occasional yellows brown direct fluorescence, poor yellowish white crush cut fluorescence, yellowish white residual ring). Interestingly, NuTech models good HC shows in the overlying Upper Brabant Limestone (not shown in figure), but the mud log indicates that no hydrocarbons are found.

In WAA-01 (input logs GR, shallow-medium-deep resistivity, sonic, density), the observed lithology is a claystone in the upper parts grading downwards to a calcareous sandstone or sandy limestone. The NuTech model shows relatively high fractions of sand and clay in the upper parts, with increasing limestone content downwards. The model is in quite good agreement. The observed hc show indicates a downward decrease in show quality, while a reverse trend is seen in the NuTech model (downward increase in show quality).

The above-mentioned scenarios are representative for more wells. For example, the lithology effect in HVB-01 is also seen in SMG-01. BRAK-01 has abundant input logs (GR, shallow-medium-deep resistivity, sonic, neutron, density, PEF) and is another example of a well with well-modeled lithology and HC shows.

Summarizing, there are wells with well-modeled lithology and shows and wells with poorly modeled lithology; there are wells with oil shows not identified by NuTech and wells with NuTech pay but no shows in mud logs.

Thus, it can be said that the NuTech model is unstable in predicting lithology and hydrocarbon shows for some wells, whereas for other wells it seems to agree with the mud logs. This may be related to various reasons. For example, the number of input logs (HVB-01) likely plays a role, where more input logs give better results (BRAK-01). However, WWK-01 indicates that relatively few input logs may also result in well-modeled lithology and HC shows. The only difference between WWK-01 and HVB-01 is that WWK-01 has run a shallow resistivity log. This suggests that this log might act as an important or even controlling factor for the model (may be related to bed boundaries/resolution enhancement process?) It may also be related to different calibration of logging tools from the different contractors, but NuTech should have corrected for this.

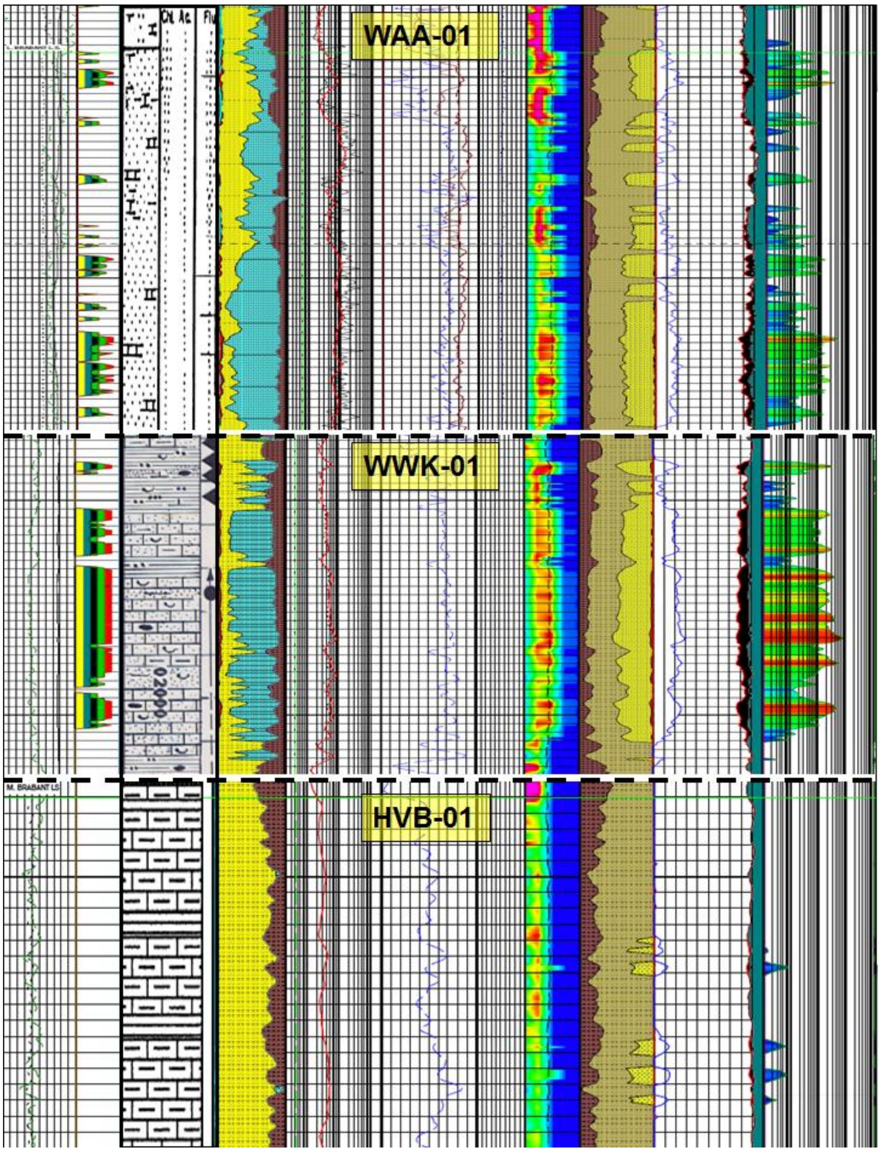


Figure 4. Modeled NuTech results and composite log lithology for WAA-01, WWK-01 and HVB-01. The three wells represent the varied interpretations by NuTech for this formation.

Dolomitic Keuper Member

The Dolomitic Keuper was identified by Lutgert et al. (2013) as a potentially overlooked opportunity. However in the study area, only OAS-01 and WED-02 have recorded shows in this formation (show database) of poor quality. The WED-02 show may be associated with the overlying Sleen Shale, that may have source rock potential (Lutgert et al., 2013). WED-02 was analyzed by NuTech, but they do not calculate significant shows in this formation. Of particular interest are wells P02-NE-02, P02-04 and Q16-02. The NuTech results and depth-matched composite log lithology are shown in Figure 4. The figure clearly shows the mismatch in lithology between NuTech and the composite log. The formation is mainly a claystone alternated with anhydrite beds and occasional dolo- or limestone beds. NuTech calculates dominantly a limestone with sandstone stringers, or, when only three input logs are available (P02-NE-02) a sandstone with minor clay and limestone. Note also the high porosities (indicated in red). It appears that when only three input logs are available (P02-NE-02), NuTech misinterprets the anhydrite beds for limestone beds. Another observation is that differentiation in lithology clearly increases when more input logs are used. The Q16-02 well had 5 input logs available

(GR, shallow-medium-deep resistivity, neutron, sonic, density). It appears that in this well, NuTech could add much more detail to the interpretation, with also dolomite in the interpretation (pink). However, the lithology does not match with the observed lithology from cuttings. This may indicate that increasing the number of input logs does not always lead to a better interpretation, at least not for this formation. It appears that, for this formation, there is no relationship between number of input logs and model accuracy. This points to failure of the NuTech model, which is clearly not calibrated to interpret this formation. It may be that certain input parameters are not correct.

In all three formations, NuTech calculates a continuous hydrocarbon column with good permeability and saturations. However for all three formations, no hydrocarbon shows are reported from mud and/or composite logs, except for P02-04 with 50-200 ppm background gas. This is clearly the result of the wrong interpreted lithology. The observed, ‘true’ lithology is dominantly a mudstone. It thus appears that already in the first step of the NuTech model (explained in section NuTech methodology), it goes wrong. This is during calculation of the Vshale. The amount of clay is consistently underestimated by NuTech in the Dolomitic Keuper. It should be noted that the above-mentioned discrepancy is not only evident in the Dolomitic Keuper, but in almost the entire Keuper stratigraphy.

There is a clear mismatch between NuTech and the observations, both in terms of lithology and HC shows. This may be caused by the number of input logs available. For P02-NE-02 only 3 input logs were available. This may have caused a wrong lithology prediction by NuTech, which in turn has caused erroneous hydrocarbon saturations. However, the Q16-02 well which was completely dry for RNKPD, had 5 input logs available. The lithologies did not match. This indicates that there may be a fundamental problem in the NuTech analysis for this formation. This may be related to the fact that anhydrite has more or less the same log response on GR and resistivity than tight limestones. It appears that NuTech consistently (mis)interpreted a limestone in cases where it had to be an anhydrite. This is more clearly illustrated in Figure 5. From this figure the relationship between high hydrocarbon saturations and low GR and high resistivity is clearly illustrated, with major discrepancies encircled in red. It is clear that the low GR and high resistivity combination has led to the incorrect interpretation of porous limestones with high hydrocarbon saturations. Note also the (incorrect) high porosities over the entire interval. The reason for the thick pay calculated in the question mark interval is not known but appears also to be related to misinterpreting resistivity.

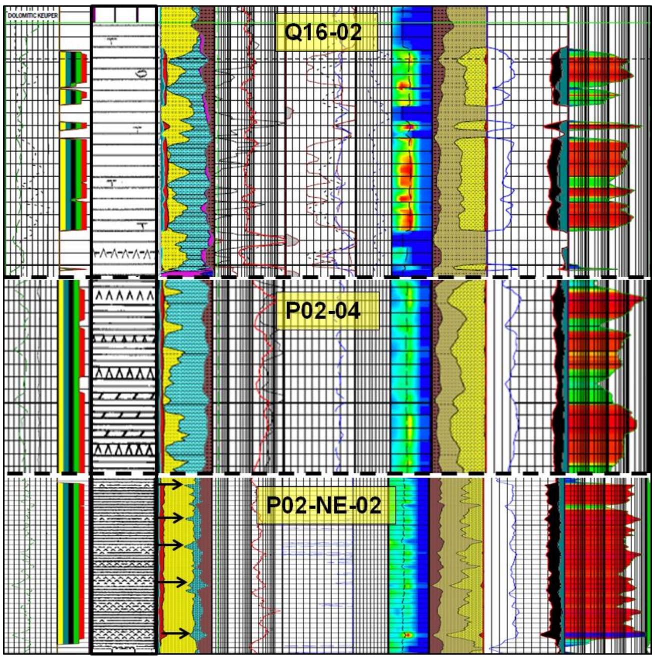


Figure 5. NuTech well log interpretation for the Dolomitic Keuper in Q16-02, P02-04 and P02-NE-02. The composite log lithologies have been drawn to the left of the NuTech lithology track (depth-matched), indicated by the black box. The black arrows indicate the possible misinterpretation of NuTech where low GR values are unfairly attributed to limestone beds instead of anhydrite.

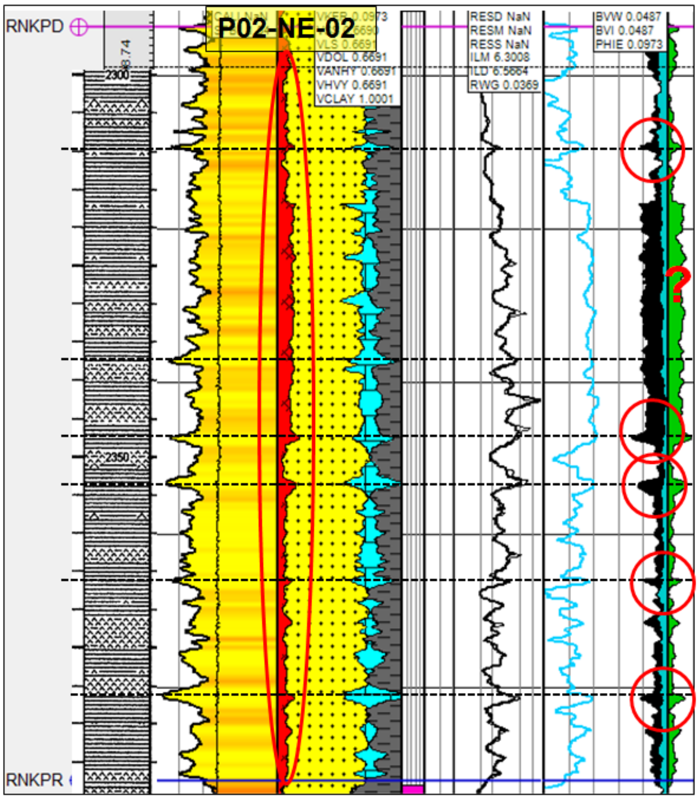


Figure 6. Mud log lithology and NuTech interpretation (loaded in Petrel) for the Dolomitic Keuper in well P02-NE-02 showing the false relationship between high resistivities, GR response and high hydrocarbon saturations. Major discrepancies encircled in red.

Muschelkalk Formation

Lutgert et al. (2013) has indicated potential for this formation in the study area, but this was not quality-checked in detail. Shows are mainly recorded from wells in the eastern part of the Netherlands in the Drenthe and Twente areas. A few wells, mainly in inverted settings (JUT-01, PKP-01, GWD-01-S1, BSKP-01), in the study area have hydrocarbon shows (Appendix; show database).

Of particular interest are wells P02-NE-02 and P06-A-02-S1 (Figure 6) for which NuTech has calculated good hydrocarbon shows.

The P06-A-02-S1 well (input logs GR, shallow-deep resistivity, sonic) shows a discrepancy between modeled and observed lithology: the modeled lithology is roughly a 70 : 30 sandstone : claystone (note areas of quite high porosity (red)). The observed lithology is an anhydritic claystone with beds of anhydrite. The presence of anhydrite in the claystones may have pushed the GR log response to overall lower values and the resistivity to higher values, misinterpreting it for a sandstone with HC saturation in the model. This “resistivity effect” was also observed in the RNKPD. The incorrect lithology had probably consequences for the hydrocarbon saturations and pay. A Rank 2 pay interval is calculated. The mud log, however, indicates a poor gas show of max 200 ppm.

The modeled lithology for the P02-NE-02 well (input logs GR, shallow-deep resistivity, sonic) shows a ~ 20 : 70 : 10 sandstones : limestone : clay lithology with increasing sandstone and decreasing limestone content in the middle part. The mud log lithology is an alternation of anhydrite, claystone and dolomitic limestone. This lithology is not observed in the modeled results. A Rank 1 pay zone is calculated for the entire interval with extremely high hydrocarbon saturation values. In reality, only 530 ppm background gas is observed.

The discrepancies may result from the relatively low number of input logs available for both wells. Judging from the resistivity log, it appears that the resistivity peaks in P06-A-02-S1 correlate with the anhydrite beds. The high resistivity is mis-interpreted by NuTech as high hydrocarbon saturation (Archie equation). The resistivity in P02-NE-02 is generally very high over the entire interval, probably reflecting anhydrite presence (cement) with the peaks corresponding to anhydrite beds. This, again, has been wrongly translated into high hydrocarbon saturations over the entire interval. It may also be that certain porous intervals in the Muschelkalk may indeed have trapped gas, probably coming from the underlying Bunter sands, in cases where the Muschelkalk acted as a leaky (top) seal.

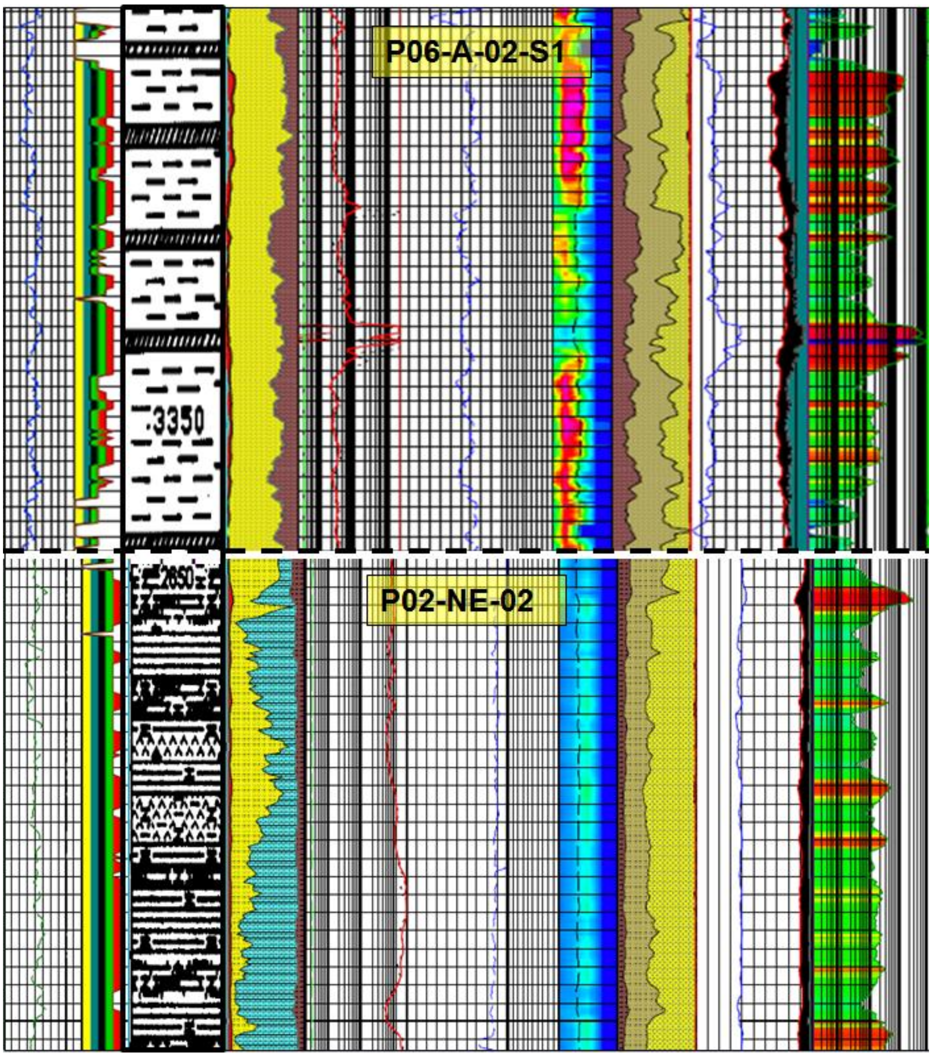


Figure 7. NuTech model results for the Muschelkalk in P06-A-02-S1 and P02-NE-02. Both lithology and pay were misinterpreted by NuTech. It appears that resistivity played a key role in both lithology and pay determination.

Zechstein Fringe Sandstone Members

Gas shows were encountered in 11 wells in the offshore WNB area – four of which NuTech analyzed. Three fields are currently producing from this formation. Well P18-01 (1988, Amoco) deserves special attention as it probably is a clear example of bypassed pay (Figure 7). The exploration well was drilled to evaluate the Rijnland, Bunter and Zechstein reservoirs. The NuTech interpretation calculates an extremely large uninterrupted hydrocarbon pay interval of 45m for the ZEZ2S, with average porosity and permeability of 12.5% and 9.3 mD, respectively. This is in perfect agreement with the composite well log, that has recorded gas shows over the same, entire 55m interval with peak gas concentrations reaching up to 1.12% (10,900 ppm). The interpreted lithology is a sandstone with minor clay content (VClay = 0.06) with downwards increasing clay content, which is in perfect agreement with the composite log lithology (black box, depth-matched). The average NuTech water saturation (Sw) is 0.36, plus theoretically all water is capillary-bound. Hence, the well should be capable of water-free production. No well testing was done. The field produces from the Bunter - Zechstein is not perforated.

Comparison of other wells in the area with NuTech interpretations generally yielded a consistent, good lithological interpretation by NuTech, and overall good match with hydrocarbon occurrences.

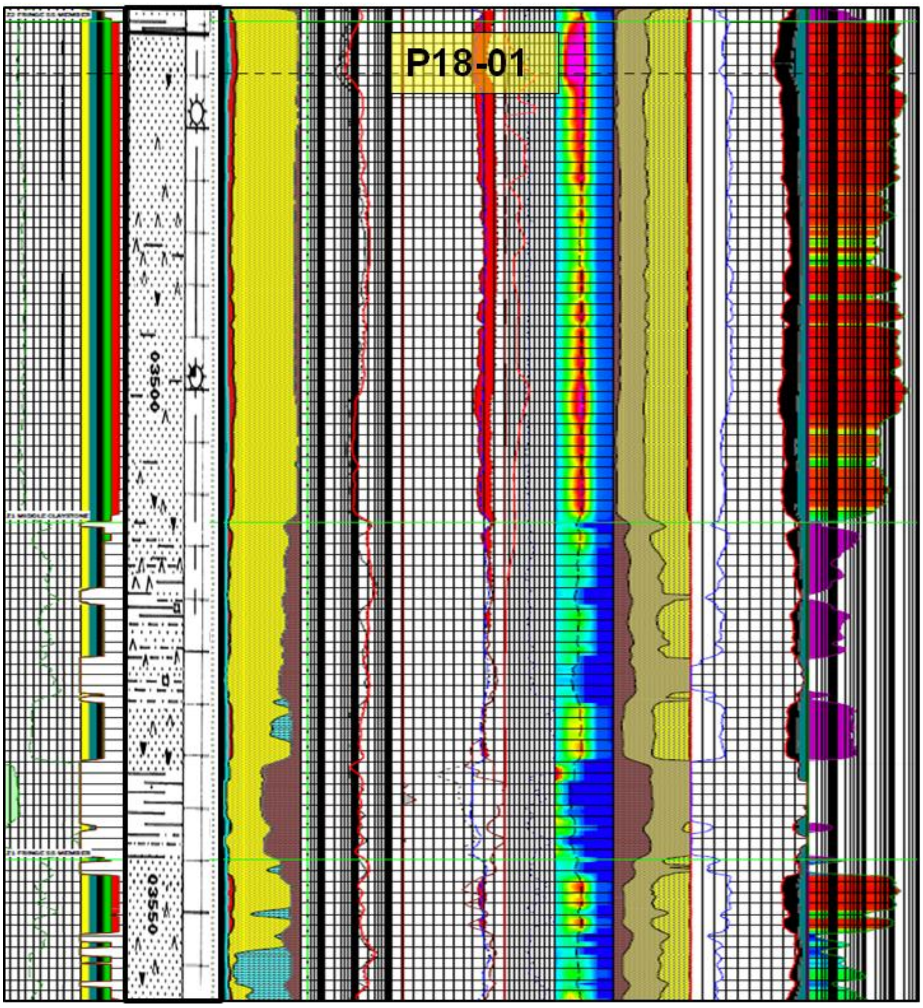


Figure 7. ZEZ2S and ZEZ1S NuTech interpretation for P18-01 showing that modeled and observed well logs are in perfect accordance. Input logs used for the modeling: GR, shallow-medium-deep resistivity, sonic, neutron, density. Middle track in red is the neutron-density cross-over.

Zechstein 1 Fringe Carbonate Member

The Upper Permian Zechstein 1 Fringe Carbonate Member (ZEZ1F) is the carbonate fringe equivalent of the basinal Z1 carbonate and anhydrite sequences. It is primarily found along the southern fringe of the Southern Permian Basin. The unit consists of grey limestone or dolomite with occasionally minor anhydrite.

Oil and gas shows of good quality have been recorded from this formation (show database), mainly in the Q-blocks and onshore (~11 wells). P06-04-A and Q13-07-S2 are analyzed by NuTech and discussed here (Figure 8). In both wells the lithology is rather well computed by the NuTech analysis, where limestone is the dominant lithology. In Q13-07-S2, an oil show is recorded in the bottom 5m of the figure, which is also modeled by NuTech (though a bit underestimated). In P06-04-A, a poor gas show of 1000ppm background gas was observed. Both wells had abundant input logs available (input logs GR, shallow-medium-deep resistivity, sonic, neutron, density) and may have helped considerably in the sound lithology and HC show interpretation.

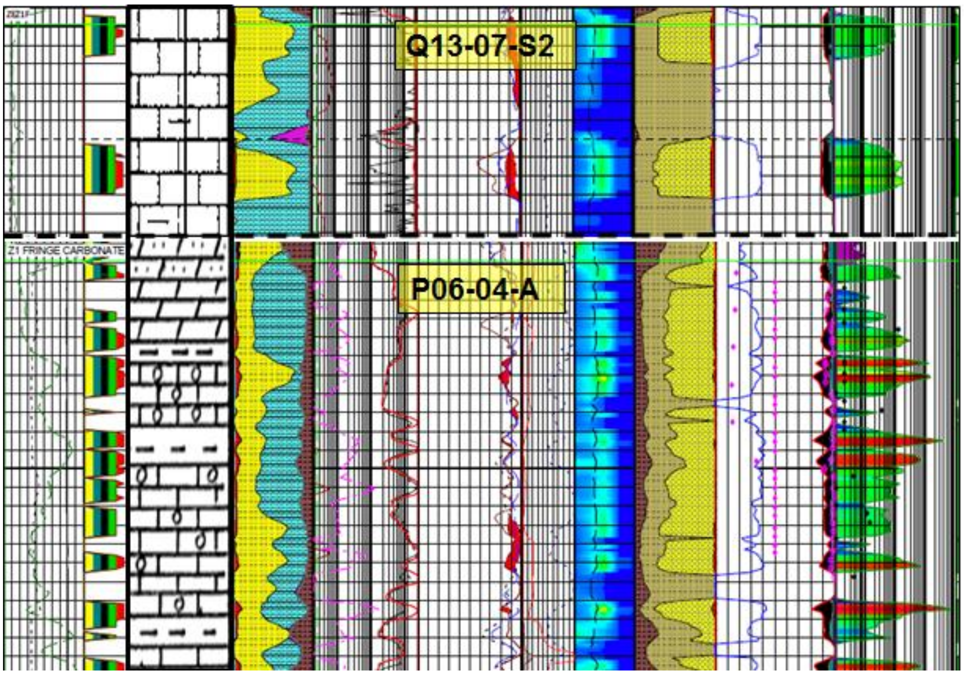


Figure 8. NuTech log interpretation and mud log ltihology comparison for Q13-07-S2 and P06-04-A, indicating the reliable interpretation of NuTech for this formation, likely as a result of abundant input logs available.

Hellevoetsluis Formation (Westphalian C/D)

In the show database, some 10 wells have encountered gas and oil shows in the area, predominantly in wells in inverted settings (OTL-01, STH-01, PKP-01, MRK-01, HST-01/-02-S1, EVD-01). WED-02 and EVD-01 were analyzed (Figure 9).

The observed lithology in WED-02 (input logs GR, shallow-deep resistivity, sonic) is dominantly a sandstone, locally calcareous, with some shale intervals. The modeled lithology is a sandstone with limestone in its middle part. The lithology is rather well predicted, but the limestone section in the middle part is overestimated and not observed. This may have been caused by the extremely low average GR over that interval. The oil show (aceton + fluorescence indications) agrees with the modeled show, but NuTech overestimates the show. Moreover, there is a water-bearing interval calculated which does not seem to be present in reality.

The EVD-01 well (input logs GR, shallow-deep resistivity, density, sonic) shows a sandstone alternated with thinner shale beds. This lithology is modeled perfectly. NuTech clearly predicts the sandstone and shale intervals. The oil show is perfectly modeled as well. The upper and lower part have better show quality, reflected in the model by higher saturation values; the shale section in the middle has worse show quality, reflected in the model by low porosity and saturation values.

The difference in input data between the two wells is the density log, which was run in EVD-01 but not in WED-02. If it is assumed that the logging tools for both wells were the same, and that the gross rock lithology is the same for both wells (which is not an unreasonable assumption as the Westphalian sequence is dominated by sand-shale alternations in the Netherlands (Van Adrichem-Boogaert & Kouwe, 1993-1997)), it may be concluded that the density log likely acted as a controlling factor for the model.

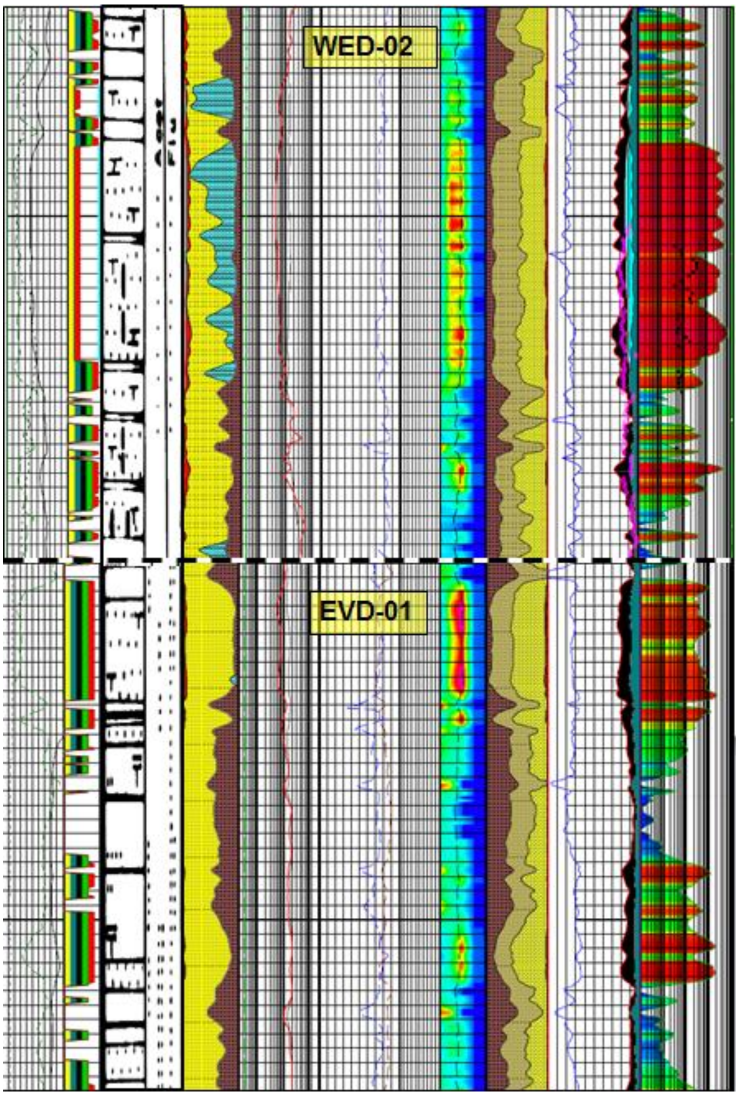


Figure 9. NuTech log interpretation and mud log oil shows and lithology for the Westphalian C/D in WED-02 and EVD-01 indicating that NuTech has reliably modeled the hydrocarbon shows.

Wrap-up and quantitative NuTech analysis

During the QC of the above-mentioned formations, the accuracy of the NuTech interpretation was not quantified, merely on a subjective basis. To analyze NuTech's results in a more quantitative way, the mud/composite log show thickness (as recorded during drilling) was plotted against the amount of pay that NuTech calculated. This was done for the Zechstein Fringe Sandstones, Westphalian C/D (Hellevoetsluis Fm), Delfland and Brabant Formation. Because of limited data the Holland Greensand was not analyzed further. It was chosen to use only those hydrocarbon shows with a Fair or Good quality indicator from the show database because incorporating weak HC shows would cost too much time without adding relevant information. Besides it may result in unreliable conclusions. It is stressed here that only those wells were plotted in which shows from mud logs have been recorded. Cases for which there was no mud log show, but NuTech did calculate pay are plotted in the next paragraph. Results are presented and shown in the figures below.

Figure 10A shows the cumulative mud log show thickness (meters), as identified from the show database or from well logs, plotted against the modeled Pay by NuTech (meters), for four wells that have encountered Zechstein Fringe Sandstones. For all four wells, GR, shallow-medium-deep resistivity, sonic, neutron and density were available. In general, there are no outliers. There is a quite good correlation with the 1:1 trend line; the wells plot close to this line, indicating that there is good agreement between the NuTech show and observed show. For example, the P18-01 show (discussed above) is a 55m gas show from the mud log – NuTech slightly underestimates and calculates 45m. NuTech slightly underestimates all wells. This good agreement may be explained by the abundant available input logs for all wells. This, in combination with gas shows in a nearly 100% pure sandstone lithology, have likely played a key role and indicates that NuTech's model is well calibrated to predict gas shows in sandstone lithologies.

The oil and gas shows in the Westphalian C/D Sandstones (Hellevoetsluis Fm; Figure 10B) show predominantly a good correlation with the modeled NuTech shows. The only outlier is OTL-01. For this well, the standard input logs (GR, shallow-medium-deep resistivity, sonic, neutron, density) plus PEF were available. There is clearly something wrong with the NuTech model, that calculates no shows at all. There appears to be no relationship between accuracy and input logs, as other wells (WED-02, EVD-01, JUT-01) have considerably less input logs available but a much better accuracy.

The oil shows recorded in the Delfland Sandstones (Figure 11A) show a rather good correlation with NuTech modeling results. There are, however, outliers. These may be related to the number of available input logs as there seems to be a rather good correlation (Figure 11B). Less input logs will result in a poorer modeling result. The WOB-01 outlier had no GR log available but only SP. This may indicate the controlling factor of the GR (however this is only based on 1 well). The GAG-01 outlier may also be related to limited input logs. It may also be that outliers are related to show type. This formation has predominantly oil instead of gas shows. Gas has a much stronger density contrast with water compared to oil and water, therefore having a stronger effect on some logs (resistivity, density). It may be that NuTech's model is better calibrated to predict gas shows.

The oil shows in the Brabant Formation (Figure 12) show generally a mixed correlation. NuTech generally underestimates the oil shows in the Lower Brabant Formation. Most wells have good correlation; there are 2 outliers. Most notably the WED-03 well shows poor correlation, for which abundant input logs were available but NuTech calculated completely no pay. The WAA-01 well had 3 input logs available; NuTech calculates about 20m Rank 2 hydrocarbons with low volumes. This is in contrast to the composite log that shows a roughly 50m oil show (chlorothene + fluorescence + acetone). In the Middle Brabant Limestone NuTech models some wells with overestimated pay (WWK-01; may be related to 'resistivity problem') and some wells with no pay at all (HVB-01, WED-03). The Upper Brabant Limestone shows one outlier (WWN-03). For comparison, the wells that had no recorded mud log shows were also plotted (Figure 12D). This figure indicates that for all the Brabant Limestone Members, there are abundant wells in which NuTech has calculated minor shows, but there are also some very large outliers (SMG-01; WWN-01).

The best example of how increasing the input logs does not increase model accuracy is probably demonstrated by the WWN-03 well for the Brabant Limestone, shown in Figure 13. In this well, the Upper Brabant Limestone has abundant logs available (GR, shallow-medium-deep resistivity, sonic, neutron, resistivity, PEF) and a Good oil show was found (mud log). NuTech however models nearly no pay. The Middle and Lower do not have abundant input logs available, (but also do not show too good model results).

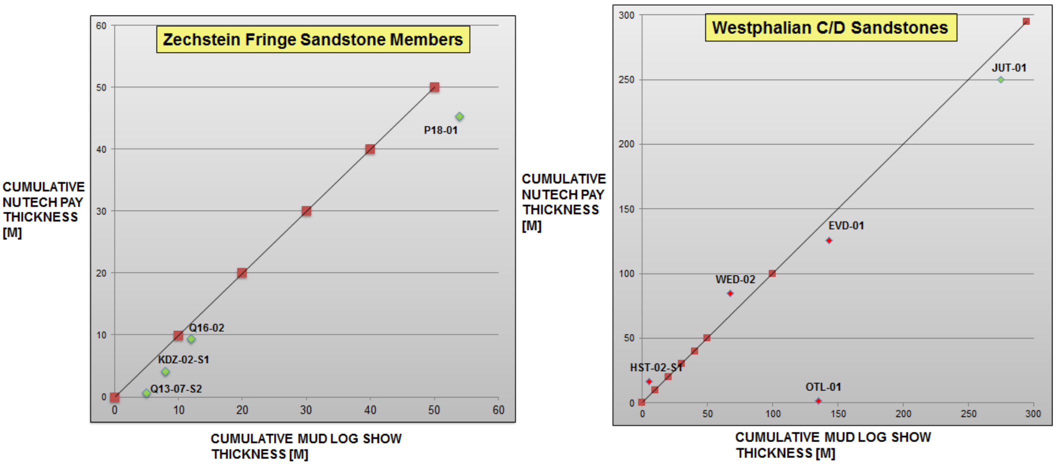


Figure 10. Show comparison between mud log and NuTech for the Zechstein Fringe Sandstone Members (a) and Westphalian C/D (b). This is used as an indicator of the accuracy of NuTech's model.

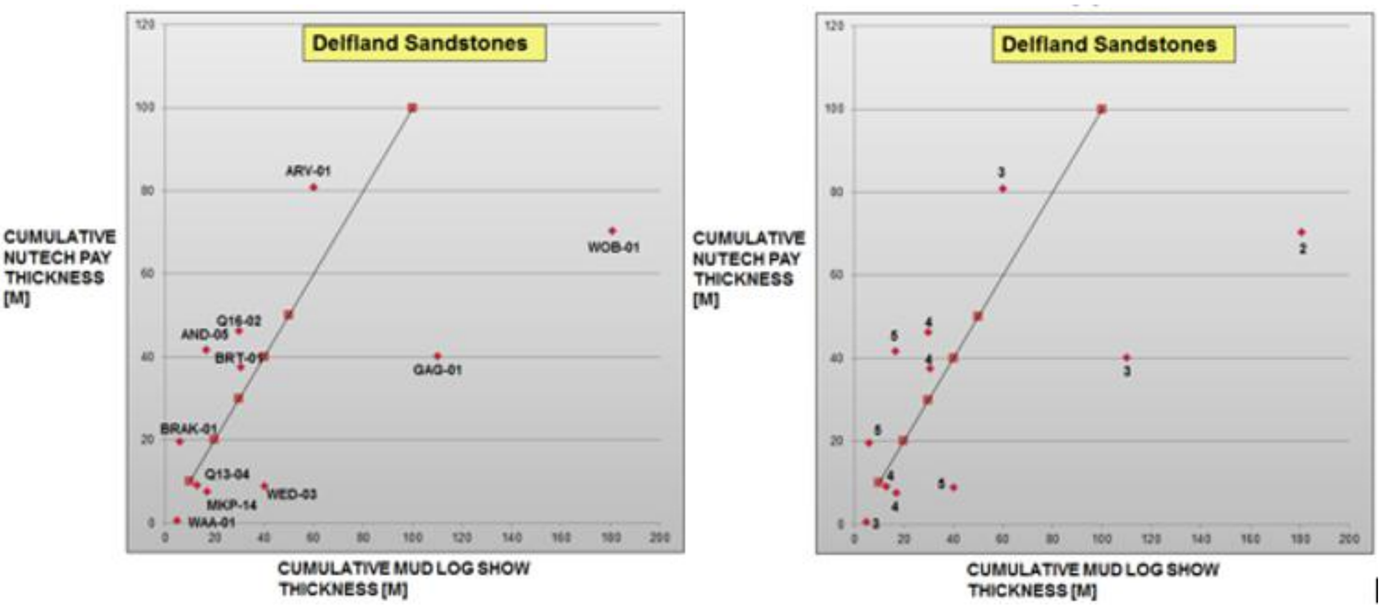


Figure 11. a) Mud log show thickness vs NuTech pay for the Delfland Sandstones. b) Same figure, plotted for each well the number of available input logs. Using more input logs generally results in a more accurate result for the Delfland.

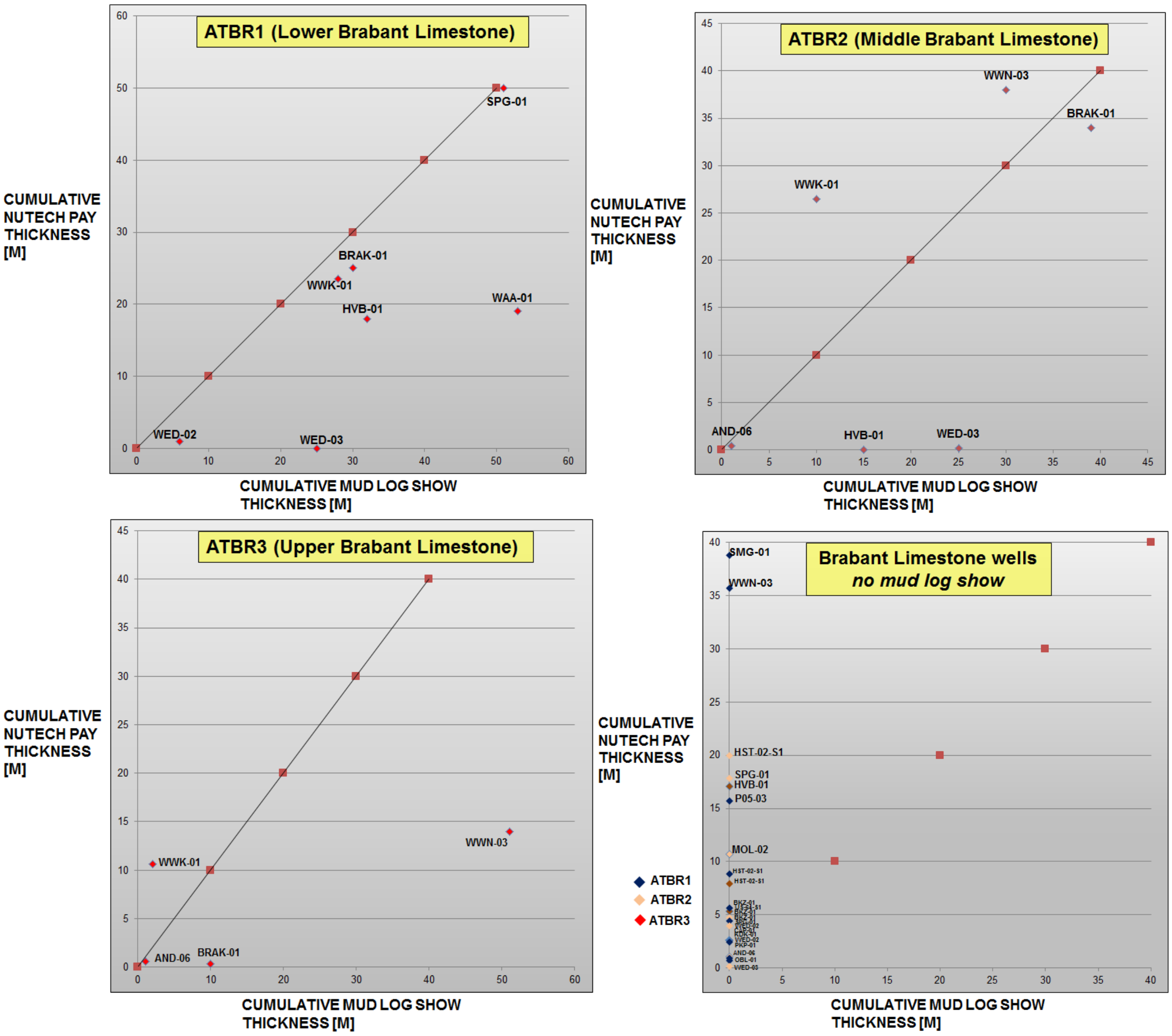


Figure 12. Mud log show thickness vs NuTech modeled net pay for the Brabant Formation: Lower (A), Middle (B) and Upper (C) Brabant Limestone. D) All wells in which NuTech calculated pay, but for which no mud log show was found both after petrophysics-checking and calibration to EBN oil and gas shows database. This shows that there are quite some wells in which NuTech modeled 'false pay'.

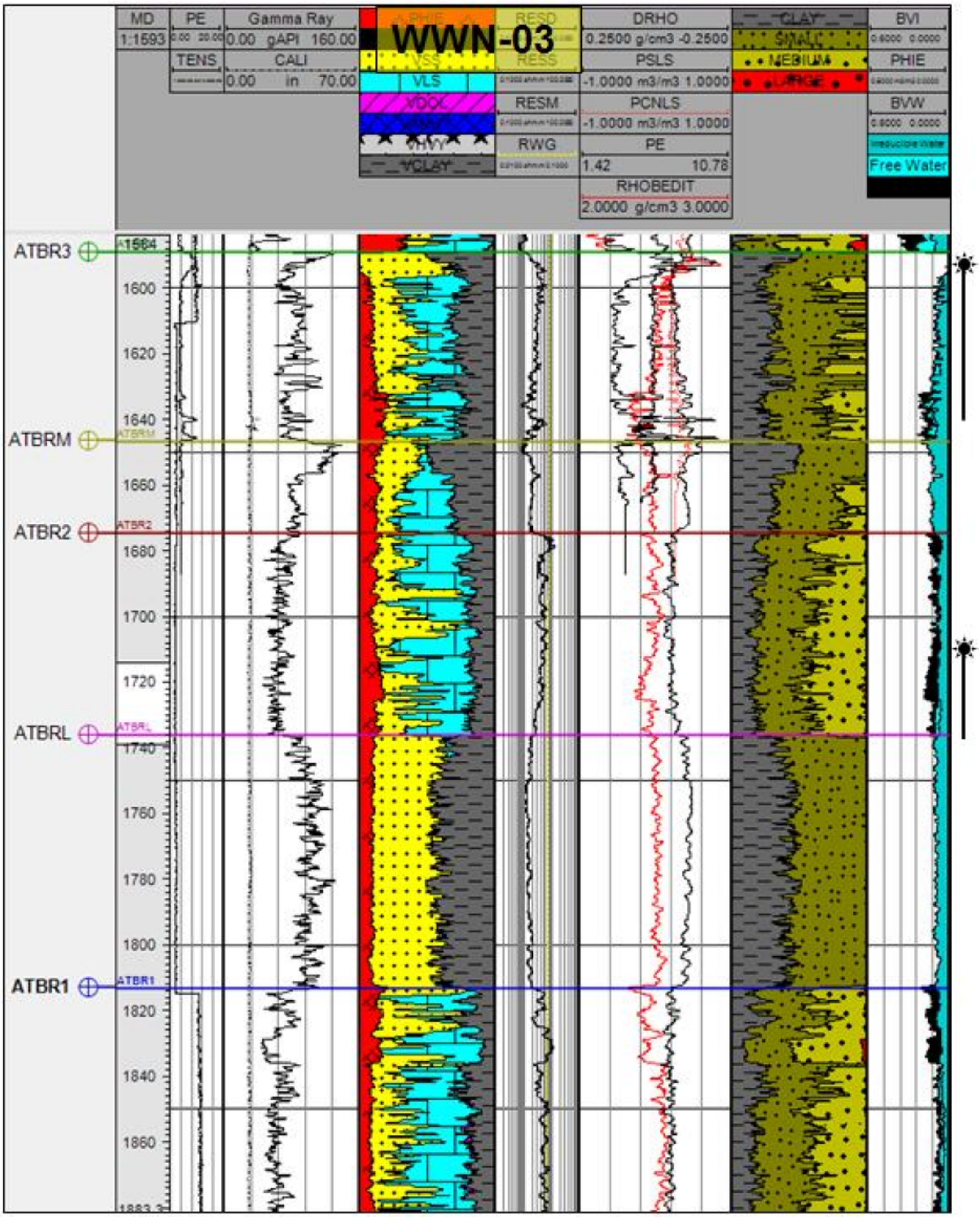


Figure 13. NuTech Pay and oil show from mud log for the Brabant Formation in WWN-03. The discrepancy between NuTech and mud log is clearly visible and also indicates that more input logs does not necessarily lead to better modeling results.

Possible explanations for observed discrepancies

Limited availability of input logs – this likely plays a dominant role. As already pointed out by numerous examples above, the limited amount of input logs available for some wells are likely to have strongly affected the NuTech model – in a negative way, leading to incorrect lithology and general over- or underestimation by NuTech. However, there are also examples of where input log availability does not seem to have played a big role but there are only a few examples of this. The best example of this is probably the WWN-03 well for the Brabant Limestone (Figure), in which the Upper Brabant Limestone has abundant logs available (GR, shallow-medium-deep resistivity, sonic, neutron, density, PEF) and NuTech models nearly no pay (only some HCs with water in the bottom part). However, a Good oil show was found over the entire interval (mud log). Ironically, for the Middle Brabant Limestone (no neutron, no PEF), the pay is well modeled and in accordance with the mud log show. This indicates that increasing input logs does not lead to better results for this carbonate formation.

Overestimation during mud logging. This may be caused by several factors: show logging in open hole (for gas) and mineral fluorescence instead of oil fluorescence (for oil). Show logging in open hole may have overestimated mud log shows. This happens when the drilled formations are not yet behind the casing and gas can continuously enter the annulus of the well. This overestimates the mud log show – in reality there is a much lower gas concentration. There are also cases where fluorescence, acetone and/or chlorothene indications are recorded but the cut (color of the cutting under UV light to indicate oil quality) has *not* been recorded. In this case it remained unclear whether the show was a true oil show or may have resulted from mineral fluorescence. In the analyses it was assumed that it was an oil show, but as just pointed out, this thus may lead to overestimation of the mud log show.

Underestimation by mud log. This may be caused by using high mud weights during drilling, for example in salt-rich lithologies as the Keuper, Muschelkalk and Zechstein. This may suppress the gas concentration and as such, the mud log may not be representative of actual gas concentration.

Overestimation by NuTech. This may be caused by several reasons, for example the “resistivity problem” or wrong input parameters (wrong model). Misinterpreting high resistivities for high hydrocarbon saturations has been observed in the anhydrite-dominated Dolomitic Keuper and carbonate-rich Muschelkalk and Brabant Fm. High resistivities may occur in anhydrites, or in water-filled tight or cemented carbonates for example, when pores are not or very poorly connected and electrical charge cannot find a path through the rock. It is thought that this may have played a dominant role in failing NuTech analyses where carbonates are frequently modeled as hydrocarbon-bearing when in fact, they are not. This may have been the case for the Muschelkalk and Brabant Formation in some wells, e.g. WWK-01. The effect is not seen in the Chalk; this may be related to the lithology and diagenetic history of this formation: a soft, uniform lithology which has not been buried to great depths, therefore less affected by diagenetic effects. The effect is not seen in the Zechstein Carbonates; this formation is often part of the well’s target objective, therefore abundant input logs over this formation generally ensure a sound interpretation of this formation. This, again, points to the dominance of input log availability as a strong control on model accuracy.