AES/TG/11-34  Mapping of the Vlieland Sandstone Formation in the northern Netherlands onshore area

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TU Delft
Department of Geotechnology  Delft University of Technology
Title : Mapping of the Vlieland Sandstone Formation in the northern Netherlands onshore area

Author(s) : Ewout Johannes van Pelt

Date : September 2011
Professor(s) : Dr. G.J. Weltje
Supervisor(s) : Dr. M.E. Donselaar
              Dr. J.H. ten Veen
              Dr. H. Kombrink

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Postal Address : Section for Applied Geology
                Department of Applied Earth Sciences
                Delft University of Technology
                P.O. Box 5028
                The Netherlands

Telephone : (31) 15 2781328 (secretary)
Telefax : (31) 15 2781189

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Abstract

One of the important aquifers for geothermal purposes in the Netherlands is the Lower Cretaceous Vlieland Sandstone Formation (VSF). The VSF is deposited in a eustatic transgressive phase and has a dispersed distribution in the northern Netherlands, which is not very well understood. This study produced a depositional model and a thickness map for the VSF, based on available wells, biostratigraphy, cores and seismic data. The area of investigation is the northern part of the onshore Netherlands: Groningen, Friesland, Drenthe, the Wadden area. Regional tectonics and faulting determined the formation of the depocentres: the Vlieland and Lower Saxony basins. Subrosion and halokinetic effects in the Zechstein strata affected the paleogeography and influenced the deposition of VSF. In the early transgressional stage (Ryazanian, Valanginian), the basins are probably separated by the Friesland Platform, which is probably flooded during the Late Valanginian. Sandstones deposited at the end of the transgression (Hauterivian, Barremian) are found on the Friesland Platform and in the Lower Saxony Basin. Most VSF on the platform is reworked and the preserved sandstones represent mainly lower shoreface facies. This study shows that previous depositional models are outdated and comes up with a new depositional model and thickness map of the VSF.
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Introduction

Context
In order to quickly assess the geothermal potential of an arbitrary location in the Netherlands onshore area, TNO has developed the publicly available information system ThermoGIS™. This application can be used both for exploration (site-selection) as well as for policy making. Reservoir data of over 10 potential subsurface aquifers can be easily retrieved. An important aquifer is the Lower Cretaceous Vlieland Sandstone Formation.

The Vlieland Sandstone Formation
The Vlieland Sandstone Formation (VSF) belongs to the Rijnland Group (Van Adrichem Boogaert & Kouwe, 1993) and is divided in several members, of which the Friesland Member (KNNSF) is present in the northern Netherlands (Herngreen et al., 1991). The VSF was deposited following a Jurassic rifting event, during a period in which thermal subsidence became important. Simultaneously, a new eustatic transgressive phase began. The Friesland Member represents the transgressive coastal-barrier sands deposited during the transgression in the northern part of the Netherlands onshore. It is overlain by the open-marine mudstones of the Vlieland Claystone Formation (Herngreen & Wong, 2007). The Friesland Member reaches a maximum of 160 m in the Zuidwal Field in the Wadden Sea, but is less than 50 m or absent in large parts of the northern Netherlands (Cottonçon et al., 1975).

Many wells in the northern part of the Netherlands onshore area penetrated the basal sandstones of the VSF, but since they did not serve as the primary target for most wells, detailed studies of the distribution of the VSF have not been performed in the public domain. The main aim of this study is to produce a reliable depositional model for the Friesland Member, based on a detailed review of all available well, seismic and core data. This model could serve as an input for ThermoGIS™.

Research topics
The study consists of the following activities:
- getting a better understanding of the distribution of the VSF by studying the available well logs and cores,
- studying the Base Cretaceous unconformity on seismic data,
- reconstructing the paleogeography,
- constructing a geological conceptual model of the facies distribution and thickness variations.

Deliverables
The deliverable for the completed project is a conceptual depositional model and a thickness map of the Vlieland Sandstone Formation.
Acknowledgements
I want to thank a number of people who helped me a lot during my project. The colleagues at TNO are thanked for the nice environment to work and the social moments. Some of them were a great help in the process of this thesis as well. Nora Witmans and Peter Fokker are thanked for introducing me to TNO, in March 2004 already. It was a great pleasure to be back and to do my thesis at TNO. Dirk Munsterman and Roel Verreussel interpreted the palynological data, which are an important part of my dataset. Kees van Ojik and Jan Penninga (NAM) are thanked for the raw data they provided and the possibility to study some cores in their excellent core shed. TNO is also thanked for the possibility to join in a 3 day Applied Ichnology Course. Johan ten Veen, one of my supervisors at TNO, was helpful in the whole project, but especially in the seismic interpretation part. Harmen Mijnlieff is thanked for his advice during the project, which is really appreciated. Rick Donselaar and Gert Jan Weltje (TU Delft) are thanked for their input, Rick with the core study and Gert Jan in the whole project. Finally I want to thank Henk Kombrink, the other supervisor at TNO, for supervising my project, but also for taking care of me during my internship and for the first review of this report.
Regional geology

The Vlieland Sandstone Formation
The area of investigation is the northern onshore part of the Netherlands, comprising roughly the provinces Groningen, Friesland, Drenthe, the Frisian Islands and the Wadden Sea. It is bounded to the east by the Dutch-German border, in the south by the 52º 30’ N latitude and in the south-west by the former Texel-IJsselmeer High, see Figure 1.

The Vlieland Sandstone Formation (VSF) is found at the base of the Cretaceous succession, which unconformably overlies older rocks. The depth of the base of the VSF varies from less than 1000 meter in the south-eastern part of the study area to over 2500 meter in the western part (see Figure 2). The most recent thickness map is published by Herngreen et al. (1991) (see Figure 3). The thickest parts are found in the Zuidwal field, in the middle of the Vlieland Basin, where it reaches a thickness up to 140 meters. The VSF shows a dispersed but much thinner succession on the Friesland and Groningen Platforms. In the Lower Saxony Basin, on the eastern side of the Friesland Platform, the Vlieland sandstone is divided in several members, the Bentheim Sst Mb is of Valanginian age and the Gildehaus Sst Mb is of Hauterivian age. The Friesland sst Mb. In the Vlieland Basin is of Late Ryazanian to Lower Hauterivian age (Wong et al. 2007). The Gildehaus and Bentheim sandstone members are deposited in a comparable transgressive stage, migrating up to the Groningen Platform from the Lower Saxony Basin. They show a decreasing thickness towards the platform too.

The Vlieland Sandstone Fm is overlain by the Vlieland Claystone Fm, which is unconformibly overlain by the Holland Fm, of Aptian and Albian age (Herngreen et al., 1991).

Tectonic development of the area
In the study area, the structural elements are the Texel-IJsselmeer High, the Vlieland Basin, the Friesland and Groningen Platforms, and the Lower Saxony Basin (see Figure 1). Herngreen et al. (1991) suggested that the Vlieland Basin was initiated as a pull-apart basin, tectonically related to the North Sea Central Graben and the Lower Saxony Basin. The NW-SE trending faults have been established in the Variscan Orogeny, or possibly even as a result of Caledonian events (Herngreen et al., 1991). Right lateral strike slip movements along these faults resulting in a pull-apart basin are related to the Cimmerian tectonics (Herngreen et al., 1991). After the volcanic event during the Oxfordian, the basin widened and deepened during Late Jurassic and Early Cretaceous times, by the combination of load of the volcanics, thermal relaxation of the lithosphere and the subsequent load by sediment infill (Herngreen et al., 1991). Finally the Alpine Orogeny resulted in deformation of the basin.
Figure 1; Early Cretaceous structural elements. Kombrink et al. (in prep)
Figure 2; Depth of Rijnland Group. (Wong et al., 2007)

Figure 3; Thickness map of Vlieland sandstone as it was interpreted in 1991 (Herngreen et al., 1991)
Subcropping strata
The Vlieland basin developed during the Late Jurassic, and sediments of this age are found in the areas around the Zuidwal and Harlingen gas fields. Herngreen et al (1991) assigned these sediments to the Delfland Fm, where previous authors (Cottencon et al., 1975) regarded these sediments as Wealden Fm. Jurassic sediments are subcropping in the Lower Saxony Basin as well. In the platform areas in between these basins, Early Cretaceous sediments unconformably overlie mainly Triassic and Zechstein strata, but locally (Texel IJsselmeer High) Carboniferous rocks are present below the Base Cretaceous unconformity (see Figure 3). A detailed study of the effects of the subcropping strata on the distribution of the VSF is discussed in chapter Subcrop.

Figure 4; Subcrop map Base Cretaceous. Dots indicate well locations. Subcrop polygons based on mapping of the Dutch subsurface (TNO).

Sedimentology of the Vlieland Sandstone
The sedimentology of the Vlieland Sandstone is described by Cottencon et al (1975) and in more detail by Perrot & Van der Poel (1987). Perrot & Van der Poel distinguished 9 different facies types in the Zuidwal and Oude Inschot wells, from shale, via shaly fine grained sand, to sandstones with different types of cement. They suggest that the lower part of the sandstone in these wells was deposited in a period of NW-SE transgression. While shallow marine conditions stabilized, a fine, shaly sandstone was deposited, followed by an influx of sandstone. Ongoing transgression deposited a fining upward combination of argillaceous sandstone and Vlieland Claystone Formation, which seals the gas reservoirs in the Lower Cretaceous reservoirs.
Figure 5; Stratigraphical chart of the Vlieland Basin, Terschelling Basin and Central Graben, Van Adrichem Boogaert & Kouwe (1997)
Figure 6; Stratigraphical chart of the Lower Saxony Basin, (Van Adrichem Boogaert & Kouwe, 1997)
Palaeogeography

Two publications deal with the palaeogeography of the area. The first is the Geological Atlas of Western and Central Europe by Ziegler (1990). It is based on both sedimentological and tectonic data. The main structural elements and sediment transport directions are illustrated on his maps, of which a detail is shown in figure 7. According to Ziegler, a small connection between the Central Graben and the Lower Saxony Basin was established during the Berrasin – Valanginian.

A second publication dealing with palaeogeography, by Jeremiah (2011), was published during the end of this thesis work. This reconstruction is mainly based on biostratigraphical data. According to this study, a much wider connection existed between the Lower Saxony Basin and the Central Graben, see figures 8 and 9.

This thesis work, focusing on understanding the distribution of the transgressive Vlieland Sandstone Fm, will also present facies distribution maps (see chapter Discussion).
Figure 8; Regional facies map: K20 sequence Polyptychites Zone (Early Valanginian). Note for all facies; lighter shading depicts areas of post and syn-depositional erosion. Jeremiah et al., 2011.

Figure 9; Regional facies map: K30 sequence regale Zone (Early Hauterivian). Jeremiah et al., 2011.
Data set

The data set in the area of investigation comprises 2D and 3D seismics, well logs, cores and biostratigraphical data. More than half the area is covered with 3D seismic (see figure 10). About 970 wells in the area reach the base Cretaceous, of which 418 lie in the Schoonebeek area. Different well logs and a lithostratigraphic subdivision are available for most of these wells. In about 435 wells no Vlieland sand is found (figure 10, white dots), in the others the thickness of sand varies from less than a meter to 190m (figure 10, colored dots).

Cores and cuttings are available for 85 wells (figure 10, blue dots) in the TNO core shed, while some additional cores were studied at the NAM core facility. Biostratigraphical datings of 12 wells are available from TNO reports. NAM also provided palynological raw data from the lower Cretaceous in 53 wells (figure 10, red dots), 20 of them are interpreted at TNO by Dirk Munsterman and Roel Verreussel.

Figure 10; Data set Vlieland sandstone. In purple the outline of the research area, in grey the areas covered with 3D seismics. The dots represent wells penetrating the Base Cretaceous, with white dots for wells in which no Vlieland Sandstone Fm was found and coloured dots for the wells in which Vlieland Sandstone Fm was found. Blue and red dots indicate wells in which cores were taken, of which the red dots are biostratigraphically interpreted.
Methodology and Results

Different methods are used to process the data set. A number of cores have been studied to gain facies information, the dataset has been handled to get thickness maps using stochastical methods, biostratigraphical data has been interpreted, a subcrop map has been created and finally both well logs and seismic data have been studied to understand the depositional setting of the VSF. This chapter handles these different methods in separate subchapters, providing both the results and a first step to the interpretation of these results. For further interpretation, see chapter Discussion.

Core study

Five cores were studied in the TNO core shed in Zeist, and three cores were studied at the NAM core facility in Assen. The objective of this core study was to get a correlation between the well logs and the facies of the rock itself. The results of these core studies can be found in Appendix A - Core study. The cores in Zeist are carefully studied and represent a large part of the dataset. The cores in Assen were studied in a one day visit and are therefore only roughly described, but they proved to be a valuable addition to the described facies and their variability, representing cores from areas that are not present in the TNO core shed.

High resolution gamma ray logs from the original LAS files are depth calibrated with the cores, using e.g. clay-sand transitions and cemented intervals. A rough description of the whole core is made and in more detail GR trends are investigated to see what they represent in the core. Finally a facies interpretation of the core is given.

A facies log with this interpretation is added to the corresponding wells in Petrel. The GR – facies correlation found in this 8 studied wells is manually extrapolated to other wells in the Petrel project.

Results

Facies types

Four types of facies are distinguished in the studied cores, see Table 1. A facies log was added in the well section panels in Petrel. These facies logs were filled with facies described in the studied cores (see Table 2). Based on the log expression of the different facies in these wells, facies logs were created for the other wells as well.

Two well section panels were created along a W-E cross-section and an NW-SE cross-section through the Vlieland Basin and the Friesland Platform. These well section panels are flattened on the base Holland Fm and relatively spaced, based on their real position. The zones within the lithostratigraphic horizons (the well tops) are colored: yellow for
the VSF, gray for the Vlieland Claystone Fm, light and dark green for respectively the Holland Fm and the Chalk Gp.

Table 1; Facies types

<table>
<thead>
<tr>
<th>Facies type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper shoreface</td>
<td>very well sorted, clean sand</td>
</tr>
<tr>
<td>Lower shoreface</td>
<td>well sorted, bioturbated, low shale content</td>
</tr>
<tr>
<td>Marine</td>
<td>shale</td>
</tr>
<tr>
<td>Mouth bar / storm layer</td>
<td>poor sorting, (very) coarse grains and clasts, high clay content.</td>
</tr>
</tbody>
</table>

Some of these intervals interpreted as mouth bar, others may be storm layers.

Table 2; Facies found in cores

<table>
<thead>
<tr>
<th>Core</th>
<th>Facies Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suawoude-3</td>
<td>lower shoreface</td>
</tr>
<tr>
<td>Opeinde-1</td>
<td>lower shoreface, storm layer</td>
</tr>
<tr>
<td>Opeinde-2</td>
<td>upper shoreface, lower shoreface, storm layer</td>
</tr>
<tr>
<td>Noordwolde-1</td>
<td>mouth bar, lower shoreface</td>
</tr>
<tr>
<td>Zuidwal-1</td>
<td>lower shoreface</td>
</tr>
<tr>
<td>De Wijk-17A</td>
<td>storm layer</td>
</tr>
<tr>
<td>Wanneperveen 1</td>
<td>storm layer, shale, lower shoreface</td>
</tr>
<tr>
<td>Schoonebeek 495A</td>
<td>upper shoreface, lower shoreface, shale.</td>
</tr>
</tbody>
</table>

From the studied cores a correlation of GR and facies was derived. These GR logs are calibrated to the API standard and should therefore be comparable, but in practice the GR values of uniform lithostratigraphic units differ a lot between wells. To compare well logs, the maximum GR values are truncated at a maximum of 150 and the shale content is determined as a ratio of the cleanest sand readings and the maximum shale readings.

Upper shoreface is sand with a shale content of maximum 0.2, lower shoreface has a shale content between 0.2 and 0.5 and everything with a higher shale content is lumped in the marine facies. No distinction is made between marine muds, lagoonal muds and fluvial muds, as they all show the same gamma ray readings and they are all considered non-reservoir sediments.

Another bulk facies is the mouth bar / storm layer. It is characterized by high clay content, large grains and clasts, all poorly sorted. These intervals are interpreted as storm layers (compare Jeremiah, 2010), or possibly also very proximal mouth bar deposits as described in Reineck & Singh (1986). The palynomorphs found in this facies indicate a marine origin (pers. comm. Dirk Munsterman).

Different cement species are found in the cores. Calcite, quartz, pyrite and siderite are found both in nodules and as cement. The large quantities of siderite cement in some
well (e.g. ZDW-01) are striking. Pyrite is formed shortly after deposition in the anoxic zone just below the sediment-water interface. Siderite is thought to be early-diagenetic as well, probably formed in a restricted bay environment (pers. comm. Harmen Mijnlieff). Cemented zones may drastically impact the porosity and permeability of the cores. An example of this is found in SCH-495 (see Figure 11), where the Bentheim Fm is dark brown of oil, except for some carbonate cemented intervals that do not contain oil at all. Glauconite is abundant in some cores, indicating deposition on a marine continental shelf, where there is some turbulence, low sedimentation rates and some organic matter available (Reineck & Singh, 1986).

![Figure 11; Carbonate cemented interval in oil filled Bentheim Fm, well SCH-495. The carbonate cemented sand is grey, the non-cemented oil-filled sands are dark brown.](image)

A complication in the automatic facies correlation based on the gamma ray log is the presence of some of these cements and other minerals. Glauconite, pyrite and siderite are abundant in some cores and some cores contain micas. Glauconite and micas have a higher natural radioactivity, increasing the gamma ray log readings in. An example of this is shown in Figure 12, where the VSF has an even higher gamma ray reading than the overlying Vlieland Claystone.
Figure 12: Detail from well log KMP-02. The left column shows the GR log and the sonic log (dashed log trace), the right column shows the bulk density log and the neutron porosity (dashed line). The Gamma Ray readings in the KNNSF are higher than in the KNNC, due to the abundance of glauconite. The difference between sand and clay is reflected in the sonic log and the bulk density log.

Bioturbation is also a common feature in most shoreface sands. Bioturbation traces contain organic material and mud, increasing the gamma ray readings as well.

A last complication with comparing GR logs is the impact of the casing. There are differences between wells logged with the logging tool run in an open hole or run in the casing. An example of this is shown in Figure 13, where the casing ended in the Bentheim Formation (KNNSP). The upper part of the well is logged in the casing, while the lower part is logged in the open hole. Although both are calibrated to API values, there is an absolute difference of 15 API between both GR logs.
Figure 13: The difference of the GR tool run through an open hole and run through the casing. The upper part of the well is logged in the casing, while the lower part is logged in the open hole. Although both are calibrated to API values, there is an absolute difference of about 15 API between both runs.

Figure 14: well section cross sections
Figure 15; Well section panel, northwest-southeast crosssection indicated in orange in Figure 14.

Figure 16; Well section panel, west-east crosssection indicated in blue in Figure 14.
**Statistical analysis**

A lithostratigraphic subdivision of all wells is available in the DINO database (Data en Informatie van de Nederlandse Ondergrond), maintained by TNO. Using this dataset the thicknesses of both the VSF and the total thickness of the Vlieland Subgroup in each well are calculated. Only true vertical depth values are used in the deviated wells. Wells in which faults are logged in the Lower Cretaceous section are excluded. Wells in which no subcropping strata are logged are not representing the whole Lower Cretaceous section and are excluded as well.

To obtain a thickness map of the VSF, all strata below the uppermost Vlieland Claystone Formation are summed. In the Vlieland Basin and the adjacent platforms, this implicates the sum of different sandstone bodies, if present. In the Lower Saxony Basin this implicates the summation of the Bentheim Sandstone Mb and Gildehaus Sandstone Mb, as well as the interbedded Bentheim Claystone Fm, Westerbork Mb and Ruinen Mb. The Ruinen Mb and Westerbork Mb are sometimes not distinguished and together they are called the Schoonebeek Mb.

The thickness map of the Vlieland Subgroup is based on the summation of true vertical thicknesses of all strata below the Holland Formation.

Based on these thicknesses two thickness maps were made using a kriging technique with the following parameters: a spherical semivariogram, a range of 40000, a sill of 1 and a nugget of 0.001.

**Results**

Two maps were made: the thickness of the Vlieland Subgroup (Figure 17) and the thickness of the sands and intercalated shales below the Vlieland Claystone Formation (Figure 18). These maps only show a stochastic analysis of the thickness distribution and do not include any geological concepts. These maps will be discussed after the addition of the biostratigraphic results.
Figure 17; Thickness of Lower Cretaceous sediments below the Vlieland Claystone Formation, which is the sum of Vlieland Sandstone and intercalated shales (if present).

Figure 18; Thickness of the Vlieland Subgroup, which is the sum of all Lower Cretaceous sediments below the Holland Formation.
Well tops

The measured depths of important intervals were imported as well tops for all wells used in the Petrel project. This was done by filtering the intervals from the DINO database. The bases of all main groups were marked, as well as all subdivisions within the Vlieland subgroup, see Table 3. A Base Cretaceous well top was added at the depth of the lowermost Cretaceous well top. Duplicates in the database due to faults were manually removed. These well tops are used in well section panels. An existing TNO project provided well tops in TWT for a selection of wells. These well tops were used to tie seismic horizons to wells.

Table 3; Well tops

<table>
<thead>
<tr>
<th></th>
<th>Base Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Base North Sea Supergroup</td>
</tr>
<tr>
<td>C</td>
<td>Base Chalk Group</td>
</tr>
<tr>
<td>KNG</td>
<td>Base Holland Formation</td>
</tr>
<tr>
<td>KNNC</td>
<td>Base Vlieland Claystone Mb</td>
</tr>
<tr>
<td>KNNCE</td>
<td>Base Ruinen Mb</td>
</tr>
<tr>
<td>KNNCS</td>
<td>Base Schoonebeek Mb</td>
</tr>
<tr>
<td>KNNCV</td>
<td>Base Bentheim Claystone Mb</td>
</tr>
<tr>
<td>KNNCW</td>
<td>Base Westerbork Mb</td>
</tr>
<tr>
<td>KNNS</td>
<td>Base Vlieland Sandstone Fm</td>
</tr>
<tr>
<td>KNNSF</td>
<td>Base Friesland Mb</td>
</tr>
<tr>
<td>KNNSG</td>
<td>Base Gildehaus Sandstone Mb</td>
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<tr>
<td>KNNSP</td>
<td>Base Bentheim Sandstone Mb</td>
</tr>
<tr>
<td>K</td>
<td>Base Cretaceous</td>
</tr>
<tr>
<td>S</td>
<td>Base Upper Jurassic</td>
</tr>
<tr>
<td>A</td>
<td>Base Lower Jurassic</td>
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<tr>
<td>RN</td>
<td>Base Upper Trias</td>
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</tr>
<tr>
<td>D</td>
<td>Base Limburg Group</td>
</tr>
<tr>
<td>X</td>
<td>Base Zuidwal Volcanic Fm</td>
</tr>
<tr>
<td>F</td>
<td>Fault</td>
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</table>
Biostratigraphy

Biostratigraphical interpretations were obtained from 28 wells, either from TNO reports from the past or from new biostratigraphical interpretations based on NAM data, interpreted by Dirk Munsterman and Roel Verreussel (TNO). All biostratigraphic interpretations are listed in Table 4, subdivided in four stages: the Ryazanian, Valanginian, Hauterivian and Barremian stage, see Table 5. Twelve of these are based on TNO reports, 18 of these are new interpretations. The filled boxes indicate the ages of the palynomorphs found in the cores. Shaded boxes are datings based on little data and thus unreliable. Dotted boxes are datings in the Vlieland Claystone, indicating that the underlying VSF is from that age or older.

Table 4: Biostratigraphical interpretations

<table>
<thead>
<tr>
<th></th>
<th>Ryazanian</th>
<th>Valanginian</th>
<th>Hauterivian</th>
<th>Barremian</th>
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It is possible to divide these 28 data points in two sets: the sand bodies from the Ryazanian and Valanginian and the sand bodies from Hauterivian and Barremian age. In the Lower Saxony Basin, both sand bodies are present. The oldest one is represented by the Bentheim Formation, the youngest is the Gildehaus Formation.

There is also a difference in geographical distribution. The Ryazanian and Valanginian sands are deposited in the centre of the Vlieland and Lower Saxony Basins and the edges of the Platforms. In contrast, the Hauterivian and Barremian sands are found on the platforms, although the Gildehaus Formation is also present in the Lower Saxony Basin. See Figure 19.

![Figure 19: biostratigraphical datings. In blue Ryazanian and Valanginian datings, in orange Hauterivian and Barremian datings.](image-url)
**Subcrop**

The Base Cretaceous is an unconformity, so the subcropping sediments may have impact on the paleogeography during the Lower Cretaceous, and therefore on the distribution and preservation of the VSF. A subcrop map is a valuable instrument to investigate these effects. Regional grids published by TNO on [http://www.nlog.nl/nl/pubs/maps/geologic_maps/NCP1.html](http://www.nlog.nl/nl/pubs/maps/geologic_maps/NCP1.html), were used to create a subcrop map of the area, shown in Figure 20. This subcrop map is combined with the thickness of the Vlieland Subgroup from the previous chapter and the faults in the Base Cretaceous, see Figure 21.

There is a strong correlation between the thickness of the Vlieland Subgroup and the presence of late Jurassic sediments. In the areas where late Jurassic sediments are present, the Vlieland Subgroup is thick. The transition between Jurassic and Cretaceous sediments is sometimes conformable, sometimes slightly unconformable, which indicates that both basins were already active during the Jurassic. This will be commented further on in chapter Building block 4.

Other factors that seem to restrict the distribution of the Vlieland Subgroup are active faults (e.g. the Lauwerszee trough) and the presence of Zechstein salt. To investigate all factors possibly acting on the deposition and preservation of the VSF, the area is subdivided in 7 building blocks: cross-sections through a part of the area. For the map location of these building blocks, see Figure 22.

![Figure 20; Subcrop map Base Cretaceous](image-url)
Figure 21; subcrop map Base Cretaceous combined with Vlieland sand thickness.
**Building blocks**

To investigate all factors possibly acting on the deposition and preservation of the VSF, the area is subdivided in 7 building blocks: cross-sections through a part of the area. The following 7 subareas are investigated, see Figure 22:

1. Northeast part of the area
2. Lauwerszee trough
3. Friesland platform
4. Western edge of Lower Saxony Basin
5. Cross-section through Wanneperveen area
6. Active faulting in Lower Saxony Basin
7. West-east cross-section

These so-called building blocks will be discussed using well section panels and seismic surveys. For each building block a hypothesis will be proposed about the factors controlling the sand distribution. A building block with subcropping Posidonia Shale proved to be irrelevant, a few notes on that can be found in Appendix B - Posidonia shale.

Well section panels and seismic profiles are generally flattened on the Base Holland Fm or the Base Chalk Gp. The Holland Fm and the Chalk Gp are deposited in a marine setting and are fairly uniform. Assuming that the Holland Fm and Chalk Gp are also fairly uniform in thickness and that they are non-erosive, flattening on these surfaces gives some insight in the paleogeography of the Early Cretaceous.

Figure 22: subcrop map with the subareas of the building blocks. Building block 7 is a comprehensive NW-SE cross-section
Building block 1

Building block 1 is the northeastern part of the area. The subcropping strata in this area are mainly of Triassic age, but there are some patches where Zechstein salt subcrops. It appears that above these Zechstein patches VSF is present, of up to 30 meters in thickness, while in the areas of Triassic subcrop almost no sand is found. A cross-section through this area should give more insight in this phenomenon.

Cross-section 1 comprises the following wells, in SW-NE order: HRS-01, EKL-12, POS-11, LRM-10, BIR-06 and HND-01. See Figure 23 for the location of the area, Figure 24 for the seismic profile and Figure 25 for the well section panel. The seismic profile and well section panel are flattened on the Base Chalk. The northeastern part of this area is not covered with 3D seismics, therefore Figure 24 does not contain wells BIR-06 and HND-01, and the salt ridge of BIR-06.

Figure 23; Detail of subcrop map with wells. In yellow the investigated cross section, containing an area of subcropping Zechstein salt and one salt ridge.
Figure 24; seismic cross-section 1. On the right side (NE) the disappearing pink grid (Base Trias) indicates the breakthrough of the salt ridge, found in well BIR-06. Note for all seismic sections: dashed lines are regional grids mapped by TNO. Solid lines are interpretations of the author of this thesis. In green: Base Chalk, in purple: Base Holland, in blue: Base Cretaceous, in dark blue: Base Jurassic, in pink: Base Trias, in yellow: Base Zechstein. Below: interpretation of seismic section; Zechstein in light yellow, Triassic in pink, Vlieland sandstone in yellow, Vlieland Claystone in grey.

Figure 25; well section panel 1. For legend of colors in this and following well section panels: see Figure 16; Well section panel, west-east crosssection indicated in blue in Figure 14.

Observations
The seismic profile (Figure 24) shows a thickening of the Vlieland Subgroup above the Zechstein subcrop. The well section panel shows that the Vlieland Subgroup is almost doubled in thickness above the Zechstein. These wells contain several tens of meters of sand. The hypothesis is proposed that Zechstein strata are easier erodible than Triassic strata, causing local depressions in which the VSF is preserved.

Interpretation
This hypothesis is tested by checking the DINO database for the underlying Zechstein strata in these wells. It appears that the Zechstein Upper Claystone Formation (ZEUC) is
subcropping in all these wells, a claystone layer which is supposed to protect the underlying evaporates against erosion. This could mean that the depression above the Zechstein is caused by subrosion: dissolution of the evaporates below the surface, caused by groundwater flow (Lohmann, 1972). Another possibility is that the ZEUC is actually the caprock that contains remainings of Zechstein strata after erosion or dissolution, which is abusively called the ZEUC Formation by the lithostratigraphic interpreters.

The hypothesis that dissolution of Zechstein strata, either by erosion or subrosion, caused a depression in the palaeogeography seems valid for the northeastern part of the area. The thickness of the VSF should therefore be correlated to the outline of the subcropping Zechstein strata.

Building block 2

Building block 2 is situated in the northern part of the area. The reason to study this building block is to understand the distribution of the VSF in the Lauwerszee area. The thick VSF in the Vlieland and Lower Saxony Basins are expected, because both are basins, but the distribution of VSF in the Lauwerszee area is quite striking on the thickness maps in Figure 17 and Figure 18. Does the Lauwerszee area belong to the Vlieland depocentre or is it a separate depocentre in the Lauwerszee Trough?

Two cross-sections are studied: cross-section 2A runs in W-E direction and cross-section 2B runs NW-SE. Cross-section 2A comprises the following wells: BLF-107, TRN-01, ANJ-04, ANJ-03, VHN-03 and VHN-02. Cross-section 2B comprises the wells AME-105, AME-103, MGT-02, ANJ-03 and MKZ-01. In well ANJ-03 both cross-sections intersect. See Figure 26 for the location of both cross-sections, Figure 27 and Figure 29 for the seismic sections and Figure 28 and Figure 30 for the well section panels. The seismic profiles are flattened on the Base Chalk and the well section panels are flattened on the Base Holland Fm.
Figure 26; Detail of subcrop map with wells. In yellow cross-section 2A, in blue cross-section 2B. The area of interest is the Lauwerszee area.

Figure 27; Seismic section 2A

Figure 28; Well section panel 2A
Figure 29; Seismic section 2B. Below: interpretation of seismic section; Triassic in pink, Vlieland Sandstone in yellow, Vlieland Claystone in grey.

Figure 30; Well section panel 2B

Observations
The VSF in this region is deposited on top of Triassic sediments. It is pinching out in eastward direction without indications of faults or any structural feature limiting the VSF (see also the unflattened seismic sections in Figure 31 and Figure 32. In the western part of cross-section 2A a salt ridge is visible breaking through the Cretaceous. Just to the west of this salt ridge it is unclear what happens to the Lower Cretaceous sediments. This is the intersection with the Hantum Fault, one of the bounding faults of the Lauwerszee Trough. Outside this through, in the most western part of cross-section 2A, the Lower Cretaceous sediments are much thinner or absent.
Interpretation
The hypothesis in this building block is that faulting in the Lauwerszee Trough led to a half-graben landscape, dipping westward until the western boundary fault, the Hantum Fault Zone. The Hantum Fault Zone is separating the Lauwerszee Trough and the Friesland Platform.

Figure 31; Seismic section 2A unflattened

Figure 32; Seismic section 2B unflattened
Building block 3

Building block 3 is situated in the northern part of the area. The reason to study this building block is to find out the southward limitations of the VSF in the Lauwerszee and Leeuwarden areas.

Cross-section 3 comprises the following wells, in N-S order: ANJ-01, EWM-01, TID-101, TID-502, LEW-02, AKM-10-S1, AKM-03, GWG-01 and HRV-01. See Figure 34 for the location of this cross-section, Figure 35 for the seismic profile and Figure 36 for the well section panel. The seismic profile and well section panel are flattened on the Base Chalk.
Figure 34; Detail of subcrop map with wells. In yellow cross-section 3. The particular interest of this building block is the north-south limitation of the sands around Leeuwarden.

Figure 35; Seismic section 3

Figure 36; Well section 3

Observations
A thin layer of VSF is deposited over the Triassic sediments. The thickness of the VSF increases where the Zechstein subcrops, but in southward direction it is thinning out.
The thickness of the VSF seems to be correlated with the thickness of the subcropping Zechstein strata: the Zechstein subcrop thins out in southward direction, forming the southern limit of the VSF in the Leeuwarden area.

**Interpretations**

The VSF in the whole area is overlain by marine deposits: the Vlieland Claystone Fm, the Holland Fm and the Chalk Group. This means that the transgression depositing the VSF flooded the whole area and probably deposited sand during this process. Therefore the southern limit of the VSF is not a matter of deposition, but of preservation. This preservation is a function of the gradient of the platform, which is so low that all sediment is reworked in the ongoing transgression. This will be discussed in chapter Discussion.

**Building block 4**

Building block 4 is situated in the southeastern part of the area, on the western edge of the Lower Saxony Basin. The aim of investigating this subarea is to find out how the basin ends in westward direction and what the relation is to underlying Jurassic sediments.

Cross-section 4 comprises the following wells, in NW-SE order: HRV-01, NWD-01, DIV-01, DWL-02, DWL-01, BEI-01, WES-01, OSH-05, OSH-04 and SND-01. See Figure 37 for the location of this cross-section,

![Figure 37](image)

Figure 38 for the seismic profile and Figure 40 for the well section panel. The seismic profile and well section panel are flattened on the Base Chalk.
Figure 37; Detail of subcrop map with wells. In yellow cross-section 4. The particular interest of this building block is the western basin edge of the Lower Saxony Basin.

Figure 38; Seismic section 4, flattened on the base Chalk. Below: interpretation of western edge, with Vlieland sandstone in a depression at the location of subcropping Zechstein. Zechstein in light yellow, Triassic in pink, Jurassic in blue, Vlieland sandstone in yellow, Vlieland Claystone in grey.
Figure 39; Detail of seismic section 4 (unflattened). Faulting influenced the thickness of the Lower Cretaceous sediments. Normal faulting is visible in the downthrow of the thick Triassic clays, but reactivation of this fault is visible in the Base Chalk (green).

Figure 40; Well section panel 4

Observations
In the western part of this seismic section, an equivalent of the principle in building block 1 is found. Between wells NWD-01 and DIV-01 is a depression in the Base Cretaceous visible, probably due to erosion or subrosion of Zechstein strata. This depression decreases westward with the decreasing thickness of the Zechstein itself.

The thickness variations of the VSF in the central part of this cross-section are complex. The thickness increases and decreases gradually in eastward direction. Truncation of
underlying sediments is found at the Base Cretaceous, but also within the Vlieland Subgroup at the Base Holland Fm (see Figure 41).

**Interpretations**

The eastward thickness increase as visible in

![Diagram](image)

Figure 38 is probably the result of syn-depositional folding. This folding could be related to salt movements, where a rim syncline is formed above the zone of withdrawn salt. A rim syncline seems to be reasonable at first sight, with withdrawn Zechstein salt in below the thick Vlieland subgroup and a symmetrical thickness increase and decrease of the Vlieland Subgroup. However, closer investigation reveals that a rim syncline can not be the explanation of this thickness variation: a salt pillow or ridge is lacking on the eastern side, the structure is quite large scaled for a typical rim-syncline and more importantly the Vlieland sediments do not decrease in eastward direction, but are truncated by the Holland Fm, see Figure 41. Salt movement may have influenced the deposition of the VSF, but can not be the only explanation. Therefore it is thought that the syn-depositional folding in the central part of the basin is related to regional tectonic movements, with the movement of the Zechstein salt being a side effect.

Not only the Base Holland Fm is erosive, the Base Cretaceous itself is also erosive: it truncates the underlying Jurassic sediments (see Figure 41). This is an indication of the complex development of the basin, in which in this cross-section two faults are crucial: the fault between OSH-04 and SND-01 and the fault between wells DWL-01 and BEI-01. Both are part of the Gronau Fault Zone. Stepwise progression of movements along these faults could explain the different stages of this part of the basin, with erosive surfaces in between. Some remarks on this in the context of regional geology can be found in chapter Discussion.

The faults that caused the formation of the basin during the Jurassic are the same faults that formed the basin during the Cretaceous. This explains the correlation of the VSF distribution with the subcropping Jurassic sediments. It seems reasonable to adapt the thickness map of the Vlieland sandstone in this part of the area to trends of these two important faults and to the distribution of the subcropping Jurassic sediments.
Building block 5

Building block 5 is situated in the southern part of the area, on the western edge of the Lower Saxony Basin. This building block is investigating the relation between the De Wijk and Wanneperveen sands and the Lower Saxony Basin and the connectivity between the Wanneperveen, Nijensleek and Noordwolde Fields.

Cross-section 5A comprises the following wells, in W-E order: LTG-01, WAV-03, WAV-07, WAV-06, WAV-08, WYK-30, WYK-23, WYK-13, WYK-02-S1, WYK-21 and WYK-05. Cross-section 5B comprises the wells WAV-06, ESV-01 and NWD-01.

See Figure 42 for the location of this cross-section, Figure 43 and Figure 44 for the seismic profiles and Figure 45 and Figure 46 for the well section panel. The seismic profile is flattened on the Base Chalk, the well section panel is flattened on the Base Holland Fm.
Figure 42; Detail of subcrop map with wells. In yellow cross-section 5A, in blue cross-section 5B. In green the outlines of gas fields, with the Wanneperveen, De Wijk, Nijensleek and Noordwoolde fields indicated. The particular interest of this building block is the connection between the Wanneperveen and De Wijk fields, and also their connection to the western basin edge of the Lower Saxony Basin.

Figure 43; Seismic section 5A

Figure 44; Seismic section 5B
Observation

The connection between the Lower Saxony Basin and the Wanneperveen Field is not very clear. The sands in the De Wijk Field are overlying mainly Jurassic and Upper Trias sediments. The Lower Triassic Bunter Group is not overlain by VSF, except for the western part, where the sands of the Wanneperveen Field are deposited. The connectivity of the Wanneperveen sands with the Nijensleek and Noordwolde Fields is investigated with a north-south cross-section. No sands are found in Eesveen (ESV-01). The Base Cretaceous in this section is hardly traceable, but the thickness of the Vlieland Subgroup in the Wanneperveen area seems to be fairly constant in northward direction. Just south of Eesveen the Vlieland Subgroup a thickness decrease is visible, probably the result of a fault. The Nijensleek Field, just northwest of Eesveen, is located in a downthrown faultblock and contains VSF. The same holds for Noordwolde, where VSF is found, in contrast to the nearby Weststellingerwerf well, which seems to be fault-controlled as well. The sands in Noordwolde and Wanneperveen are comparable in terms of facies: very poorly sorted conglomeratic sand, which is thought to indicate a very proximal deposition (see chapters Core study and Appendix A).

Interpretation

The sands of the Wanneperveen seem to be deposited in small horst – graben structures that are the result of minor faults. These faults however are not very clear in the seismic section and their extent is not mapped. The sand accumulations in Noordwolde and Nijensleek are also located in downthrown fault blocks. The
Wanneperveen, Nijensleek and Noordwolde Fields are all fault-controlled. These faults are minor faults, and the sand distribution is probably a local phenomenon. The proximal conglomeratic facies is supporting this hypothesis. These faults should be mapped to enable a correlation of the faults with the sand accumulations. This has not been done in this study.

The De Wijk sands are representing sands of the Lower Saxony Basin. The age of both sediments is the same. The Wanneperveen and Noordwolde sediments contain both marine palynomorphs, so probably these fault blocks were connected to the Lower Saxony basin.

**Building block 6**

Building block 6 is situated in the southeastern part of the area. The reason for this cross-section is to find out why there is a large thickness increase just north of the Schoonebeek field. This cross-section intersects at well SND-01 with the eastern end of cross-section 4.

Cross-section 6 comprises the following wells, in N-S order: EMM-09, SND-01, SCH-088 and SCH-388. See Figure 47 for the location of this cross-section, Figure 48 for the seismic profile and Figure 49 for the well section panel. The seismic profile and well section panel are flattened on the Base Chalk.

**Observation**

Just north of SND-01 a fault is visible in the seismic section, which was active during the deposition of the Jurassic and Cretaceous sediments and ended during the deposition of the Holland Fm. The VSF increases in thickness to the north until the fault. The top of the Vlieland Subgroup is truncated by the Holland Fm, which is also found in building block 4.

**Interpretation**

North of the fault the distribution of VSF is correlated to the subcropping strata. In EMM-09, a thin interval of VSF is present, with subcropping Jurassic sediments. In the seismic section there is a very clear correlation between the subcropping Jurassic strata and the depression in the Base Cretaceous, where the VSF is found. This is an analogue of building block 4, supporting the hypothesis that the presence of VSF is related to basin formation during the Jurassic and the presence of Jurassic subcropping sediments. Again the truncation of Jurassic sediments by the Base Cretaceous indicates a stepwise and complex basin development.

The correlation between subcropping Jurassic sediments and the presence of VSF found in building block 4 is supported, which gives rise to the adjustment of the thickness map to this correlation across the whole Lower Saxony Basin area.
Figure 47; Detail of subcrop map with wells. In yellow cross-section 6. The particular interest of this building block is the large thickness increase of the VSF just north of the Schoonebeek field.

Figure 48; Seismic section 6 N - S

Figure 49; Well section panel 6. The well section panel misses the fault and the anticline in the pre-Cretaceous sediments between EMM-09 and SND-01. The Cretaceous sands in both wells are not connected, contrary to what is suggested by this well section panel.
Building block 7 is a NW-SE cross-section through the entire area. This cross-section should combine the insights of previous building blocks and give an overall impression of the factors influencing the VSF distribution.

Cross-section 7 comprises the following wells, in NW-SE order: L12-05, VLO-01, ZDW-03, ZDW-01, HAW-01, HRL-03, BWD-01, BLH-01, ESG-01, WAV-03, WAV-01, WAV-06, WAV-08, WYK-17-S1, WYK-20, ZUW-02 and SND-01. See Figure 50 for the location of this cross-section and Figure 53 for the well section panel. The well section panel is flattened on the Base Holland Fm.

As visible in Figure 10, a large part of this cross-section is not covered with 3D seismics. For the eastern part of this cross-section which is covered with seismics, see building block 5, covering almost the same section. A cross-section through the Zuidwal Field and the western part of this cross-section are shown in Figure 51 and Figure 52.
Figure 51; Seismic section over the Zuidwal Volcano in the centre of the Vlieland Basin

Figure 52; NW-SE seismic section offshore Vlieland
Observation
Because of the lack of seismic data, the large scale structure in the Vlieland Basin is best expressed in the well section panel. The Vlieland Subgroup is over 500 meters thick in the northwestern part, which is the depocentre of the Vlieland Basin. The Vlieland Basin came to existence during the Jurassic, and the Vlieland sediments are unconformably overlying Jurassic sediments, comparable to the Lower Saxony Basin.

Westward offshore, beyond the borders of this project, the Vlieland Subgroup is also overlying Jurassic sediments, as visible in Figure 52. In this direction the Vlieland Basin was connected to the Central Graben, opening the area to the open marine setting.

Onlapping of seismic reflectors to the eastern basin edge is visible in a W-E seismic section in the Leeuwarden area, shown in Figure 54.

Interpretation
The eastward limitation of the VSF in the Vlieland Basin is not linked to faults. This limitation is probably a matter of preservation. The gradient of the platform is very low compared to the basin and probably all sand is reworked during or after deposition.

Over the Friesland Platform eastwards the Hauterivian sands of the Wanneperveen and De Wijk fields are found, which are related to the Lower Saxony Basin, see building blocks 4 and 5.
Figure 54; W-E seismic section in the Leeuwarden Area, showing the edge of the Vlieland Basin. Detail: onlapping seismic reflectors in the Base Cretaceous. Below: interpretation of seismic section; Triassic in pink, Jurassic in blue, Vlieland sandstone in yellow, Vlieland Claystone in grey.
Discussion

A large dataset of seismic data, well logs, cores and palynological data in the northern onshore part of the Netherlands is analyzed to get grip on the different factors acting on the distribution of the Vlieland Sandstone Formation (VSF). Faulting and regional tectonics proved to be crucial in the development of the Lower Saxony Basin in the eastern part of the area, subcropping strata did have some impact in the distribution and preservation of the sand and erosive surfaces within the Vlieland Subgroup removed a large part of the deposited sediment, especially on the Friesland and Groningen platforms.

Building blocks

7 so-called building blocks, small parts of the area, were investigated to study the different factors acting on the VSF. In the east building block 4 revealed complex faulting in the Lower Saxony Basin. It turned out that the basin development and thus the shoreline development are directly linked to local faults and not solely determined by eustatic sea level changes or regional tectonics. Therefore it is impossible to correlate sequences in different parts of this basin. The Subhercynian and Laramide tectonic phases caused strong differential subsidence and tectonic inversion, which influenced the preservation of the VSF. Internal erosional surfaces are found within the Lower Cretaceous strata. These are thought to be related to these inversion pulses, but no attempts have been made to correlate these surfaces over different fault blocks in the Lower Saxony Basin area. Ziegler (1990) related this inversion to the Alpine foreland compression, but Kockel (2003) states that the driving mechanisms of these inversions in the Lower Saxony Basin remain unsolved.

The Vlieland Basin basin was pulled apart in the Kimmerian Orogeny and the boundary faults were not active anymore during the deposition of the VSF. Thermal relaxation and the load of volcanics and sediment infill are thought to be the driving mechanisms of the subsidence in this basin (Herngreen et al., 1991). The VSF was found onlapping on the basin edges and overlying the platforms.

In the Lauwerszee area, the thickness of the VSF is increasing at the active Hantum Fault Zone in the west and it is thinning out eastward onto the platform. The platforms have a low gradient, on which sands are not preserved. This limits the sand distribution in the central part of the area.

In the northeastern part of the area, Zechstein salt ridges are subcropping. Due to erosion or subrosion these form depressions in the palaeogeography (compare e.g. Lohmann, 1972). In these erosion or subrosion depressions VSF is preserved. A core study to the VSF and the Zechstein subcrop in these wells should be done to test this hypothesis. There is a good possibility that these depressions formed high energy
sediment corridors, with heavy currents or large tidal fluxes. In these high energetic environments good reservoir sands could be deposited. Unfortunately no cores from these wells are available in the TNO core shed. Increasing sand thicknesses above subcropping Zechstein are not restricted to salt ridges in the northeast, but are found in the whole area, see also building block 4. However, this dissolution effect requires a certain thickness and in areas where the subcropping Zechstein is very thin, such as at the Friesland Platform, this effect is not visible.

All described relations are assimilated in the adjusted VSF thickness map in Figure 55.

Figure 55; Thickness map VSF

Core study
The core study on 8 cores revealed the abundance of lower shoreface sediments and shelf deposits and the scarcity of upper shoreface sediments. It is likely that these upper-shoreface sands are reworked during the ongoing transgression and not preserved in the stratigraphical record. Helland-Hansen and Hampson (2009) proposed the concept of trajectory analysis (see Figure 56), generalising the sequence stratigraphic interpretation to a matter of depositional processes versus geomorphological changes. A low-angle (nonaccretionary) transgressive depositional system is associated with missing facies belts, the presence of laterally extensive erosional surfaces and relatively low preservation of the shoreline deposits. This is exactly what we found in this area: low preservation of upper shoreface sands and internal erosional surfaces. In the classical sequence stratigraphy interpretation this would be interpreted as wave-ravinement surfaces.

The large quantities of siderite cement in some wells (e.g. ZDW-01) are striking. These siderite cemented beds are found only in wells the Vlieland basin. There are different
theories on the formation of siderite, one of them stating that siderite is early-diagenetic and formed in a restricted bay environment (pers. comm. Harmen Mijnlieff). If this is correct, the presence of siderite may indicate that these cemented-beds are deposited during a period in which the Vlieland Basin was not yet connected to the Lower Saxony Basin. That this siderite cement is found mainly in the depocentre of the Vlieland Basin, in the earliest deposited sandstones, supports this theory.

Figure 56: Left: Shoreline trajectory classes. Heavy lines indicates trajectory of shoreline. Right: Depositional and erosional responses to variable shoreline trajectories applying Bruun’s rule (Bruun, 1962). For simplicity, the slopes of the coastal plain, shoreface and offshore profiles are shown with straight lines. Sectors A and B: Deposition of nonmarine and marine sediments. Sector C: Deposition of shallow marine sand and erosion/bypass of nonmarine and lower shoreface/offshore transition sediments. Sector D: Erosion of marine and nonmarine sediments. Sector E: Erosion of foreshore and nonmarine sediments and deposition of (thin) shoreface and deeper marine sediments. (a) Nonaccretionary transgression (trajectory intersecting nonmarine slope, foreshortened succession, erosion); (b) and (c) accretionary transgression; (d)-(f) ascending regression, with trajectories not intersecting depositional slopes (no erosion, diminishing expansion of successions from d to f); (g) descending regression, trajectory not intersecting depositional slopes (foreshortened succession, no erosion); (h) descending regression, trajectory intersecting marine slope (foreshortened succession, erosion); (i) trajectory intersecting all slopes (erosion and nondeposition). (Helland Hansen & Hampson, 2009).

Paleogeography
Conceptual facies distribution maps are made for the Ryazanian-Valanginian, Latest-Valanginian-Early Hauterivian and Late Hauterivian-Barremian, see

Figure 57. The sandstones in the Vlieland depocentre are all of Ryazanian-Valanginian Age. In the southeastern part of the area (Wanneperveen, de Wijk, Lower Saxony Basin) sandstones of Hauterivian-Barremian age are found. In between both sand accumulations a thick clay layer is found, the Ruinen, Westerbork and Schoonebeek Members. These marine clay layers indicate a split in the overall transgression, with the Bentheim Member and overlying claystones deposited during a transgression, followed by a regression and another transgression, depositing the Gildehaus Member. Reworking of Valanginian sediments is found in the early Hauterivian sandstones in the De Wijk and Wanneperveen fields, but on the platform there is a hiatus of sediment deposited at the maximum flooding surface between the Valanginian and the Late Hauterivian. These deposits seem to be all eroded or reworked. This hiatus is also shown in the stratigraphical chart of the Lower Saxony Basin in the nomenclature by Van Adrichem Boogaert & Kouwe (1997), see figure 6. The connection between the Vlieland and Lower Saxony Basins over the platforms, which occurred probably in the Late Valanginian, is not preserved in the rock record. It is important to realize that the facies distribution map of this period is just conceptual and based on little data besides the Ruinen and Westerbork members in the Lower Saxony Basin.
Figure 57: Conceptual facies distribution maps, in yellow upper shoreface, in orange lower shoreface and in blue marine shale. 1: latest Ryazanian - Early Valanginian. 2: Late Valanginian. 3: Latest Valanginian - Early Hauterivian. 4: late Early Hauterivian – Barremian. Arrows indicate sediment input directions. During the Hauterivian and Barremian, proximal sandstones are deposited in faultblocks in Noordwolde, De Wijk and Wanneperveen, here indicated in orange. Black line indicates the location of the cross-section in figure 58.

Figure 58: Conceptual crosssections of the facies distribution maps in figure 57: in yellow upper
shoreface, in orange lower shoreface and in grey marine shale. 1: latest Ryazanian - Early Valanginian. 2: Late Valanginian. 3: Latest Valanginian - Early Hauterivian. 4: late Early Hauterivian – Barremian. The black line in figure 4 is an erosive surface of forced regression.

One of the remaining questions in the analysis of the VSF is the origin of the sandstones. The structural highs during the Early Cretaceous are the Texel IJsselmeer High in the southwest of the area, the Pompeckj Swell and the Rhenish Massif in Germany and the Ringköbing-Fyn High in Denmark (see Figure 1). The Friesland and Groningen platforms were also exposed during the early stage of transgression. The Texel IJsselmeer High is relatively small and local. The Pompeckj Swell and the Rhenish Massif are feeding the Lower Saxony Basin, while the Central Graben and the Vlieland Basin receive sediments from the Ringköbing-Fyn High. According to Ziegler (1990) the regional transgression during the Valanginian reached the Lower Saxony Basin via the Vlieland Basin, see Figure 7. In that case the sediment sources are mixed, a hypothesis that could be tested by performing a provenance study. Sediments of the Bentheim formation in the Lower Saxony Basin and the Friesland Member in the Vlieland Basin could be analyzed and compared. If there was no connection, we expect both sediments to originate from different source areas and to have different signatures.

The sandstones deposited during the Valanginian show a division between the two depocentres, the Vlieland Basin and Lower Saxony Basin. The connection that Ziegler shows in Figure 7 is not found in the distribution of Valanginian sands in the dataset. There are two possible explanations. The first is that there indeed was a connection, but post-depositional erosion removed all traces. The second hypothetical explanation is that there was no connection, in which case the synchrony between the transgressional stages in both basins are coincidence, or the result of an eastward connection of the Lower Saxony Basin to the central Graben and therefore the product of the same eustatic sea level fluctuations. Both basins are thought to be connected only during the Hauterivian. However, we find erosion, for example around the western edge of the Lower Saxony Basin. We therefore suggest that there was indeed a connection between both basins at the end of the Valanginian, but these sediments are eroded due to the forced regression in the Early Hauterivian.

Jeremiah (2011) suggests that from the Early Valanginian on a connection between both basins is established along the northern part of the area. Sediments are deposited in the whole area, including the Friesland and Groningen platforms, but these sediments are eroded during of after deposition, see the regional facies maps in Figure 8 and Figure 9. Apparently he states that the Pompeckj Swell and Ringköbing-Fyn High are flooded during the Valanginian already, suggesting an open marine setting in the north, in contrast to the paleogeographic interpretation of Ziegler (1990). The facies maps proposed in this thesis (figure 57) are in general comparable with the framework in Jeremiah’s study.
Conclusions

Different factors were important in the distribution and preservation of the Vlieland Sandstone Formation. The accommodation space in the Vlieland Basin is caused by subsidence due to sediment load and post-rift thermal relaxation, with Cretaceous sediments linked to the presence of the Jurassic subcrop. In the Lower Saxony Basin the basin development is still ongoing during the deposition of the Vlieland Sandstone Fm. This region is tectonically complex, with different fault blocks. Vlieland sandstone is on the Friesland Platform only locally, related to minor faults and horst-graben structures, in which the sandstone is preserved. The rest of the sandstone is eroded, either during deposition on the flat platform, or after deposition as a result of an erosive surface of forced regression. An interesting actor in the preservation of sand is the presence of subcropping Zechstein, which caused depressions in the palaeogeography during deposition; examples of this are found in northeast Groningen and along the western edge of the Lower Saxony Basin.

The timing and development of the connection between the Vlieland Basin and the Lower Saxony Basin is still not very clear, due to erosion and thus a lack of data, but a provenance study to Valanginian sediments may reveal more information on this problem. In order to use this thickness map as an input for geothermal feasibility studies, the porosity and permeability of the different facies should be studied.

We may conclude that the main relevant geological processes acting on the deposition and preservation of the sands are addressed and the thickness distribution of the VSF (Figure 55) is much better understood than before (compare Figure 3).
Appendix A - Core study

In the TNO core shed in Zeist the following cores are studied: SUW-03, OPE-01, OPE-02, NWD-01 and ZDW-01. During a visit to the NAM core shed in Assen, WAV-01, WYK-17-S1 and SCH-495-S1 are studied. A three-day Applied Ichnofacies course (organized by the AAPG, SEPM and KNGMG, led by George Pemberton) provided some insight deriving facies information from trace fossils.

This appendix includes for each core the studied section (in measured depth), a general description of the core, some notable details and facies interpretations.

Suawoude-03
[2953-2981]

General
One of the two polymer slabbed cores studied for this project. Very fine sand, heavily bioturbated. Some pyrite. No internal surfaces or variations visible. Base and top are marked by a sudden change in grain size, although the exact transitions are missing in the polymer slabs.

Figure 59; 2972: Very fine (lower) quartz sand, heavily bioturbated with Pascichnia.

Bioturbation
Mainly Pascichnia. This is a grazing structure, indicating low energy, fully marine conditions (Pemberton et al, 2011).

Facies
Based on the very fine sand and the Chondrites burrows, this core is interpreted as Lower Shoreface.
Shallow marine facies: based on bioturbation and grain size. The grazing structures of surface feeding animals are visible in the core, eg at a depth of 2978m, indicating conclusion that these are lower shoreface deposits.
Opeinde-01
[1900-1917]

General
Subcrop: brown/grey alternating claystone. At 1912.5: base sandstone: a fine grained sandstone, well sorted, with some glauconite and pyrite. At 1909 an interval with siltstone / clay clasts, almost conglomeratic. Uppermost interval well sorted, cemented and bioturbated.

Figure 60; OPE-01 1908 (upper left) - 1910 (lower right) m MD.

Figure 61; OPE-01 1912 (upper left) - 1914 (lower right) m MD. Transition of the Triassic clays to clean Cretaceous sand.

Facies
The clean, very well sorted sandstone at the base is interpreted as upper shoreface: the very well sorting indicates wave reworking. The middle interval seems to have a mixed sourcing of well sorted marine sands and occasional pebbles. The sandstone contains
some clay and bioturbation traces. This interval is interpreted as lower shorefaces, with occasional storm events bringing in the clay pebbles. The uppermost interval shows a lot of bioturbation features and has a finer grainsize, this is interpreted as lower shoreface.

**Opeinde-02**

[1888-1905]

**General**
The sand interval consists of 2 parts. The bottom part has a conglomeratic base, with a fining upward grain size, via medium grained sand to fine sand, and increasing bioturbation. At 1900.5m a second sand body starts with a fine/very fine sand above a claystone interval. The upper 10 meter has a uniform grain size. The sands are heavily bioturbated, well cemented (with quartz and pyrite).

**Bioturbation**
Bioturbation is abundant in the whole cored section. Thalassinoides and Chondrites traces are found, and probably also Ophiomorpha and Diplocraterion. This assemblage is interpreted as a Cruziana Ichnofacies, in a proximal lower shoreface to proximal offshore setting.

**Diagenetic features**
Just above the conglomeratic base of the sandstone, a lot of iron oolites are found. Iron oolites are found in the whole core, but are concentrated in thin intervals. Pyrite cement and siderite are also found.

**Facies**
Based on bioturbation and grain size the sandstones of this well are interpreted as lower shoreface, with a conglomeratic interval at the base and a marine shale interval separating two sandstone units.
Figure 62: 1904-1906 – base Cretaceous unconformity with subcropping Triassic claystone. (length of ruler: 8cm)

Figure 63: 1904.8 m – Conglomerate (left side) and iron oolitic sandstone (right side, brown little dots are the oolites)
Figure 64; 1903 m – 50 cm clay interval between both sandstone items (length of ruler: 8cm)

Figure 65; 1894 m – Iron Ooliths
Figure 66; GR log OPE-02, with the shale interval as a high GR peak at 1903 m.

Noordwolde-01
[2238-2256]

General
Subcrop of Triassic claystone.
2253 m: Fine sand, low shale content. Sand is cleaning and coarsening upwards, with patches of some very coarse sand. 2249 m: silt to coarse sand, bad sorted. Grain size is increasing to very coarse at 2248.7 m and conglomeratic at 2247.2 m. From 2247 m upwards, the shale content increases, ultimately a clay/siltstone with grains in it, as well as calcite crystals in the mud.

Figure 67; GR log NWD-01
Figure 68; 2246.35-2247.25 Top of clean sandstone. Increase of bioturbation and clay content. (Ruler is 8 cm)

Figure 69; 2252.74-2253.66, cleaning upward sand, very bioturbated at the bottom and clean on top. (Ruler is 8 cm)

Figure 70; 2245.43 m. Coarse grains and little clay clasts are visible. The white dots are calcite crystals.
Facies
The claystones contain very much coarse grains and the sands are highly variable in bioturbation grade, indicating a changing environment or sedimentation grade. The palynological data indicate a marine origin of these sediments. The facies is interpreted as near-shore, possibly in a mouthbar or distributary channel.

Zuidwal-01
Cored interval: [1893-1909 m MD]

General
Fine/very fine sand, reddish/grey/yellowish coloured. Bioturbation and amount of pyrite cement are both variable. The reddish zones contain siderite cement. At 1898 an interval of 20 cm medium grained sand.

Bioturbation
The core shows a lot of bioturbation. Asterosoma, Thalassinoides, Chondrites and Skolithos are found, a varied assemblage of the Cruziana Ichnofacies, associated to lower shoreface.

Figure 71; ZDW-01 1933.8 m MD. Largest burrow in the cored section (Skolitos, reworked by Chondrites).
Figure 72; Left: 1902.3m: red sandstone, siderite cement is abundant. Right: 1902.9m: transition from almost clean to fully bioturbated sandstone. Bioturbation: Skolithos and Chondrites are visible in the left section.

Figure 73; GR log ZDW-01.
GR trends
The GR log in the cored section is relatively constant, with a minimum of 30 API at 1896 m MD and a maximum of 48 API at 1893 m MD. The section 1896-1898 m MD shows a cleaning upward trend in the GR log. The peak of 40 API in the GR log at 1898.3 m MD corresponds to a heavily bioturbated part of the core, while the minimum of 30 API at 1896 m MD corresponds to a very clean section of very fine sand. The same correlation is found in the 1903-1905 m MD section. A maximum of 46 API at 1903.9 m corresponds to a heavily bioturbated section, with a lot of siderite cement, while the minimum of 32 API at 1905.2 m MD corresponds to a very clean section with no bioturbation and few pyrite cement. This supports the hypothesis that the fluctuations in the GR reflect fluctuations in the amount of pyrite cement, related to the amount of bioturbation.

Figure 74; 1902 (upper left) - 1903.4 (bottom right) m MD.

Facies
Based on grain size and Cruziana ichnofacies the core is interpreted as lower shoreface.

De Wijk 17A
[1367-1375]

General
One of the two polymer slabbed cores studied during this project. The De Wijk core comprises a conglomeratic section of 5 m thick, see Figure 75. The upper two meter of the Vlieland sandstone was not available. A general cleaning upward trend was found in the bottom part of the section, and a shaling upward in the top of the section. The sandstone consists of a framework of sand, fining upward from very coarse to very fine, with large clasts in between.

Facies
The sandstone consists of sand and large clay clasts, suggesting a mixed sourcing due to storm events, cf OPE-01. However, the sorting of the framework in this sandstone is
worse than in OPE-01. Knowing that this sandstone is deposited in a faultblock (see Building block 4 and 5), and that palynological data indicate a marine origin, this may be a very proximal coastal environment.

Figure 75; WYK-17-S1. Left: 1372m, conglomeratic base. Middle: 1371 m. Right: 1369m
Wanneperveen 1

General
The Wanneperveen 1 core is very old and of bad quality. No better cores of the Vlieland Sandstone Formation in the Wanneperveen area are available. The core was very fragmentary, resulting in a depth uncertainty of 2 meters for each core piece. The overall impression of this core is a very shaly, poor sorted sandstone, see Figure 76, which is probably comparable to the sandstone found in De Wijk.

Figure 76; WAV-01, 1474 m

Schoonebeek 495A
[938-1020]

General
This cored section comprises the Bentheim sandstone member (44m thick) and the bottom 10 meters of the Gildehaus sandstone member, separated by the shaly Schoonebeek member (27 m thick). The Bentheim Formation is a uniform interval of unconsolidated very well sorted sand, filled with oil. Some intervals are carbonate cemented and not oil filled, see Figure 77. The Gildehaus member is a shaly sandstone, with a lot of glauconite (see Figure 79). It is partially oil-filled (Figure 80).

Facies
The Bentheim sandstone, which is very clean and well sorted, is interpreted as upper shoreface. The Gildehaus is shaly and poorer sorted, containing shale intervals with a lot of glauconite, which indicates deposition on a shelf margin. The Gildehaus sandstone is therefore interpreted as lower shoreface with intervals of marine shale. The Schoonebeek Mb is also a fully marine shale.
Figure 77; SCH-495-S1, 979 m – carbonate cemented interval in Bentheim Mb

Figure 78; 1000m – oil filled sand in the Bentheim Mb
Figure 79; 959m – Glauconitic section in the Gildehaus Mb

Figure 80; 945m – oil-filled section in the Gildehaus Mb.
Appendix B - Posidonia shale

As mentioned in chapter Building blocks, an additional subarea has been investigated. This had to do with a depression in the Base Cretaceous related to the subcropping Posidonia shale, as suggested in Figure 82. Another striking feature in this cross-section was the large amplitude of the Base Cretaceous reflection in this depression, which could be an indication of sand, contrasting with the surrounding shales. A hypothesis was made that the Posidonia Shale Formation was easier erodible than the overlaying Werkendam Formation or the underlying Aalburg Formation. This could even be an interesting new play, as the Posidonia shale is known as a source rock, a depression in the Base Cretaceous unconformity increases chances of preserved VSF and a stratigraphical trap could be formed with the overlaying Vlieland Claystone as a seal.

To test this hypothesis, 5 additional cross-sections were made through the area. However, this depression in the Base Cretaceous unconformity did not occur in other cross-sections, see Figure 84 - Figure 88. A closer look to Figure 82 again revealed that what looked as a depression was in fact nothing at all. The regional grids were erroneous and the Base Cretaceous in this cross-section should be interpreted as in Figure 83. The high amplitude of the seismic reflector at the Base Cretaceous is then explained by interference of the Base Cretaceous reflector with the high amplitude Posidonia Shale reflector.

This appendix shows that the subcropping seismic reflectors have a large impact on the amplitude of the Base Cretaceous unconformity. One must be very cautious about drawing conclusions on the nature of the Base Cretaceous sediment based on the amplitude of the Base Cretaceous reflector. It also shows that interpreting the Base Cretaceous unconformity is not a matter of picking the strongest reflection, but instead requires accuracy in picking the truncations of the subcropping reflectors.
Figure 81; Location of cross-section PosA

Figure 82; cross-section PosA; regional grids indicating a depression in the base Cretaceous where the Posidonia shale subcrops.
Figure 83; new interpretation of the Base Cretaceous in cross-section 7.

Figure 84; Cross-section through the Posidonia subcrop. The Posidonia Shale Fm is the bright red reflector, which is truncated by the Base Cretaceous unconformity. The subcrop map of the subarea shows the location of this cross-section in yellow.
Figure 85; Cross-section through the Posidonia subcrop. The Posidonia Shale Fm is the bright red reflector, which is truncated by the Base Cretaceous unconformity. The subcrop map of the subarea shows the location of this cross-section in yellow.
Figure 86; Cross-section through the Posidonia subcrop. The Posidonia Shale Fm is the bright red reflector in the middle, which is truncated by the Base Cretaceous unconformity. The subcrop map of the subarea shows the location of this cross-section in yellow.
Figure 87; Cross-section through the Posidonia subcrop. The Posidonia Shale Fm is the bright red reflector in the middle, which is truncated by the Base Cretaceous unconformity. The subcrop map of the subarea shows the location of this cross-section in yellow.
Figure 88; Cross-section through the Posidonia subcrop. The Posidonia Shale Fm is the small bright red reflector right of the middle, which is truncated by the Base Cretaceous unconformity. The subcrop map of the subarea shows the location of this cross-section in yellow.
References


