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**Digital Geological Model of the Upper Jurassic
and Lower Cretaceous of the West
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How to read this report

This report presents results of a geological study on the Dutch West Netherlands Basin (WNB). It should be considered as a progress report that merely contains a description of the work that has been done, a listing of the results that have been achieved and hyperlinks to the digital files that are archived on the server. A full-blown report with properly scaled maps, correlation panels and figures will be generated in the first quarter of the year 2023. For now, the preliminary correlation panels and seismic panels are added as pdf's in the appendices.

Because of time constraints and also in view of the future full-blown report, many figures that are listed in this report are not in line with the text, but are included in an Appendix. These figures are reference with the abbreviations RV, which stands for Roel Verreussel, and H, which stands for Harald de Haan.

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1 Introduction

In this report from the Geomodelling department of TNO Geological Survey of the Netherlands the preliminary results of a geological study on the mainly onshore Dutch West Netherlands Basin (WNB) are described. The study was carried out in the year 2021 within the framework of the government funded Geo-information Program for the deep subsurface (GIP Diep 2021). The aim was to construct a 3D geological model of the various Late Jurassic and Early Cretaceous formations and members of the Schieland and Rijnland groups. A 3D digital model on group level already exists for the entire on- and offshore of the Netherlands, but the energy transition, in particular the quest for geothermal energy, calls for more detailed models.

Within GIP Diep 2021, other geological studies were also carried out by the Geomodelling department, e.g. a sedimentological and stratigraphical study on the Early and Middle Jurassic Werkendam and Brabant Formation of the Altena Group but these are not included in this report.

Note that it was not possible to fully complete the WNB study within the existing financial framework, only the formations and members of the marine Early Cretaceous Rijnland Group were fully modelled. The mainly non-marine Schieland Group, including the Delft Member which is very relevant for geothermal energy, still requires a significant amount of work.

An important part of the work on the WNB consisted of compiling existing data. These data included consultancy reports, biostratigraphic data, student theses, scientific publications and former studies carried out by TNO. Other work on the WNB included new 3D seismic interpretations and stratigraphic analyses. For the stratigraphic analyses, lithostratigraphic units were correlated from well to well in cross-sections and well panels along strike. Note that the seismic interpretation was carried out in concert with the stratigraphic analyses, which is key for the quality of the end results.

The seismic analyses were carried out by Harald de Haan, who no longer works for TNO (now EBN). The stratigraphic analyses were carried out by Geert-Jan Vis and Roel Verreussel. In addition, valuable support was provided by Anuska Kaliar, Sander Houben, Maryke den Dulk. The study was supervised by Johan ten Veen and Tessa Witteman, who acted as project leads for GIP Diep. In addition, QC sessions with invited experts such as Jeroen van der Molen, Harmen Mijnlief and Wiebe van Driel (TNO AGE) were organized during the course of the project.

2 Scope

The WNB is situated in the western part of the Netherlands and covers a large part of the province of Zuid Holland. The WNB extends into the offshore Q and P Quadrants (Figure 1).

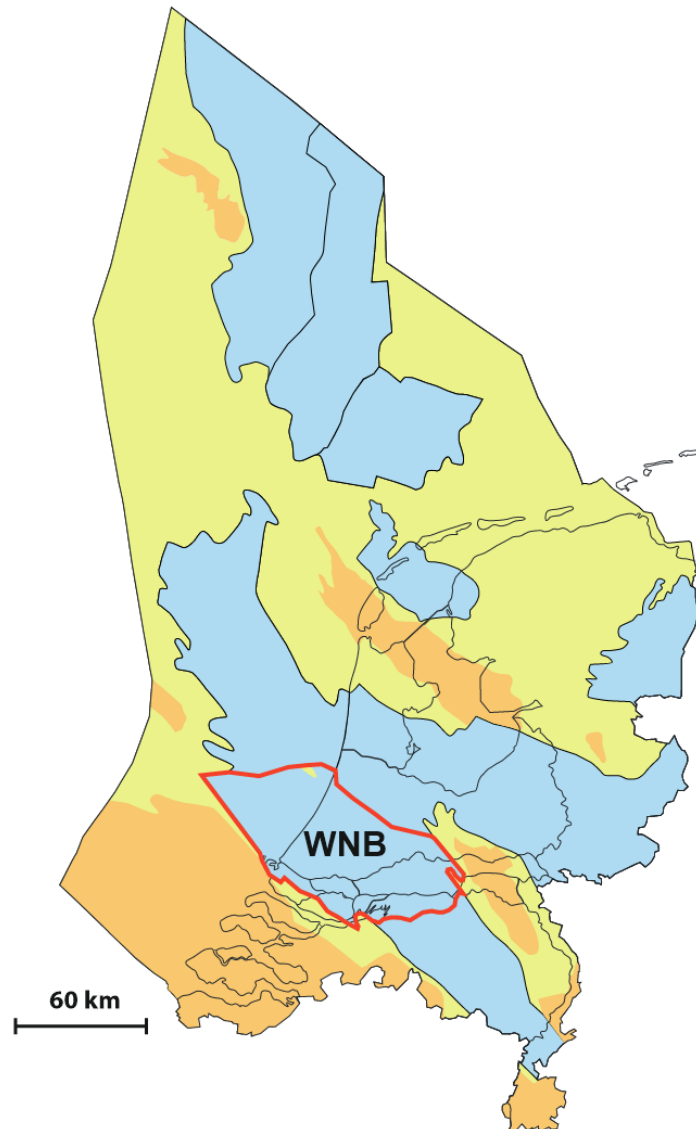
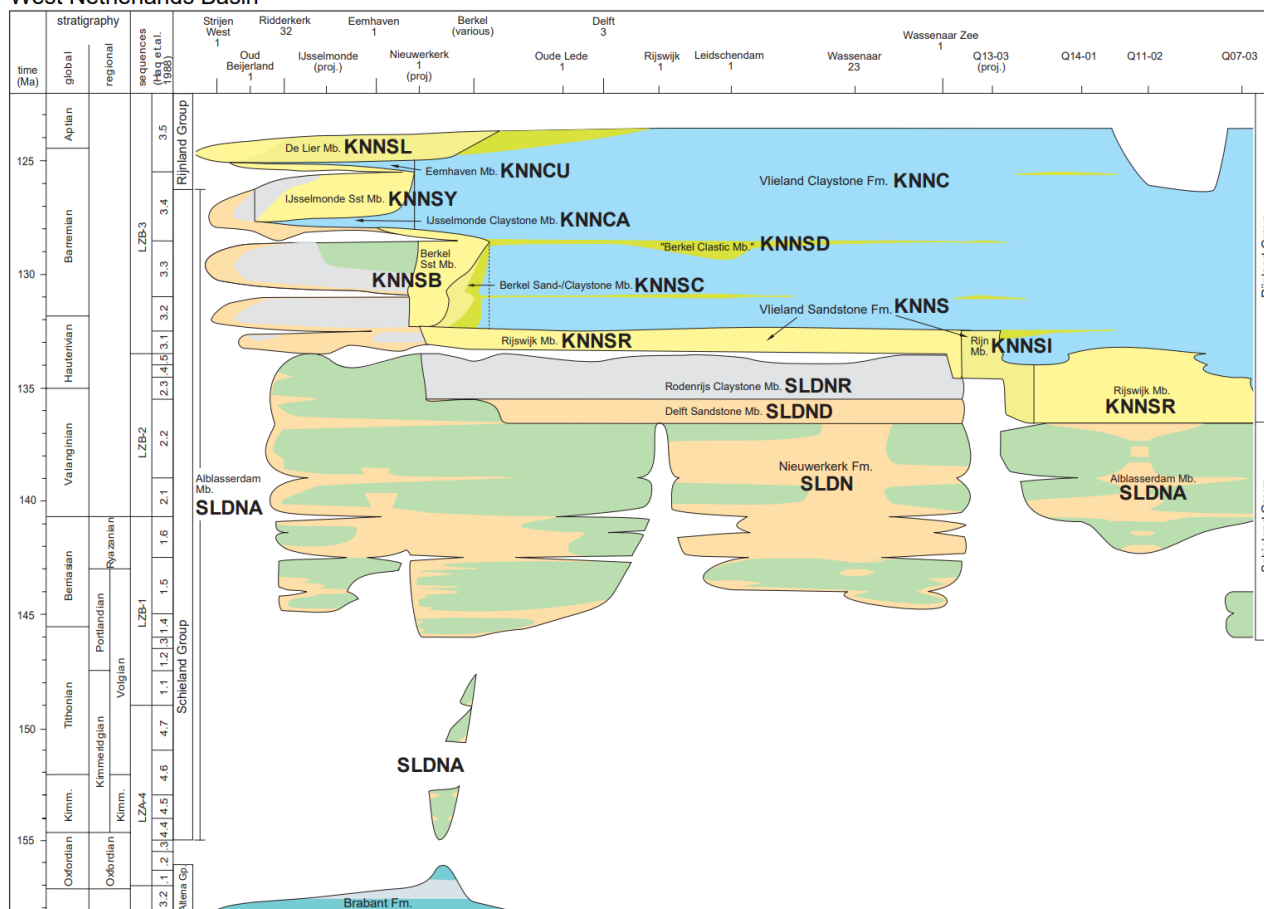


Figure 1 Location of the West Netherlands Basin

The stratigraphic scope of the study was limited to the Upper Jurassic and Lower Cretaceous Schieland and Rijnland groups (Figure 2).

West Netherlands Basin



Source: Van Adrichem Boogaert & Kouwe (1993). Stratigraphic nomenclature: Section G - Upper Jurassic and Lower Cretaceous - Mededelingen Rijks Geologische Dienst 50

Figure 2 Lithostratigraphic framework of the Upper Jurassic and Lower Cretaceous of the West Netherlands Basin. Two groups and three formations are included in the stratigraphic scope of the study: the Nieuwerkerk Fm (Schieland Group), the Vlieland Sandstone and the Vlieland Claystone Fm (Rijnland Group). Only the Rijnland Group was mapped in detail.

3 Database

3.1 Seismic data and quality

The distribution of the Lower Cretaceous Vlieland Sandstone Formation is almost entirely covered by two NAM surveys that are the result of the pre-stack merger of several 3D surveys and the subsequent (re)processing of the merged data. The resultant Monster (R3256, 2016, Kirchhoff and RTM) and Donkersloot (R2823, 2011, Kirchhoff PreSDM) surveys cover respectively the western and eastern part of the southern West Netherlands Basin. To the north the reprocessed Wassenaar survey (R-881, 2001, PreSTM) was loaded to cover the most northern extent of the Vlieland sandstone.

The Monster survey looks different from the other two surveys in a sense that the image looks very smooth. The continuity of the reflectors is higher which makes autotracking easier. But the negative effect is that the reflectors “smear” the fault intersections, making it harder to pick faults. Also the seismic facies is harder to recognise since seismic intervals with discontinuous reflectors are absent. Despite this distinguishment in facies can be made between more reflective and less reflective intervals in this survey. The Donkersloot survey shows more detail but also more noise. However, differences in seismic facies are easier to pick up as well as the recognition of imaging disturbing features in the overburden. The used 3D seismic data is zero phase processed. The seismic polarity of the surveys is such that an increase in impedance is corresponding to a trough (negative number). In this report a trough is displayed in blue while a peak is displayed in red.

3.2 Literature and reports

Although numerous papers appeared on the structural geology, stratigraphy and the basin evolution of the West Netherlands Basin, the actual amount of ‘hard’ data, such as core descriptions and biostratigraphic data, that is presented in these papers is surprisingly low. The ‘richest’ paper is probably Jeremiah et al. (2010). This paper presents a stratigraphic framework for the WNB and displays several seismic and correlation panels and even some core descriptions. Unfortunately, the biostratigraphic data that underpin the stratigraphy in this paper are not disclosed. Apart from peer-reviewed papers, many consultancy reports and students theses on the West Netherlands Basin exist, many of which are listed in Chapter 7. The actual papers and reports are included in the digital deliverables of this project, the hyperlinks are included in Chapter 6. The papers and reports are briefly discussed in the next section.

Peer reviewed papers

Most publications focus on one or more sandstone units from the Upper Jurassic and Lower Cretaceous units, often in relation to the structural development of the basin. Three key publications are discussed below:

Van Adrichem Boogaert & Kouwe (1993)

Often referred to as “the nomenclature”, the publication contains a chapter on the stratigraphy of the Upper Jurassic to Lower Cretaceous of the West Netherlands Basin that is still very useful to the present day. All lithostratigraphic units, still valid today, are defined in that publication. The Upper Jurassic to Lower Cretaceous units are classified into two main groups, a predominantly non-marine group, the Schieland Group, and a marine group, the Rijnland Group (RV-06). The Transgressive nature of shoreface complexes towards the Oosterhout Platform/Zeeland High was already recognized.

Jeremiah et al. (2010)

This paper is the end product of an extensive study for NAM and is a follow-up of the DeVault & Jeremiah (2002) paper (RV-07). Jeremiah et al (2010) paper presents a sequence stratigraphic framework for the Lower Cretaceous (Ryazanian to Albian) of the WNB, the Broad Fourteens Basin, Vlieland Basin and Western Saxony Basin. The stratigraphic framework is constructed with a strong emphasis on maximum flooding surfaces, these serve as anchor points and correlatable horizons (RV-01). The age assessments are based on nannofossils and palynology, but the underlying data are not included in the paper. Figure RV-01 shows a simplified version of the Ryazanian to Barremian stratigraphy of the WNB and Broad Fourteens Basin, next to the palynological zonation of Duxbury that was used in the study. Figures RV-02, RV-03 and RV-04 show the link to TNO’s palynological zonation and an indication of the approximate ages of several lower Cretaceous lithostratigraphic units from the WNB.

Willems et al. (2020)

The first author Cees Willems conducted a PhD study at TU Delft on the geothermal aspects of the Upper Jurassic/Lower Cretaceous of WNB. This paper, co-authored by scientists from TU Delft, Panterra and TNO, can be regarded as the final result of these efforts. One important finding is the diachronous nature of the Delft Sandstone Member, see Figure RV-05.

Consultancy reports

Most consultancy reports are standard biostrat reports, but two reports are more elaborate and therefore discussed below:

Speksnijder (2011)

This Panterra study was conducted for the CATO project and included seismic analyses and well log correlations. The explanatory text in the report is kept to the bare minimum while emphasis was put on the 24 correlation panels (sic!) with 180 wells. Some biostrat from NAM reports is sort of less integrated in the correlation panels, but the dataset pre-dates the geothermal era, so no GT (geothermal) wells are included. A total of 19 seismic horizons is picked; 4 of which express excellent pick quality according to the author (Top De Lier FS, Base Rijswijk, Delfst Sst SB, Papekop Sst SB). Speksnijder proposes a rift phase with active horst and graben structures for the Schieland Group and a more uniform, bowl-shape basin development hinging on the NW-SE trending London-Brabant massif with minor normal fault movement near the southern basin margin (RV-08).

Interesting fact of this paper: Speksnijder erects two informal units within the Nieuwerkerk Formation: the Papekop and Pijnacker units, both representing stacked sandstone bodies.

Speksnijder also noted that a large part of the Alblasterdam-Delft-Rodenrijs-Rijswijk is represented twice in well NWK-02 due to a large reverse fault cutting through the well. Interestingly, the upper part (1100 – 1450m) is thicker than the lower part (1730 - 1930m), which is, according to Speksnijder, due to the fact that the fault was originally a normal fault that was active during deposition. DGM Deep 2021 largely agree with this, but also notes that another fault incepts around 1170m that probably also doubles part of the section (RV-09).

Papekop > fine-grained coarsening upward clastic sediment (KDZ-02; VAL-01) = base Schieland Groep; base Alblasterdam) only preserved in the structurally deepest grabens. AGE UNKNOWN

Pijnacker > regional (previously unrecognized) unconformity. Overlain by thick sandstone package. Angular relationship with underlying rocks on seismic.

RYAZANIAN

Other findings and conclusions according to the author:

Delft > total peneplanisation at beginning of Valangian. Easy to recognize on seismic and in well logs. NB Total Delft and Rodenrijs thickness is fairly uniform!

Delft and Rodenrijs comprise a blocky basal sand with sharp lower boundary; fining upward silts/shales often with abundant coal; and coarsening upward shales/siltst /sandstones. The regionally correlatable Rodenrijs flooding surface occurs at transition from fining upward to coarsening upward. EARLY VALANGINIAN
Rijswijk > Transgression during HAUTERIVIAN; Rijswijk sandstone thickness varies strongly.

Berkel and IJsselmonde Sandstones > only occur in the southern part of the basin. A number of flooding surfaces can be traced within and on top of these sandstones. In southern part of the basin IJsselmonde can almost directly overlay Schieland age terrestrial sediments (RZB-01).

De Lier Sandstone > flooding surface excellent pick. De Lier shales out from South to North. In the very South, De Lier overlies terrestrial Cretaceous/Upper Jurassic.

Melvin (2007)

An elaborate field study of the Q13 Amstel Field. Primarily sedimentology and reservoir architecture, focussing on the informal 'Amstel Sandstone' unit. The report includes core descriptions from several Q13 wells, including Q13-09. In addition, a paleogeographic reconstruction is provided (RV-10).

Student theses

Most theses are from TUDelft students and focus on reservoir character aspects of one or more sandstone units from the Schieland and Rijnland Group. A gradual shift in focus occurred over the years 2000 to 2020: from reservoir characteristics related to the oil and gas industry to aquifer thickness prediction and correlation related to geothermal projects. For all reports and student theses, please be aware that lithostratigraphic assignments, such as e.g. the Delft Sandstone Member, may have changed in time. For example the long core of well MKP-11, studied in e.g. Loerakker (2009), is listed as Delft Sandstone Member, but assigned to the Rijswijk Member of the Rijnland Group in our panels (RV-11).

Munsterman reports

Most of the reports from Munsterman provide age assessments based on palynological analyses. These results were used to correlate the producing aquifers of geothermal projects. In general, budgets of these projects were relatively low, resulting in uncertainties. Nevertheless, based on quantitative pollen and spore

data, a quite reliable age and correlation model was developed for the Delft Sandstone Member in which the Valangian Paratollia maximum flooding surface plays a key role (RV-12). This model was subsequently applied and published in e.g. Vondrak et al. (2018) and Willems et al. (2020) (RV-13).

Duxbury reports

During the late 90's and early 00's Duxbury produced a number of palynological reports focussing on Upper Jurassic and Lower Cretaceous sandstone units in the WNB for NAM. Most samples used for these studies were side-wall core and core samples, so these reports are quite important. Unfortunately, most of the studied wells were sampled in a low resolution, ranging from 2 samples per well to 20 samples. In the peer-reviewed paper Jeremiah et al. (2010), the results from the Duxbury studies were combined with nannofossil analyses (possibly from Jeremiah, but these data are nowhere to be found) and processed into a stratigraphic framework. Note that the zonation used changed from the first report to the last, as did the chronostratigraphic correlation. Also note that typographic errors in the well names occur.

JUSTRAT report

The JUSTRAT project was a large research project that was part of the so-called TKI innovation programme, funded for 50% by the Dutch government (RVO) and the other half by partners from the E&P industry. The research consisted of palynological and stable isotope analyses from many wells of the Dutch offshore, including the Broad Fourteens Basin (RV-14), the westernmost tip of the offshore part of the West Netherlands Basin (RV-15) and the Step Graben.

4 Stratigraphy

For the mapping project of the Upper Jurassic and Lower Cretaceous in the onshore part of the West Netherlands Basin, detailed well-to-well correlations are established. The results of the correlation exercise are displayed in correlation panels that were established in conjunction with the seismic analysis. Five correlation panels are oriented SW-NE, perpendicular to the basin axis (Figure 3), another three correlation panels are oriented NW-SE, along the basin axis (Figure 4).

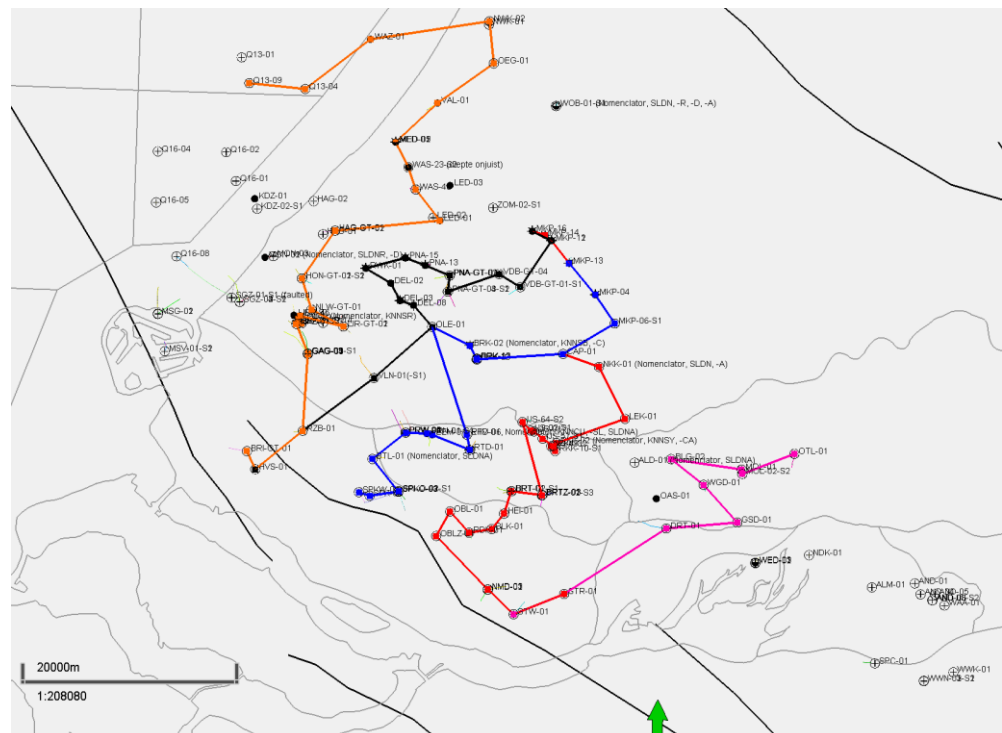


Figure 3 Location map of five SW-NE trending correlation panels, perpendicular to the basin axis. From NW to SE: panel SW-NE_1 (orange), panel SW-NE_2 (black), panel SW-NE_3 (blue), panel SW-NE_4 (red) and panel SW-NE_5 (pink).

Only wells with at least SP or GR logs were selected. In many cases these logs had to be digitized from CWL's or spliced based on separate LAS-files. If possible, preference was given to wells also containing DT logs. We added the cored intervals for the Upper Jurassic and Lower Cretaceous interval to the selected wells. For that purpose we used the GDN DINO database, the overview of cores hold at NAM in Assen and information from CWL's. Biostratigraphic information was added as comment to the wells, as were other observations such as errors, casing shoes or fault details. Faults were added as well tops in a separate well-top folder. Initially fault were numbered consecutively, later they were named with the well name, type of fault and information source.

The West Netherlands Basin is dissected by numerous faults, many of which were active at the time of deposition. The well-to-well correlations are based on the combination of wireline log signature and seismic imagery and are calibrated by

biostratigraphic data, in case these data were available. In order to maximize the information from biostratigraphy, an inventory of the available data and an assessment regarding the quality of the data was made. If possible, the age assessments derived from the inventory were annotated on the well sticks from the correlation panels and were also included in a separate spreadsheet. The annotated age assessments can be found in the digital deliverables of this project: in the Petrel file “WNB_DGM_Zuid_v3_RD_Petrel2020” and in the Excel file “Well list.xls”, the hyperlinks to the appropriate documents are included in Chapter 6.

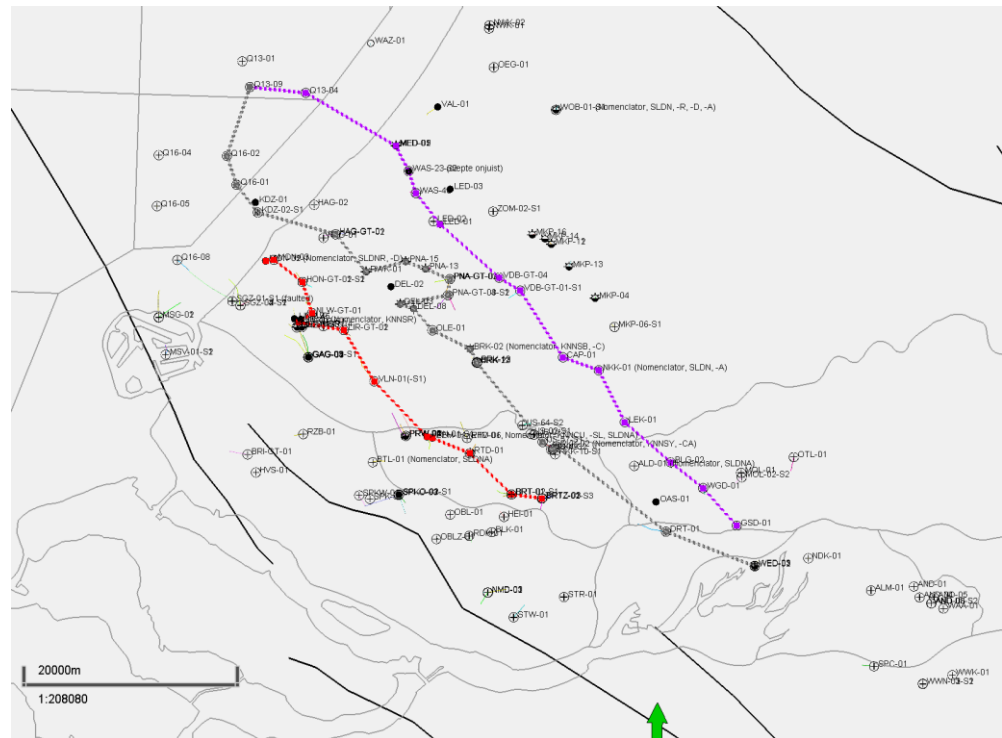


Figure 4 Location map of five NW-SE trending correlation panels, along the axis of the basin. From NE to SW: panel NW-SE_A (purple), panel NW-SE_B (grey) and panel NW-SE_C (red).

During the course of the project, it became apparent that the Rodenrijs, Delft and Alblasserdam members of the Nieuwerkerk Formation are poorly constrained in terms of lithology, age, geographic distribution and depositional setting. Because of its economic importance with respect to geothermal energy, a proposal for a systematic sedimentological and bio- and chemo-stratigraphic study on the Nieuwerkerk Formation was set up in conjunction with Panterra Geoconsultants as a sideline to this mapping exercise. A hyperlink to the proposal is included in Chapter 6.

5 Seismic

5.1 Seismic facies and picked reflectors

The Lower Cretaceous interval is overlain by either the Upper Cretaceous Chalk Group or the Paleocene Lower North Sea Group. In the latter case a clear angular unconformity can be observed at the top of the Vlieland Formation in many places. If the Chalk Group is present the base of the limestones interval is a clear soft kick (impedance decrease, peak). While the Ommelanden consists of limestones the Texel formation is more clastic in nature in this area. This means that the base overlying the Upper Holland Marl Member is not always that clear.

The Holland Formation itself is reflective by nature. This is caused by the alternation of marls, shales and greensands. Especially the base of the Upper Holland Marl member is a very clear reflector, but also the bases of the Middle Holland Claystone Member and of the Lower Holland Marl member can be correlated over large distances, the latter representing the top of the De Lier Sandstone Member or the Vlieland Claystone Formation. In some places the Holland Greensand and Spijkenisse Greensand Members are present. In places where hydrocarbons are present in these intervals bright- and flatspots can be visible.

The upper part of the Vlieland Formation is generally quite transparent in seismic character. The claystone intervals are quite homogenous in acoustic properties. Only if sandy intervals appear in the sequence more reflectivity is observed. In this study the tops of the IJsselmonde and the Berkel Sandstone Members are picked and correlated. Although the tops are not always a consistent increase or decrease in acoustic impedance on logs it is possible to pick an event that is close to the top of the intervals. The top IJsselmonde sst is chosen to be picked on a peak, which is right in case the sandstone is well developed with a reasonable porosity. As soon as the sandstone is less well developed (thin, shalier) or is more cemented the picked peak does not necessarily correspond exactly to the top. The picking of the top Berkel sst is challenging. In some areas there is a distinct trough close to the top Berkel Sandstone Member, while in other areas a peak is clearly dominant. In the synthetics from CAP-01 (Figure H7) it is shown that at this location the top Berkel picked on the GR is not corresponding to a trough or peak but is close to a zero crossing. Already above the actual picked top Berkel there is an increase in Acoustic Impedance. The higher AI values continue in the top part of the Berkel but drop to lower values in the "cleaner" sandstone interval below. This results in a trough peak combination around the actual top Berkel. It is the interference pattern partly caused by these thin high velocity/high density intervals that define the seismic character of the top Berkel. The effect of these relatively thin cemented zones that vary laterally is making the exact picking of the tops on seismic impossible. The difficulty in picking the right phase makes the interpretation of top Berkel rather uncertain. Although the exact pick is difficult the "near" top Berkel can be interpreted and correlated as the uppermost reflector of a relatively reflective interval, especially in places where the IJsselmonde Sandstone is absent. The reflectors corresponding to the tops of these intervals can also be interpreted outside the areas where the sands are well developed. From log correlation it is evident that log patterns can still be correlated outside the areas where these sands are developed in a sandy facies. The corresponding seismic reflectors correlated

over large areas are probably more chronostratigraphic events than lithostratigraphic boundaries.

5.2 Regional geology and syn-sedimentary thickness changes

Two unconformities resulting from two major tectonic phases encompass the Upper Jurassic and Cretaceous strata. The Mid-Kimmerian event at the base of the Nieuwerkerk Formation (base Alblasterdam Member) and the Sub-Hercynian inversion event at the top of the Ommelanden Chalk are expressed as clear (angular) unconformities in the seismic data. During the Sub-Hercynian inversion many normal faults transecting the Upper Jurassic-Lower Cretaceous sequence have been reactivated as reverse faults. Essentially the faults that are running NNW-ESE are most prone to reactivation and the inversion structures are arranged in an en-echelon pattern, where the pop-ups tend to align along WNW-ESE structures, though the dominant fault trend is running NW-SE. This is nicely demonstrated in Figure H2 showing the TWT map of the base KNGLU where pop-ups are arranged along three NW-SE running faults systems in an en-echelon way trending slightly obliquely to the main fault trend.

(Figure H2)

Many of the inverted, originally normal faults show thickness changes of the Upper Jurassic-Lower Cretaceous sequence. Besides these faults there are normal faults affecting the thickness that have not been reactivated during the inversion phase. Comparing the thickness of the Upper Jurassic Schieland Group derived from the DGM 5 model with the thickness of the Lower Cretaceous Rijnland Group from the same model there are remarkable differences in the way the thickness is distributed. The thickness map of the Schieland Group shows rapid variations in thickness over short distances along faults, with local depocentres on the hanging wall of faults and reduced thickness on the footwall structural highs. Surprisingly the variation over short distances is even larger than thickness changes in the interval between the Posidonia shale and base Schieland Group. Either a paleotopography has been filled in rapidly during the deposition of the Schieland Group or some of the local faults were active in this period (or a combination). The thickness of the Rijnland Group shows less rapid variations and it appears that the WNB has subsided gradually with the depocenter in the middle of the bowl shaped basin. However, there are still faults that show steps in thickness indicating synsedimentary fault activity in this Lower Cretaceous period.

(Figure H8)

In this study thickness changes along faults have been analysed by extracting the (time)thickness between two reflectors that are quite prominent and, in most places, interpretable without much uncertainty. The derived thickness is hence not very sensitive to potential mispicking of the reflector and steps in thickness over faults are indicative to synsedimentary fault movement. The base of the Upper Holland Marl member (KNGLU) and the base of the Lower Holland Marl member (KNGLL) have been used to make a time thickness map of this interval. It is clear from observations on seismic data that the thickness changes in the Vlieland subgroup correlate very well with thickness changes in the Holland Formation. In places where seismic quality is poorer and correlation of Vlieland reflectors is difficult

thickness changes of the more reflective Holland can be used to help the intra-Vlieland correlation.

In Figure H4 the time thickness of the Middle and Lower Holland is displayed. Along faults there are some sharp thickness anomalies which are caused by calculating thickness over reverse faults resulting in locally increased thickness. Comparing the thickness of this Holland interval with the present depth (in TWT) of the Base Upper Holland (KNGLU) it is clear that as well on a basin scale as on sub-basin scale the areas with the thickest Lower and Middle Holland have experienced the strongest inversion. In Figure H4 this inverse correlation between the Holland thickness and present day depth is illustrated. Also in SW_NE seismic panel 3 (Appendix XXX) the thickness increase of the Holland formation from the platform area in the SW toward the Berkel area is evident, showing the thickest section in the area that is currently at shallowest depth. The former normal faults that have contributed to the higher accommodation space during deposition have later been reactivated as reverse faults bringing the thicker sections to shallower depth. The inverted hangingwall sediments put loading pressure on the footwall sediments causing these to subside and subside resulting that the thinner Holland intervals are currently deeper buried than the thicker intervals.

(Figure H4 and H5)

In Appendix 3 composite seismic sections are shown that are close to some of the well panels (Appendix 2). Of each section there is an uninterpreted version and a version with interpretation. Seismic Panel 1 (Appendix 3a) has also a version that is flattened on base KNGLU to illustrate the lower Cretaceous thickness changes. On the seismic panels GR/SP logs and well tops are displayed. In order to display these data in time Time-Depth curves have been used based on regional velocity models. This gives in general a decent match in time but is not 100% accurate, resulting in (small) mismatches between well tops and interpreted horizons.

Seismic Panel 1 (Appendix 3a) runs SW-NE across the western part of the WNB running from the RZB-01 area through the centre of the basin (HON-HAG-LED) to the Wassenaar area. While RZB-01 and GAG-01 are located on the “platform” area with relatively thin Lower Cretaceous sediments the thickness increases over the boundary fault with LIR_40 and MNZ-01 NE of this fault located in the hanging wall fault block. This fault block is currently at shallower level as a result of inversion along this boundary fault. The LC thickness continues to increase toward the NE culminating in the strongly inverted LED-WAS area but drastically decreasing in the VAL-01/OEG-01 area and slightly increasing in the offshore Q13 block. The variation in thickness is also illustrated in map form by the thickness of the Middle and Lower Holland in Figure H4.

Seismic Panel 2 (Appendix 3b) runs NW-SE along strike through the central part of the WNB from the offshore Q13/Q16 blocks through the strongly inverted Pijnacker area to the Berkel and IJsselmonde/Ridderkerk area. The thickness of the Lower Cretaceous sediments are fairly constant along the axis of the WNB. There is however a change in facies of the lower part of the sequence grading from marine sediments of the Vlieland Group into continental fluvial sediments of the Alblasserdam Member. The reflectors on the seismic sections representing timelines can however be correlated despite the facies change. Effectively it means that correlating a reflector at Rijswijk sandstone level in the NW ends up in the

Alblasserdam in the SE, though it is probably still the same timeline. This diachronicity with Alblasserdam in the SE lying next to the marine facies in the NW is also illustrated in Figure H9 between the VLN-01 well and the RTD-01 well.

Seismic Panel 3 (Appendix 3c) runs from the Spijkenisse area in the SW along the Rotterdam and Berkel area to the elevated Moerkappelle block. The Spijkenisse wells in the SW are located on a platform area with relatively thin LC sediments. Thicker basinal sequences are found crossing two inverted boundary faults towards the NE in the well EEM-01 gradually further increasing in thickness to the Berkel area. After crossing an inverted normal fault the sediments are thinner in the footwall to the NE drilled by the CAP-01 well. The section ends in the Moerkappelle block where LC sequences are very thin and eroded at the top by the base of the North Sea Group.

6 Archive

Paleoenvironmental information

Reports and theses that provide information on paleoenvironment are located here. The documents are organized per lithostratigraphic unit. Note that the collected documents are far from complete, more documents should be added.

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Stratotype sections

Composite well logs displaying the holo- and para-stratotype sections of all formations and members of the Rijnland and Schieland groups from the WNB are archived here. The composite well logs are derived from the stratigraphic nomenclator of NLOG.

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QC-sessions

Peer-assist sessions were organized in order to maintain the quality of the output. Especially colleagues from AGE participated in these sessions. The presentations and feedback of these sessions are archived here.

"\\tsn.tno.nl\data\sv\sv-070739\Peer-assist_WNB_20 april 2021"

Well data

265 wells are listed in this Excel sheet. For each well the following boxes are checked:

- B Biostrat available
- C Core description available
- D CORE in Schieland or Rijnland Group
- E Type section for lithostratigraphic unit from Schieland or Rijnland Group
- F included in JUSTRAT report
- G included in Willems 2017
- H included in Willems 2020
- I included in Panterra CYCLOG
- J included in Jeremiah 2010
- K included in DeVault
- L included in 2002 DGM Diep
- M included in SPEKSNIJDER report
- AH to AY are age indicators, with the appropriate depth allocated

"\\tsn.tno.nl\data\sv\sv-070739\BIO & LITHOSTRAT\Wells\Well list WNB_DGM Zuid.xlsx"

Petrel project

Because of workability, the work on the stratigraphy was organized and saved in a separate Petrel project than the work on the seismic. The Petrel project with the latest stratigraphy is saved here.

"\\tsn.tno.nl\data\sv\sv-070739\Petrel\WNB_DGM_Zuid_v3_RD_Petrel2020_30-11-2021"

The work on the seismic is saved here.

"\\tsn.tno.nl\data\sv\sv-070739\Petrel\WNB Handover HDH"

Report and appendices

The progress report and the figures and appendices included in the report are here.

"\\tsn.tno.nl\data\sv\sv-070739\Rapportage"

7 References

Peer reviewed literature

Den Hartog Jager, D.G., 1996. Fluvio-marine sequences in the Lower Cretaceous of the West Netherlands Basin: correlation and seismic expression. In *Geology of gas and oil under the Netherlands* (pp. 229-241). Springer, Dordrecht.

DeVault, B. and Jeremiah, J., 2002. Tectonostratigraphy of the Nieuwerkerk formation (Delfland subgroup), West Netherlands basin. *AAPG bulletin*, 86(10), pp.1679-1707.

Donselaar, M.E., Groenenberg, R.M. and Gilding, D.T., 2015. Reservoir geology and geothermal potential of the Delft Sandstone Member in the West Netherlands Basin. In *Proceedings world geothermal congress* (p. 9).

Jeremiah, J.M., Duxbury, S. and Rawson, P., 2010. Lower Cretaceous of the southern North Sea Basins: reservoir distribution within a sequence stratigraphic framework. *Netherlands Journal of Geosciences*, 89(3-4), pp.203-237.

Racero-Baena, A. and Drake, S.J., 1996. Structural style and reservoir development in the West Netherlands oil province. In *Geology of gas and oil under the Netherlands* (pp. 211-227). Springer, Dordrecht.

Van Adrichem Boogaert, H.A. & Kouwe, W.F.P., 1993. Stratigraphic nomenclature of the Netherlands, revision and update by RGD and NOGPA, Section A, General. *Mededelingen Rijks Geologische Dienst* 50: 1–40.

Vondrak, A.G., Donselaar, M.E. and Munsterman, D.K., 2018. Reservoir architecture model of the Nieuwerkerk Formation (Early Cretaceous, West Netherlands Basin): diachronous development of sand-prone fluvial deposits. *Geological Society, London, Special Publications*, 469(1), pp.423-434.

Willems, C., Nick, H.M., Weltje, G.J., Donselaar, R. and Bruhn, D., 2015. Influence of fluvial sandstone architecture on geothermal energy production. In *World Geothermal Congress 2015*.

Willems, C., 2017. Doublet deployment strategies for geothermal Hot Sedimentary Aquifer exploitation: application to the Lower Cretaceous Nieuwerkerk Formation in the West Netherlands Basin.

Willems, C.J., Vondrak, A., Munsterman, D.K., Donselaar, M.E. and Mijnlief, H.F., 2017. Regional geothermal aquifer architecture of the fluvial Lower Cretaceous Nieuwerkerk Formation—a palynological analysis. *Netherlands Journal of Geosciences*, 96(4), pp.319-330.

Willems, C.J., Nick, H.M., Donselaar, M.E., Weltje, G.J. and Bruhn, D.F., 2017. On the connectivity anisotropy in fluvial Hot Sedimentary Aquifers and its influence on geothermal doublet performance. *Geothermics*, 65, pp.222-233.

Willems, C.J., Vondrak, A., Mijnlief, H.F., Donselaar, M.E. and Van Kempen, B.M., 2020. Geology of the Upper Jurassic to Lower Cretaceous geothermal aquifers in the West Netherlands Basin—an overview. *Netherlands Journal of Geosciences*, 99.

BSc, MSc and PhD theses

Bussmann, M.C., 2014. Identifying overlooked exploration opportunities from bypassed pay analysis. MSc Thesis UU internship at EBN, supervised by Jan de Jager (UU) and Jan Lutgert (EBN).

Drost, G.I.A. & Korenromp, M.H.A., 2009. Sediment-petrographical analysis of the Delft Sandstone. BSc Thesis TUDelft, supervised by Donselaar.

Gilding, G.D., 2010. Heterogeneity determination of the Delft subsurface for heat flow modelling. MSc Thesis TUDelft AES/PE/10-04, supervised by Bruining, Donselaar & Wolf

Loerakker, M., 2009. A core study to determine the heterogeneities in the Delft Sandstone Member in the Moerkapelle Field. BSc Thesis TUDelft BTA/TG/09-21, supervised by Donselaar.

Persoon, R.M.N., 2011. Q13a Amstel Field Development. MSc Thesis TUDelft AES/PE/11-01, internship at TAQA Energy, supervised by Vroemen & Bruinen (TAQA Energy).

Van Wijk, C.L., 2002. Structural Definition and Risk analysis of the Lekkerkerk Field. MSc Thesis TUDelft TA/PW/02-07, internship at NAM, supervised by prof. Luthi (TUDelft) and NAM staff.

Wiggers, C.J.I., 2009. The Delft Sandstone in the West Netherlands Basin. BSc Thesis TUDelft TA3006, supervised by Donselaar & Wolf.

Willems, C., 2012. Study of the Lower Cretaceous sands in the Van den Bosch Geothermal energy concession. MSc Thesis TUDelft AES/TG/12-44, internship at Panterra Geoconsultants, supervised by Weltje (TUDelft).

JUSTRAT report

Verreussel et al., 2015. New stratigraphic framework for the Upper Jurassic-Lower Cretaceous in the southern North Sea using integrated novel techniques. TNO 2015 report R10343, JUSTRAT Project.

Munsterman reports

Munsterman, 2012. TNO-060-UT-2011-02200/B. De resultaten van het palynologische onderzoek naar de ouderdom van de Onder Krijt successie in boring Van den Bosch-04 (VDB-04), interval 925-2006m.

Munsterman et al., 2014. TNO report 2014 R11302. Biostratigraphy of well Numansdorp-3 (NMD-3), Hoeksche Waard, The Netherlands.

Munsterman et al., 2014. TNO report 2014 R10516. Biostratigraphy from the Jurassic-Cretaceous successions of 5 wells in the Hoeksche Waard, The Netherlands.

Munsterman, 2015. TNO-rapport 2015 R11740 (confidentieel). De resultaten van het palynologisch onderzoek naar de ouderdom van de geothermieboringen Honselersdijk-1 (HON-GT-01) en Pijnacker-2 (PNAGT-02).

Munsterman, 2016. TNO report 2016 R10482. Results of the palynological analysis of geothermal well Pijnacker 2 (PNA-GT-02), interval 2440-2850m.

Munsterman, 2017. TNO report 2017 R10085. De resultaten van het palynologisch onderzoek naar de ouderdom en facies van de geothermieboring Honselersdijk-02 (HON-GT-02).

Munsterman, 2018. TNO-rapport xxxx. De resultaten van palynologisch onderzoek naar de ouderdom en facies van de geothermie boring Lansingerland (LSL-GT-01), interval 1980-2690m.

Munsterman et al., 2010. TNO-034-UT-2010-00636 The biostratigraphical results of well Q13-05. A study of the Rijnland-Chalk Group, Holland-Texel Formation transition.

Munsterman, 2019. TNO 2019 R10117. De resultaten van het palynologische onderzoek naar de ouderdom en facies van boring Eemhaven-01 (EEM-01), (wand)kerninterval 1899-2455m (waarvan in bijzonder kerninterval 2019-2079,6m).

Munsterman, 2019. TNO 2019 R10566. De resultaten van het palynologische onderzoek naar het Onder-Krijt van de geothermische boringen Brielle-GT-01 (BRI-GT-01) en Maasland-GT-01 (MLD-GT-01).

Munsterman, 2019. TNO 2019 R11510. De resultaten van het palynologische onderzoek naar de kernen van de Rijswijk Member in boring Monster-02 (Westland).

Duxbury reports

Duxbury, 1999. Project No. 99/131. West Netherlands Basin: A Biostratigraphical Review of the De-Lier, IJsselmonde and Berkel Complex.

Duxbury, 1999. Project No. 99/139. Biostratigraphic Calibration of the Rijswijk and top Delfland in the West Netherlands Basin.

Duxbury, 2000. Project No. 00/152. West Netherlands Basin: A Biostratigraphical Review of the Lower Cretaceous Delfland Group.

Duxbury, 2000. Project No. 00/162b. A Biostratigraphical Analysis of Selected Samples from West Netherlands Basin Wells De Lier-2A and IJsselmonde-1.

Duxbury, 2002. Project No. 01/202. A Biostratigraphical Analysis of Selected Samples from West Netherlands Basin Wells De Lier-14 and Pernis-1A.

Consultancy reports

Speksnijder, A., 2011. Framework of Lower Cretaceous and Upper Jurassic clastic reservoirs and seals in the West Netherlands Basin. Panterra Report No. G841 for CATO, 30pp, 7 appendices including 24 correlation panels.

Melvin, A., 2007. Depositional architecture and characterization of the Early Cretaceous Upper Schieland and Lower Rijnland Group sandstone reservoirs, West Netherlands Basin, Q13 offshore The Netherlands. AM Geos Ltd. report for Island Oil and Gas PLC, 38pp, lots of figures, 8 appendices.

Lister, J.K., 1994. Biostratigraphy of 26 core samples from the Q13-9 well offshore Netherlands. Stratigraphic Services International Ltd. (SSI) report B0498 for PanCanadian Petroleum International. 24pp, 4 appendices and enclosures.

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