AES/TG/14-03  Static aquifer modelling of a Rotliegend Aeolian Sandstone for the Koekoekspolder Geothermal project.

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Title : Static aquifer modelling of a Rotliegend Aeolian Sandstone for the Koekoekspolder Geothermal project.

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This is for you mom and dad.

Allan
ABSTRACT

The development of geothermal energy projects at the moment in the Netherlands is growing. Where the first doublets were drilled in the West Netherlands Basin is now almost fully developed. Other areas in the Netherlands have also taken interest and are starting to evaluate this possibility. The Koekoekspolder in Overijssel is such a project where the aim is to develop a system producing from the Rotliegend Aeolian Sandstone. This Sandstone is situated at depths of around 2000 meters and holds formation water in the range of 65-73 degrees Celsius. This formation with thicknesses of 90-120 meters in the area has been studied for the purpose of Geothermal development. To understand the flow through this aquifer the geological model must be understood. Study of core, cuttings, seismic and well data showed that the Rotliegend is an Aeolian sandstone with bimodal lamination. This bimodal parallel lamination with predominantly anhydrite pseudo cement present in the coarse laminae have been deposited as sandsheets. The anhydrite is re-crystallized from detrital gypsum grains that has been blown during periods of increased wind intensity from its proximal Anhydrite/Gypsum crusts source. The fine grain laminae that consists of very fine to fine quartz grains have mainly carbonate cement. This carbonate cement can be attributed to diagenesis where precipitation of carbonate cement from formation water took place. The Rotliegend Aeolian reservoirs occasionally contain zones of high density. Zones with an increased density have been attributed to the presence of anhydrite/gypsum. These zones that may reach thicknesses of 15 meters are interpreted as nodular gypsum growth or as gypsum dunes.
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LIST OF ABBREVIATIONS

Wells:

DRO-01 Dronten
KAM-01-S1 Kampen Sidetrack well
KGB-01 Kraggenburg
KKP Koekoekspolder
KKP-GT-01 Koekoekspolder 01 well
KKP-GT-02 Koekoekspolder 02 well
LNH-01 Langenholte well

Formations and members:

NU Upper North Sea Group
NL Lower North Sea Group
CK Chalk Group
KN Rijnland Group
RB Lower Germanic Trias Group
ZEZ1K Zechstein Coppershale member
ROSL Slochteren Formation

Other:

SPB Southern Permian Basin
BPU Base Permian Unconformity
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1. **INTRODUCTION**

The utilization of geothermal energy in the Netherlands has taken flight during the last decade. Compared to other leading countries like Indonesia and Iceland, the Netherlands is still in a research and development phase where optimizing, regulating and sustainably using this renewable energy source is of great importance. The Kyoto protocol on the emissions of greenhouse gasses in 1997 and increasing oil prices have led to a healthy interest in exploring and exploiting this energy potential.

We can distinguish between shallow geothermal and deep geothermal activities where the use of shallow geothermal energy is more established in the Netherlands (Wong et al., 2007). There are three types of shallow geothermal energy applications. The first one is an open two-well system which uses shallow aquifers, generally at depths of less than 500 m, as heat cold storage. This open two-well system in wintertime is used to extract heat from groundwater through one well and pumps the cooled water through the other well back into the shallow aquifer. In summertime this process is reversed by pumping the cooled water back up thus cooling buildings and offices. There were more than 300 of these systems in use in 2005 (Van Heekeren, 2005).

The second shallow geothermal application is comparable to the previous system but uses a closed one-well configuration. During wintertime a fluid is circulated through a borehole where it gets heated by the subsurface formations and pumped back up through an isolated tubing inside the same well. By 2005 more than 1100 of these systems were in use for heating of houses and small buildings.

The third shallow geothermal application is the storage of surplus heat in shallow subsurface aquifers which can be extracted again when needed. By 2007 there were less than 7 of these systems installed.

![Figure 1: Shallow and deep geothermal applications (Verein Geothermie Thurgau, 2013)](image-url)
Deep Geothermal energy focuses on the extraction of heat from aquifers at depths of more than 500 meters. There are two deep geothermal usages at the moment in the world, low enthalpy (between 60 and 180 degrees Celsius) and high enthalpy (>180 °C) of which the former is the method being utilized at the moment in the Netherlands.

For this research the focus will be on deep geothermal low enthalpy extraction of heat through a Doublet configuration (Figure 1). The Doublet is a loop production-injection system where the wells are placed in a connected aquifer unit spaced 1 to 2 kilometers from each other. Preferable this aquifer should have sufficient permeability, porosity, thickness and good connectivity between producer and injector. The produced water from these aquifers, of temperatures warmer than 60 °C, is used to heat the greenhouses and buildings in the vicinity. After heat exchange the cooled water is pumped back into the earth via the Doublet system.

![Figure 1: Doublet configuration](image)

**Figure 1: Doublet configuration**

In the Netherlands there are certain areas that have more deep geothermal potential than others. Depending on the geothermal gradient, which is 3 to 4 °C/100 m, and the presence of suitable stratigraphic units in the subsurface a geothermal potential map of the Netherlands can be drawn (Figure 2). Areas with higher geothermal potential include the provinces of Noord- and Zuid-Holland, Noord Brabant and parts in the North and East of the Netherlands (Wong et al., 2007).

![Figure 2: Temperatures at depths of 2000 meters in the subsurface of the Netherlands (after Wong et al., 2007)](image)

**Figure 2: Temperatures at depths of 2000 meters in the subsurface of the Netherlands (after Wong et al., 2007)**

Up till 2012 a total of 104 applications for geothermal exploration (opsporingsvergunningen) and 4 Geothermal exploitation licenses (winningsvergunningen) were requested or issued. The majority of these applications is situated in the west of the Netherlands producing warm water from formations in the West Netherlands Basin. The increasing number of interest for deep Geothermal energy is partly the result of growing awareness for sustainable energy potential and the stimulation by the Dutch government of Green Energy. Such projects have a life-span...
of more than 30 years and have little effect on the environment. Emissions are negligible compared to the use of fossil fuels and the impact on the surroundings are hardly noticeable when compared to for instance wind energy.

The novelty of this type of energy production in the Netherlands has spurted interest from both independent entrepreneurs and research institutes like TNO and universities. Recent studies by Cees Willems (2012) were dedicated to the understanding of the producing reservoir sandstones of the Van den Bosch concession (West Netherlands Basin). Rutger Smit and Chris den Boer (2012) have both researched optimization strategies to increase the efficiency of deep geothermal doublet systems.

This research will focus on the deep geothermal potential of the Rotliegend Aeolian sandstones in the North-East of the Netherlands. The Koekoekspolder concession is the first deep geothermal project in that region and is therefore of importance for understanding the reservoir potential.

1.1. Koekoekspolder

The Koekoekspolder (KKP) concession is situated North-East of the city Kampen in the Provence of Overijssel (Figure 3) and intends to produce warm water from the Rotliegend formation, Permian age, at depths of approximately 2000 meters. Before permission for exploration was granted by the ministry of economic affairs a study was carried out to determine the potential driven by the local geothermal conditions. A geothermal-development plan was submitted and reviewed by TNO and SodM (Staatstoezicht op de Mijnen) which in turn advised the ministry if the project was sound. Such a development plan contained a geological survey of the subsurface and explored the possibilities of a proficient aquifer. Seismic data and information from nearby wells were used to predict aquifer properties. The final part of a geothermal project application is a drilling plan which holds the trajectories of the wells and the targeted aquifer units.

After approval, the wells were drilled in 2011 and production tests were carried out to determine the suitable units of the Rotliegend. In 2012 the Doublet-configuration was completed and water was pumped from 2 aquifer units with a temperature of around 72 °C.

The KKP geothermal project is currently in a testing phase and is expected to apply for an exploitation license. Because of the marginality of such a project it is important that careful planning is done to reduce the risk of underperformance. The Koekoekspolder project in theory had potential to prosper but encountered complications which are not fully understood.
1.2. Research goals
The aim of this research is to understand the geology and properties of Rotliegend aquifers in the North-Eastern part of the Netherlands so that future projects in the area may profit from this. Which factors are of importance for exploiting an aquifer in the Rotliegend for geothermal purposes. Can these factors be recognized and quantified?

1.3. Available Data
To assess the questions mentioned above a comprehensive study will be carried out using:
- 2D and 3D seismic data
- Core data from the Kampen-01-S1 well
- Well logs from nearby drilled wells
- Well logs and cuttings from the Doublet Koekoekspolder

As a frame for the static aquifer model of the Rotliegend sandstones in the research area 2D and 3D seismic data will be used (chapter 4). Within this frame there are building blocks which will internally characterise this aquifer. An integral building block is a core study that is carried out. The in 1969 drilled well (KAM-01-S1), some 1.5 km from the Koekoekspolder Doublet (Figure 4), was cored and part of this core is available at TNO for viewing or study. In addition, thin slides of carefully selected intervals of this core were made and used for microscopic analysis (chapter 3).
In and around the Koekoekspolder concession there are 6 wells drilled including the KKP-GT01 and KKP-GT02 doublet wells. The remaining 4 wells were probably drilled for the exploration of hydrocarbons. The KKP doublet wells are drilled from the same surface location as shown in Figure 4 and were deviated to the East and to the West. The Kampen-01-S1 well is also situated in the KKP concession. In the table below the Location of the wells are given with the available well logs.

Table 1: Well locations and available well logs

<table>
<thead>
<tr>
<th>Wells</th>
<th>Surface Location</th>
<th>Logs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude</td>
<td>Longitude</td>
</tr>
<tr>
<td>KKP-01</td>
<td>52°34’48.30”N</td>
<td>5°56’57.10”E</td>
</tr>
<tr>
<td>KKP-02</td>
<td>52°34’48.30”N</td>
<td>5°56’57.10”E</td>
</tr>
<tr>
<td>KAM-01-S1</td>
<td>52°35’34.78”N</td>
<td>5°57’53.16”E</td>
</tr>
<tr>
<td>KGB-01</td>
<td>52°38’15.30”N</td>
<td>5°56’59.40”E</td>
</tr>
<tr>
<td>LNH-01</td>
<td>52°33’9.90”N</td>
<td>6°15’40”E</td>
</tr>
<tr>
<td>DRO-01</td>
<td>52°39’31.10”N</td>
<td>5°48’26.80”E</td>
</tr>
</tbody>
</table>
Figure 4: Koekoekspolder concession with the location of the wells
1.4. Outline report

This report comprises an introduction in which the problem statement and aim of this research is explained. The available data is also listed in the introduction. Chapter 2 will provide the geological background of the area being studied. The well log correlations and core analysis of the Kampen core is discussed in chapter 3 which comprises a macroscopic and microscopic analysis. Chapter 4 holds the construction of the aquifer-framework in petrel using seismic and well data. Chapter 5 will cover the petrophysical evaluation. In chapter 6 the static aquifer model is completed with facies and properties modelling using the frame acquired from the seismic interpretation. Finally the results will be discussed in chapter 7. In the Scheme below an overview is given of the workflow. The final result of this research will lead to a static aquifer model of the Aeolian sandstones of the Rotliegend East North-East of the IJsselmeer.
2. GEOLOGICAL SETTING

2.1. Introduction

During the course of Geological history the area of Western Europe had been subjected to various plate tectonic phases. The Caledonian and Hercynian Orogeny (550 Ma - 310 Ma) had resulted in the formation of supercontinent Pangea (De Jager, 2007). These events have left their prints in the subsurface which can still be observed. For this research the focus will be on the times dating back to the Devonian where the Hercynian orogenic cycle took place. Later phases like the breakup of Pangea and the Alpine orogeny will also be discussed briefly.

2.2. Structural setting

The Hercynian orogeny which commenced in the Devonian (400 Ma) and lasted through early Permian (300 Ma) (Ziegler, 1990) was the result of the collision of Laurasia, in the north, with Gondwana from the south (Figure 5). During the Hercynian cycle the Appalachian fold belt in North America, the Mauretanides fold belt in Africa and the Variscan fold belt in Europe were formed (Ziegler, 1990). The Variscan E-W trending fold belt extends from Poland to Portugal and almost reaches the Netherlands in the south at the neighboring town of Aken (Mulder et al., 2003)(Figure 6). During the Namurian (327 Ma) the Variscan foreland basin, north of the Variscan fold belt, was filled with predominantly marine and deltaic sediments. A succession of Westphalian (318 Ma) coastal plain and fluvial plain with intercalated coal seams top Namurian sediments (Jager, 2007).
At the end of the Carboniferous (300 Ma) the area of Western Europe experienced early Permian wrench faulting. Magmatism and thermal uplift were features that developed during this phase. NW-SE trending features that were already established during mid-Paleozoic times were reactivated in the early Permian in response to wrench faulting (Jager, 2007) (Figure 8). As a result the area of the Netherlands, in early Permian, was uplifted and characterized by NW-SE trending swells and relative lows (less uplift). The Texel-IJsselmeer high (Figure 9) being one of the swells and the West Netherlands Basin, Lower Saxony Basin and Lauwerszee Trough areas with less uplift (Figure 9). The Netherlands, during the Permian, was land-locked with the London-Brabant Massif South-West and the Variscan Fold belt East to North-East (Figure 7). The Mid North Sea High and the Ringkobing-Fyn High further isolated the Netherlands in the North-East to North. The Southern Permian Basin stretched from the North-Sea near the UK to Poland in the East. The South Permian Basin is an inland depression within its center a perennial saline lake. It evolved from a series of early Permian rift and wrench basins into a large thermal sag basin in mid Permian times (Mijnlieff, 2011).

Figure 6: Variscan foreland basin during the Carboniferous (Mulder et al., 2003)

Figure 7: South Permian Basin (Geluk, 2007)
Permian sediments derived from the Rhenish Massif and London-Brabant Massif were transported northwards into the Southern Permian Basin. In addition the Carboniferous foredeep sediments that were uplifted during the early Permian were eroded and overlain by younger Permian sediments. The Carboniferous-Permian boundary known as the Base Permian Unconformity (BPU) can be observed in many places in the subsurface of the Netherlands often as an angular unconformity.

Figure 8: Schematic drawing of a wrench fault (Kansas Geological Survey, 2013)

Figure 9: Structural Elements in the subsurface of the Netherlands with the area of interest given in the blue box (De Jager, 2007)
As the Southern Permian Basin continued to subside, due to thermal sag during mid-Permian times (270 Ma), sedimentation could not keep pace thus expansion of the saline lake took place. At the start of the Zechstein a rapid flooding event took place as a result of rifting between Greenland and Norway. The saline lake became connected to the Barents sea which led to deposition of massif anhydrite and salt evaporates (Mulder et al., 2003).

The Mesozoic starts with the breakup of Pangea in the Triassic (250 Ma). Rifting between Greenland and Scandinavia propagated towards the South into the central Atlantic region. A branch of this rift, Central graben, evolved into the north sea area but was far less active and eventually failed. Rifting continued through the early Cretaceous (144 Ma) in the central Atlantic part opening the Atlantic ocean. During that period the rifting phase in the Netherlands area had stopped (De Jager, 2007).

After the mid Cretaceous rift phase of the north Atlantic a period of regional thermal subsidence and rising sea levels followed (De Jager, 2007). During the late Cretaceous (80 Ma) the African-Arabian plate started converging with Eurasia. This gradually developed into the Alpine orogenic system. The Alpine orogeny induced the inversion of Mesozoic extensional basins. Inversion related uplift caused the depositional thinning and erosion of the upper Cretaceous chalk and lower tertiary clastics.

The focus area of this study is in the province of Overijssel given in the blue rectangular box (Figure 9). This particular area lies on the South-Eastern flank of the Texel-IJsselmeer high. During much of the geological history the Texel-IJsselmeer high has been a positive structural...
element. This high was strongly uplifted during the early Permian as a result of the early Permian wrenching. On the Texel-IJsselmeer high rocks of late Permian to middle Jurassic have not been preserved or deposited. Uplift caused erosion down to rocks of Westphalian age. On the flanks of this high Permian rocks unconformably overlie older Carboniferous folded sediments of the Variscan foreland basin. In chapter 2.3.3 a relation will be discussed relating the type of sediment/facies to the palaeotopography. This Texel-IJsselmeer high which is near the area of interest can have a major influence on the sediment dispersal patterns and sediment type.

2.3. Stratigraphy

2.3.1. Carboniferous

The Carboniferous deposits that are present in the subsurface of the Netherlands can reach thicknesses of up to 5.5 km. This sequence of rocks, often thicker than the younger sediments stacked together, are deposited in a foreland basin (Hartog Jager, 2007). The Carboniferous can be subdivided in a carbonate dominated lower Carboniferous and a siliciclastic upper Carboniferous. The late Carboniferous comprises the Silesian which is divided into the Namurian, Westphalian and Stephanian. Deposits of late Carboniferous age in the subsurface of the Netherlands are also known as the Limburg group. The Limburg-group can be subdivided into the Epen, Ubachsberg formations (Namurian), Baarlo, Ruurlo, Maurits, Tubbergen formations (Westphalian) and Lutte formation (Westphalian/Stephanian).

The Epen formation consists of dark grey organic silt/clay sediments which were deposited in a marine/lacustrine environment. The Ubachsberg member is of fluvo-deltaic origin which formed as the system prograded towards the centre of the basin. The Ubachsberg formation is succeeded by the Baarlo formation, a cyclic claystone, coal and sandstone unit. Typical for this formation is the gradual coarsening upwards and presence of coal layers. The Ruurlo formation is a sequence of light grey sandy/silt claystone with intercalated coal layers. The Maurits formation is dominated by floodplain deposits and extensive coal layers. As a fluvial system developed over the area of the Netherlands, stacked channel sandstones were formed. These stacked sandstones are known as the Tubbergen formation. The climate during late Westphalian turned arid resulting in corresponding red-bed facies. These red-bed facies are red-brown clay/silt stone with locally red sandstones of meandering systems. These Red-beds called Lutte formation have been found in the eastern central part of the Netherlands.
2.3.2. Permian

2.3.2.1. Base Permian Unconformity (BPU)

The BPU is an unconformity where the Permian discordantly overlies the Carboniferous. It can be observed in the subsurface of the Netherlands as well as the offshore area. Rocks from the upper Rotliegend overlie deformed rocks from the Namurian to Stephanian (Late Carboniferous) (Geluk, 2007). Although it represents a Hiatus of 20 to 60 Ma years the identification of this unconformity can be difficult in some cases as the upper Rotliegend is not easily distinguishable from the Red beds of the Lutte formation (Westphalian/Stephanian).

2.3.2.2. Formations

Rocks of the Permian can be divided into the lower Rotliegend, upper Rotliegend and Zechstein groups (Geluk, 2007). The lower Rotliegend group, which comprises volcanic rocks, is rare in the subsurface of the Netherlands. The upper Rotliegend consists of the Slochteren formation and the Silverpit formation. The Zechstein group comprises five evaporate cycles in the Netherlands.
2.3.2.2.1. Lower Rotliegend

The Lower Rotliegend rocks which consists of early Permian volcanoclastics have been encountered in the Ems Graben, Dutch Central Graben and Horn Graben (Geluk, 2007). The Emmen volcanic formation located in the North-Eastern subsurface of the Netherlands (Ems Graben) (Figure 9) are basaltic lava flows and pyroclastics (Bergen et al., 2007). These basaltic volcanics were radiometrically age dated and connected to a larger early Permian (290 Ma) volcanic pulse which continues in the subsurface of Northern Germany.

Offshore occurrences in the Dutch Central Graben are linked to younger (late to middle Permian) Volcanic pulses. In the Dutch Central Graben these rocks can reach nearly 150 meters in thickness and have been identified as porphyritic rhyolite lava flows and pyroclastics. In the Horn Graben, according to Dixon et al. (1981), strongly altered basalts of mainly biotite have been found.

2.3.2.2.2. Upper Rotliegend

During the Permian the area of the Netherlands was situated around 20 degrees northern latitude which meant dry arid climate conditions. This led to deposition of extensive Aeolian sediments around a saline lake. Alluvial fan and ephemeral fluvial deposits trend from south to north towards the center of the Southern Permian Basin. The playa lake in the center of the South Permian basin was mainly filled with silt/claystone intercalated with evaporates. These different Facies were deposited lateral to each other and can be found in vertical sequences (Figure 14)

The Upper Rotliegend in the Netherlands is divided into the Slochteren formation and Silverpit formation(claystone and evaporate member). The Slochteren formation comprises of conglomerates and sandstones of fluvial, alluvial and Aeolian origin. The Slochteren formation is split into the upper Slochteren and lower Slochteren by the Ameland member which is a transgressive claystone of the Silverpit formation (Figure 12 & 14).
**Slochteren formation**

The Slochteren formation comprises Aeolian sandstones and sediments deposited in a fluvial environment. There are two major fluvial fairways, one located in the western offshore part of the Netherlands and the other one in the Eastern onshore part (Figure 13). These fluvial fairways trend from south to the north where the depocentre of the SPB is located. The Aeolian sediments include dune, sandsheet and sandflat facies. The type of sediment deposited is believed to be influenced by the topography, accommodation space, sediment input and baselevel fluctuations. Later in this paragraph the influence of topography on sediment type will be discussed.

This formation is important for this research as it is the main aquifer unit. In this report the term Rotliegend is used to imply the Slochteren formation. Rotliegend means “underlying red” in German and is given by miners who targeted the “Kupferschiefer” for its copper content. The red Aeolian sandstones Rotliegend conformable underlies the Kupferschiefer hence the name.

**Silverpit formation**

The Silverpit formation is time equivalent to the Slochteren formation. This silt/clastone sequence with intercalated evaporates has transgressive members like the Ameland and Ten Boer claystones which pinch out towards the South. The Ameland and Ten Boer members represent periods of high water runoff and/or base level (Figure 14).
2.3.2.3. Base Zechstein

The Zechstein starts with the deposition of the “Coppershale” which marks the end of the Rotliegend formation and the beginning of the Zechstein group. This Coppershale is a distinctive homogeneous dark claystone which can reach a thickness of 0.5 meters (Van Oijk, 2012). It is considered as an important synchronous event and can be found across the entire SPB. In some parts of Germany this claystone is being mined for its copper content, hence the name “Coppershale”. This rich in organic matter claystone was the result of an event which abruptly flooded the SPB and ended the deposition of e.g. Aeolian sands in the basin. The Zechstein comprises mainly evaporate sediments deposited during a period of flooding of the basin (Strohmenger, 1994).

2.4. Local geology Koekoekspolder area

The area of the Koekoekspolder (KKP) concession is situated East of the Texel-IJsselmeer High (TYH) (Figure 13). As the TYH is a structural high the area adjacent to this high is presumed also to be relatively uplifted. Figure 15 shows a cross section through the area of the KKP.

The dominant wind direction during Permian times was from the East (Glennie, 1982)
Figure 15: TNO geological survey 2004
2.4.1. The effect of palaeotopography on sediment distribution in the Rotliegend

Sedimentation during the Permian was strongly influenced by the palaeotopography on large and on smaller scale. Topographic contours of the SPB are directly related to the Pre-Variscan and Variscan structural elements. These structural elements controlled the basin architecture and subsidence patterns thus gross thickness and sediment dispersal patterns on a regional scale. On smaller scale the palaeotopography influenced the dispersal patterns, type and thickness of sediments (Mijnlieff et al. 2011). Palaeorelief and sediment distribution are taken as guideline to propose predictive models.

2.4.1.1. Large scale effect

On a large scale the structural configuration of the Southern Permian Basin (SPB) will be compared with the thickness and the distribution of lithostratigraphic units of the Rotliegend. Structural elements as seen in Figure 9 are assumed to be inherited from the Caledonian period and have been reactivated during later orogenies. Some elements like the Dutch Central graben were formed during the Variscan orogeny which also predates the Permian. The hypothesis is that these structural elements define the sediment type and sequence (Mijnlieff et al. 2011). Shown in Figure 16 is a schematic drawing of the different topographical areas. Each of these areas can have different sediment type which are influenced by the local topography. Low flat areas adjacent to the salt lake are more likely to mudflat/sandflat sediments. Dune fields seem to favour relative highs and in areas of low clastic input. Fluvial sediments are preferentially located on gentle slope or in between structural highs.

![Figure 16: Schematic drawing of different topographic settings which influence the sediment type.](Mijnlieff et al. 2011)

The palaeotopography also had an effect on the thickness of the Rotliegend. Shown in Figure 17 is the isopach map of the Rotliegend in the subsurface. Visible is the influence of structural highs on the thickness. Areas with relative uplift (Texel-IJsselmeer high (TYH)) show a decrease (eroded and/or not deposited) in thickness of the Rotliegend while at the centre of the SPB (A') the greatest thickness.
Figure 17: Isopach map of the Rotliegend with cross section A-A’. A schematic drawing is also given illustrating the structural highs and lows. (Mijnlieff et al. 2011)
2.4.1.2. Small scale effect

On smaller scale (few km) dispersal of sediment is also governed by topographic relief. Topography is defined by structural elements, topographic inversion as well as differential erosion. The folded character of the Carboniferous have led to differential erosion. Sandstone units of the Carboniferous are more likely to form topographic highs locally. Softer clay rich sediments which erode easier have formed the local depressions. Shown in Figure 18 is a schematic cross section of differential erosion of Carboniferous formations. The clay rich Maurits formation forms the relative low and is dominated by fluvial deposition. The Hospital ground formation which forms the local high is a sandstone. The main sediment input of the SPB is from the South also shown in the figure. This model proposed by Mijnlieff and Pezzati can predict the presence of sandstones related to the topography.

Figure 18: Schematic cross section of progressive infill. Sediment influx is from the South with the playa lake in the North. (Mijnlieff et al. 2011)
3. DATA AND METHODS

The data listing for this study is given in the Introduction of this report. The following chapter, “Data and Methods”, comprises three parts. The first part (3.1) will hold a GR well log correlation of all wells and the interpretation that arises from that evaluation.

The second part (3.2) will be a study of the Koekoekspolder doublet cuttings (KKP-GT01 and KKP-GT02). That will give an indication of the composition of the rocks of the aquifer units.

The third part (3.3) of this chapter will be a study of the Kampen core. This core will be evaluated macroscopically and microscopically to finally arrive at a facies interpretation.

3.1. Well correlation

Figure 19 shows the orientation and positions of the wells correlated. For a general idea of the location of the wells a more detailed map is given in Figure 4.

![Figure 19: Location of wells in and near KKP concession](image)

The correlation of the wells will be limited to the Rotliegend. For correlation of formations other than the Rotliegend there is a part (well to seismic tie) in chapter 4 devoted to this subject.

The GR log is usually used at first hand to correlate between wells. It was possible to detect the upper boundary (ZEZ1K) in all wells. The lower boundary of the Rotliegend (ROSL) is more difficult to detect and is often not penetrated by the wells. The Rotliegend, in the Netherlands limited to mainly the upper Rotliegend, can be subdivided in the Lower and Upper Slochteren formation. This subdivision is not detectable in the GR logs of the wells near to the KKP concession (Figure 20, 21). The upper Rotliegend in the KKP is therefore seen as one stratigraphic unit. It is a known fact that sequence stratigraphy is more difficult to apply to continental sediments proximal to the source (Figure 14). Closer to the SPB's (Southern Permian Basin) depocentre the presence of transgressional surfaces makes this division more clearly visible.
3.1.1. Correlation 1

Figure 20: Well correlation panel 1 based on GR
3.1.2. Correlation 2

Figure 21: Well correlation panel 2 based on GR
3.1.2.1. Correlation panel 1

Well correlation panel 1 includes 5 wells of which the LNH-01 well lies East of the Koekoekspolder concession and DRO-01 South-West of the concession. The base of the Rotliegend is not always distinctive from the underlying Carboniferous rocks in well logs. This angular unconformity is more visible in seismic sections (chapter 4). If the Carboniferous rocks contain more clay rich mineral this can be detected on the GR for instance in well KGB-01 and KAM-01-S1. In the wells KKP-GT-01, KKP-GT-02 and DRO-01 there is no conclusive evidence the Carboniferous was reached.

The horizon ZEZ1K (Coppershale) is clearly visible on the GR log because of the clay rich composition of this layer. This recognisable clay layer is found almost entirely in the South Permian Basin at the base of the Zechstein. Correlation of this shale can be done with confidence between wells.

As mentioned before the internal correlation of the Rotliegend on the basis of the GR is difficult. There is not much variation visible on the logs. It is therefore difficult to say what the facies distribution is based on this log.

3.1.2.2. Correlation panel 2

Well correlation 2 consists of the 3 wells in the KKP concession with the addition of well KGB-01 North of the concession. The GR readings of well KGB-01 are a bit excessive but the interval of the Rotliegend is still visible and correlation is possible. Like in well correlation 1 the base Zechstein can be detected in the logs of well KGB-01. The base of the Rotliegend was penetrated by this well and that is also seen in the GR logs.

Correlation 2 also lacks the detail to comment on the internal structure of the Rotliegend.

3.1.3. Conclusion well correlation

The well correlation showed that the top and, where possible, the base of the Rotliegend can be correlated between the wells. There is however little detail in the GR log to comment on the Rotliegend. For this to be possible there are other methods of research done later in this paragraph.

In Table 2 the depths of the horizons and the thicknesses of the aquifer unit is given. This information will also be used in chapter 4 where the horizons will be interpreted in the seismic. The well data is a reference to the location of the horizons in the seismic survey.

<table>
<thead>
<tr>
<th>Well</th>
<th>ZEZ1K (TVD)</th>
<th>ROSL (TVD)</th>
<th>Thickness[m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNH-01</td>
<td>2220</td>
<td>2257</td>
<td>36</td>
</tr>
<tr>
<td>KAM-01-S1</td>
<td>1794</td>
<td>1917</td>
<td>123</td>
</tr>
<tr>
<td>KKP-GT-01</td>
<td>1859</td>
<td>1959*</td>
<td>100*</td>
</tr>
<tr>
<td>KKP-GT-02</td>
<td>1850</td>
<td>1937*</td>
<td>87*</td>
</tr>
<tr>
<td>DRO-01</td>
<td>2189</td>
<td>2262*</td>
<td>73*</td>
</tr>
<tr>
<td>KGB-01</td>
<td>1693</td>
<td>1776</td>
<td>83</td>
</tr>
</tbody>
</table>

*Values extracted from seismic evaluation
3.2. Koekoekspolder-doublet cuttings analysis

As part of this research there was an evaluation done on the cuttings retrieved from the wells KKP-GT01 and KKP-GT02. As seen on the well correlation panels there was little information to be drawn from the Gamma Ray logs of those wells. One way to determine the composition of the rocks of the Rotliegend is to analyse the well cuttings and compare it to other well logs (e.g. bulk density) taken.

Figure 22: GR and Bulk Density logs. Four zones with increased density indicated with blue

Figure 22 shows the well correlation of the three wells in the Koekoekspolder concession. The correlation is extended with a bulk density log. The density log shows an increase in density for some intervals in the Rotliegend which are not detectable on the GR log (Figure 22). These increases in density can reach around 3.0 $\frac{kg}{m^3}$. Most of the Rotliegend has a bulk density ranging from 2.2 to 2.4 $\frac{kg}{m^3}$. Study of the cuttings for the well may determine what causes the increase in density.
The cuttings analysis showed that there was not much variation in the composition in the Rotliegend except for intervals that have an abundant content of a white soft material. The bulk of the samples examined was a red fine to medium grained quartz sandstone. In KKP-GT-01 as well as KKP-GT02 there were samples at certain depths that showed a difference in composition. Table 3 gives an overview of minerals observed in the cuttings. The majority of the minerals in the cuttings are fine to medium grains of Quartz with a red coating. Some samples contained an increase of silt. There were also samples examined from the formation above the Rotliegend and they comprised almost 100% of a white soft material that is known to be Anhydrite. This Anhydrite was formed during the Zechstein.

Table 3: Cuttings KKP-doublet with mostly quartz grains. An increase in white soft grains at certain depths given in red.

<table>
<thead>
<tr>
<th>MD [m]</th>
<th>KKP1-GT01</th>
<th>KKP-GT02</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Quartz</td>
<td>White soft grains</td>
</tr>
<tr>
<td>1995</td>
<td>100%</td>
<td>100%</td>
</tr>
<tr>
<td>2156</td>
<td>70%</td>
<td>10%</td>
</tr>
<tr>
<td>2168</td>
<td>95%</td>
<td>1%</td>
</tr>
<tr>
<td>2192</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>2210</td>
<td>80%</td>
<td>5%</td>
</tr>
<tr>
<td>2224</td>
<td>20%</td>
<td>70%</td>
</tr>
<tr>
<td>2258</td>
<td>90%</td>
<td>10%</td>
</tr>
</tbody>
</table>

However there are also intervals in the Rotliegend that contained similar soft white grains as the Zechstein formation above. Mixed in with the soft grains were crystal-like growth grains (Figure 23). These grains can grow up to 1 cm in length and seem to have quartz grains grown into the structure. To determine the mineral composition there was a XRF experiment taken to show which elements are present in the sample. The sample was a mixture of quartz grains, the crystal growth grains and the soft white grains.

The result of the XRF experiment is shown in Figure 24. There are four components that show a relative high quantity in the sample. The three peaks on the left of the picture are Silica (Si), Sulphur (S) and Calcium (Ca). There is a smaller peak which corresponds to the presence of Iron (Fe).
3.2.1. Interpretation cuttings KKP

Interpretation of cuttings of any well is a difficult task due to the mixing of fragments while flowing to the surface with the well-bore fluid. Determining from which depth the fragments are, is therefore one that can lead to errors. Textural features will not be preserved during the grinding and cutting process. Therefore the determination of the facies has uncertainties.

From the cuttings analysis we can conclude that the Rotliegend consists of fine to medium grained sandstone. The red coating of the grains is due to the formation of an oxidation layer which the XRF test also shows. These sandstones are Aeolian sediments. From cuttings the exact facies (Dunes, sandsheet, sandflat) cannot be determined. For that to be possible a core of the well should be examined.
3.2.1.1. Origin Anhydrite/Gypsum zones

The intervals with density of $2.7 - 3.0 \frac{kg}{m^3}$ as shown with the XRF test have relative large amounts of Sulphur and Calcium. We can conclude that this is due to the presence of Anhydrite (CaSO4) or Gypsum (CaSO4.2H2O). The Crystal-like grains also observed in these intervals are interpreted as Gypsum selenite. Combining the information of the Cuttings with the density log the conclusion can be made that there are Gypsum/Anhydrite accumulations that reach thicknesses of up to 15 meters (table 4). There are a few scenarios that could lead to the deposition/preservation of Anhydrite/Gypsum in the zones.

Table 4: Zones of Anhydrite/Gypsum in KKP wells

<table>
<thead>
<tr>
<th>KKP-GT01</th>
<th>KKP-GT02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured depth [m]</td>
<td>Thickness</td>
</tr>
<tr>
<td>Zone 2</td>
<td>2192</td>
</tr>
<tr>
<td>2207.58</td>
<td></td>
</tr>
<tr>
<td>Zone 1</td>
<td>2221.47</td>
</tr>
<tr>
<td>2226.92</td>
<td></td>
</tr>
</tbody>
</table>

3.2.1.1.1. Scenario 1: Gypsum Enterolithics

The presence of Gypsum Selenite can indicate displacive growth from evaporating brines. These phenomena have been studied by Testa and Lugli (1999). The occurrence of these displacive gypsum growth (Enterolithics) is strongly related to the groundwater level. Shallow Subaqueous or continental Sabka environments are often associated with these kinds of depositions. The studies Testa and Lugli conducted in the Messinian evaporitic basin in Tuscany (Italy) showed that Selenite Gypsum generally occurs in massive beds of a few meters thick. These Gypsum enterolithics have vertically elongated crystals and sometimes form clusters which are called cauliflower structures.

Hussain and Warren (1989) have studied Nodular and enterolithic gypsum in a continental sabkha setting (Figure 25). At shallow depths of 1-2 meters above the water table (Vadose zone) nodular gypsum in the form of chicken-wire and enterolithics can formed. Enterolithics are contorted structures of anhydrite or gypsum nodules that grow in a host sediment (Figure 26). The nodules are a result of diagenetic enlargement of gypsum rich zones as it is invaded by sulphate- and calcium-rich brines (Hussain et al. 1989). Nodule growth is driven by the capillary evaporation of pore fluids.

Gypsum selenite crystals and the increase of anhydrite/gypsum in the zones detected in on well logs and cuttings may indicate a continental sabkha origin. Textural features are however not preserved when examining cuttings of a well. Lateral extent of these zones is also not clear with the limited information at hand.
Figure 25: Schematic drawing of Coastal and Inland or continental/inland Sabkha (Yechieli 2001)

Figure 26: Gypsum enterolithics in a Sabkha setting Abu Dabi (Cambridge Carbonates 2013)
3.2.1.1.2. Scenario 2: Gypsum-sand dunes

There is also a possibility of accumulation of gypsum as dunes. The well-known white sands in New-Mexico is an example of such an accumulation. The occurrence of terrestrial gypsum dunes is related to a complex hydrological cycle driven by external factors such as climate and tectonism. The white Sands dune Field is a wet Aeolian system in which accumulation of dune strata is controlled by fluctuation of near-surface groundwater (Szyblo and al., 2010). The source of these gypsum grains are from playa/sabkha depositions which formed during wetter climate conditions. As the climate became more arid the desiccation and deflation of the playa/sabkha deposits initiated. While the deflation continues the gypsum dunes begin to form proximal to the source area. Figure 27 shows the location of White sands dune field in New Mexico. Note the position of Lake Lucero SW to the Gypsum dunes. The area of the gypsum dunes is 500 \( km^2 \) and lies North-East to a deflationary gypsum plane (Kocurek 2006).

![Figure 27: Location of the White Sands dune field with cross section A-A'. (Kocurek et al. 2006)](image)

Figure 28 shows a schematic cross section of Lake Lucero in the SW to the White sands dune field in the NE. The dominant wind direction is from the SW. The Gypsum dunes are accumulating on elevated Pleistocene pluvial Lake Otero strata. Over time the accumulation surface is a function of the water table. This accumulation surface is at or near the capillary fringe of the water table.
Figure 28: Lake Lucero in the South-West and the White Sands dune field in the North-East (Kocurek et al. 2006)
3.3. Core analysis Kampen well

3.3.1. Introduction

The Kampen well has been cored in the upper interval of the Rotliegend between 1811 meters and 1827 meters TVD. The well has also been logged for GR, Sonic and Density. There were no significant hydrocarbon quantities found at the time and the well was shut. It is the only well in the nearby area of the Koekoekspolder that has been cored in the Rotliegend. The upper Rotliegend, that in the Netherlands is called the Slochteren formation, is about 125 meters in thickness in the well Kam-01-S1 (Kampen well). As observed from the GR readings there is no significant change in the log except a peek at 1892 meters. The bulk density logs for this well (Figure 22) also shows little variation in density readings. The core taken is therefore assumed to be representative for almost the entire Rotliegend interval in this well.

The first part of this paragraph will deal with the macroscopic description of the core. The grain-size, coloring and sedimentary structures observed will be documented. Photos are used to illustrate the textural features.

The second part will be a microscopic analysis where determining the mineralogy will be important. Cement identification, mineral growth, grain contacts and boundaries will be carefully examined.

At the end of this paragraph an interpretation is made of the possible facies observed. Interesting features will also be highlighted and theories formed about the possible occurrence/origin of the sediments.

Figure 29: Kampen-01-S1 GR with the cored interval (1811-1827 m)
3.3.2. Macroscopic description lithology
Figure 30: Core description KAM-01-S1, core to log tie (GR)

Figure 31: Legenda core description
The Kampen core at first glance is observed as a homogeneous red sandstone with alternating white and red laminae. As seen in the core description in Figure 30, the core to log tie also shows little variation in the GR readings. The GR reading, for the Kampen well which corresponds to the core, reaches a maximum of 30 API units and is typical for sandstones.

The sandstone which is dominantly red of color has scouring (Sample 1, Figure 34) and fills (medium to coarse grains) up to 3 cm. Horizontal parallel lamination is the most observed feature in this core. This bimodal distribution of very fine and medium to coarse grains will be elaborated with a picture of sample 4 (Figure 32) which is representative for large intervals of the core. Other features include wavy lamination (sample 3, Figure 36) of 1-2 cm thickness. Low angle sets of laminations are visible in the core and can reach thicknesses of 0.5 meters. Wedge shape lamina of medium to coarse grains are also observed. There are some faulted zones visible where the cracks are filled with a mixture of grains and white cement.

At 1827 m the core is not intact and consists of multiple fragments of fine sandstone with some clay content. This mixture of clay and sand results in a less consolidated sandstone which can easily break. Starting at 1826 m the clay content is reduced to zero and is better consolidated. Here the dominant grain size is very fine to fine and is colored red. Thin white bands of coarse grains are visible (Sample 2, Figure 35). As we continue up the core we see an increase in alternation of red and white laminae. This alternation continues till the top at 1811 meters. From 1823 to 1821.5 the whiter lamina increase in frequency. There are intervals of low angle lamination between 1817 to 1815 meters. These intervals of up to 0.5 meters also contain wedge shape fills of medium to coarse grains.

In Table 5 the depths are given of samples taken from the core. This selection was based on the presence of slight variation in textural features. There were also thin slides made from these selected samples and will be discussed in the paragraph “microscopic analysis”.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Depth [m]</th>
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<tr>
<td>1</td>
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</tr>
<tr>
<td>2</td>
<td>1824.55</td>
</tr>
<tr>
<td>3</td>
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<td>4</td>
<td>1818.80</td>
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</table>

3.3.3. Textural features

3.3.3.1. Bimodal horizontal parallel lamination

Horizontal parallel lamination is the most prominent textural feature of the Kampen core (Figure 32). The lower part of this sample contains a 10 cm interval of horizontally parallel laminated sand. As observed there is a clear distinction of white coarser grained laminae that vary in thicknesses of 1 mm to 6 mm and fine grained red laminae varying from 1 to 3 mm. The red laminae consists of very fine to fine grains.
In sample 4 a 2 cm set of low angle laminae is also observed. Some have wedge shape of medium grained laminae alternated with fine grained laminae. In parts of the core these low angle laminae can be found in sets of up to 0.50 m.
Displayed in Figure 33 is the lower part of the core (1823.5-1827.3 meters). The remaining core photos are available in Appendix A. Also noted are the depths of the samples 1-3 taken from this part of the core.

Figure 33: Kampen core, 1823.5-1827.3 m
3.3.3.2. Scouring and fill

A Textural feature that is also present but less abundant is shown in Figure 34 (sample 1).

Figure 34: Photo of sample 1, Scouring filled with medium-coarse grains. Erosional base (Black arrows).

Sample 1 shows an example of scouring where the lower boundary (black arrows) is an erosional surface. This scour is filled with 1.5 cm of medium to coarse grains (c). The upper boundary of this lamina is a more gradual transition of medium-coarse grains to finer grains. Once again the red colors indicate the finer portions while the white coloring corresponds to medium to coarse grain lamina. Indicated with “f” is the finer grained laminae which is red colored.
3.3.3.3. Thin medium-coarse lamination

Sample 2 shows a dominantly red sandstone of fine grains with parallel laminae of medium-coarse grains. The coarse bands are 1-3 mm thick with irregular spacing in between (arrows). This sample was chosen to evaluate the thin regular bands of white grains. Macroscopically it is difficult to determine the cause of the lighter colors. Microscopic analysis will perhaps give more insight on the presence of this textural feature.
3.3.3.4. Wavy lamina

Sample 3 shows an increase in frequency of the coarser laminae with horizontally lamination of 1-3 mm. The lighter wavy laminae visible in the core has medium to coarse grains. There is some scouring visible where the finer grains have been eroded and replaced by coarser particles. Sample 3 shows a 1.5 cm thick band of coarser light colored material that has a sharp interface at the bottom (arrows). To the top of this band the grain size gradually decreases to a fine to very fine grain size. There is alteration between the finer and coarser bands.
3.3.4. From macroscopic to microscopic scale

To obtain a better understanding of the core a microscopic analysis will be carried out. Before the microscopic analysis is done a first step magnification is taken to view the features in more detail.

Figure 37: Kampen core photo of a transition of fine grain lamina (red) to coarse grain lamina at 1813m.

Also visible in the photo is a soft milky white grain with an Iron-oxide coating.

Figure 37 shows a photo of a magnified section. Focusing on the lamina of medium to coarse grains a lighter color is observed in comparison with the finer grained laminae. The color is light due to crosscutting of larger grains and a light colored cement (white arrow) that has filled up the pore space. In the centre of the photo a milky white grain (black arrow) appears to be coated with a thin red layer which are also found along the rims of neighbouring grains. The milky white grain is softer than the grains surrounding it. The sorting of the grains of this lamina is moderate to well sorted.

From this photo not much detail is seen of the fine grain lamina. The color is red which is different from the medium-coarse grain lamina. The microscopic analysis will therefore shed more light on this lamina.
3.3.5. **Microscopic analysis**

The macroscopic analysis showed that there is distinction between coarse grain laminae and fine grain laminae. To further address this observation it is important to do a microscopic analysis. Thin sections from samples 1-4 are used to study the laminae in detail.

3.3.5.1. **Fine grain red laminae**

The grains in the finer red colored lamina are subrounded-subangular and moderately sorted. The red/brown color is caused by a coating visible as rims around the grains (arrows, Figure 38). There are some medium-coarse grains in the finer lamina but they are less abundant. The grains are monocrystalline, polycrystalline and Chert. Feldspar is occasionally observed and distinguishable by the twinning and undulatory extinction when held under polarized light. The cement filling the pore space in the finer laminae have a rhombohedral shape and high order interference colors under polarized light which is common for carbonate cements (Figure 39).
Figure 38: Non-polarized thin section of finer grained lamina. Red/brown coatings of the grains give this lamina a red color which is seen macroscopically. Q (quartz), P.Q. (polycrystalline quartz).

Figure 39: Rhombohedral carbonate cement is predominantly filling the pore space in the laminae of the finer grains. Quartz (Q), polycrystalline quartz (P.Q.).
The use of 2D photo’s is a practice commonly done as a first and fast estimation to determine porosity. These techniques, referred to as image analysis, rely on image detect methods which quantify different colors. The thin section must therefore be treated with a special coloring fluid to highlight the pores. A condition for this technique to work is the presence of visible pore space for the coloring fluid to occupy. Figure 39 shows the lack of pore space present in the finer lamina for image analysis. Estimating porosity visually from thin sections for this core will therefore be done by means of lab measurements of core plugs.

3.3.5.2. Coarser grain light laminae

The coarser grain laminae comprises largely monocrystalline Quartz and some polycrystalline Quartz which are moderately to well sorted. An Iron coating (arrows in Figure 40) is visible around the grains. At grain contacts the Iron coating is not always or vaguely present. Cementation in the pore space is a pore-filling cement that entirely occupies the space in between the grains (Figure 41). This cement, that shows higher order interference colors, lights up under polarized light. Anhydrite seems to fit the description of the cement being described.
Figure 40: Coarse grain lamina. Arrows indicate a red coating around the quartz grains. Quartz (Q), polycrystalline quartz (P.Q.), Anhydrite (A).

Figure 41: Coarse grain lamina under polarized light. Quartz grain lamina with high interference color Anhydrite (A) cement in the pore space.
Visually determining the porosity for the coarse laminae is, like in the case for the finer laminae, an unreliable method. Pore-filling Anhydrite cement is in this case the limiting factor of visually determining the porosity.

3.3.5.3. Cementation

Figure 42: Coarse grain lamina. Quartz grain (Q) appears to be floating. Oversized pores (O.P.) with Anhydrite cement (A).

The quartz grains, in the coarse grain laminae, sometimes have minimal contact with each other and some appear to be floating in Anhydrite cement (Figure 42). This observation can be useful to explain the diagenetic history of this sandstone.

Figure 43: Quartz grain with two phases of silica growth. The black transparent arrow indicates a previous grain boundary, while the red arrow indicates the boundary that has been eroded during the latest transportation of the grain and coated with a red oxidation layer. The green arrow represents the silica growth of the last burial diagenesis. (1)
indicates the first phase silica growth, (2) indicates second and latest phase silica growth.

As observed in the previous photo’s (Figure 39, 41) the conclusion is drawn that there are two dominant cements. A carbonate cement that mainly occupies the pores in the finer lamina and Anhydrite that is more common in the coarser lamina. There are however portions where both types of cements occupy the same pores. Interesting is the growth of the cements relative to each other. In Figure 43 the Anhydrite cement (A) occupies the centre of the pore space as elongate laths. Carbonate cement seems to be present in the pore throats and along the quartz grains. There is however evidence of carbonate cement present as inclusion (Figure 44). The arrows indicate rhombohedral crystals of carbonate cement. The pore space around these carbonate cements are further occupied with Anhydrite.

Other cements recognized in smaller quantities are Kaolinite (not in photo’s) and quartz (Figure 43). The quartz growth as seen in Figure 43 (arrows) appears to have been formed during multiple erosional, transport and deposition phases.

Figure 44: Rhombohedral shape crystals of a carbonate cement (arrows) are enclosed by Anhydrite cement. The pore is part of the coarse grained lamina.
3.3.5.4. Summary

The lithology description and microscopic analysis yielded a number of observations:

1. The sandstone has a bimodal distribution of coarse and fine grains.
2. The sandstone shows horizontal parallel and low angle lamination with sometimes wedge shapes varying from 1 mm to 25 mm.
3. The coarse laminae have oversized pores filled with Anhydrite cement while the finer laminae are more densely packed and have a dominant carbonate cement filling.
4. The sandstone predominantly comprises Quartz grains. Little amounts of Feldspars have been encountered in the thin sections.
5. The Quartz grains seem to have gone through multiple phases of erosion, transportation and deposition.

In the table below the percentages of the minerals observed are given. The porosity could not be determined microscopically and is therefore not included in Table 6. Monocrystalline quartz is the dominant mineral observed in the thin sections followed by polycrystalline quartz. Other minerals are mainly feldspar and opaque minerals.

Autigenic minerals have been formed in the pores between the detrital grains. They are either formed from chemically weathered detrital minerals or have crystallized out from pore fluids. Anhydrite and Calcite/Dolomite are the dominant authigenic minerals. Pore-filling Kaolinite and quartz overgrowths are also encountered.

<table>
<thead>
<tr>
<th>Table 6: Mineral composition</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detrital composition</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Monocrystalline Q</td>
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<td>28%</td>
<td>35%</td>
<td>41%</td>
</tr>
<tr>
<td>Polycrystalline Q</td>
<td>25%</td>
<td>23%</td>
<td>35%</td>
<td>29%</td>
</tr>
<tr>
<td>Chert</td>
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<td>Other</td>
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<tr>
<td>Authigenic minerals</td>
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<td></td>
</tr>
<tr>
<td>Anhydrite</td>
<td>17%</td>
<td>11%</td>
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<td>6%</td>
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<tr>
<td>Gypsum</td>
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<tr>
<td>Calcite/Dolomite</td>
<td>11%</td>
<td>11%</td>
<td>3%</td>
<td>12%</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>1%</td>
<td>11%</td>
<td>2%</td>
<td>3%</td>
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</tbody>
</table>

A difference in mineral composition is recognizable when the fine and the coarse grain laminae are studied separately. The macroscopic analysis showed visible color differences between both laminae. The microscopic analysis enabled a more detailed view of the minerals present. Table 4 gives a quantitative overview of the minerals present in the fine grain laminae and the coarse grain laminae.
Table 7: Mineral composition of fine and coarse laminae

<table>
<thead>
<tr>
<th></th>
<th>Fine grain red lamina</th>
<th>Coarse grain light lamina</th>
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<tbody>
<tr>
<td>Detrital composition</td>
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<tr>
<td>Monocrystalline Q</td>
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<td>Gypsum</td>
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<tr>
<td>Calcite/Dolomite</td>
<td>20%</td>
<td>1%</td>
</tr>
<tr>
<td>Kaolinite</td>
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<td>3%</td>
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</tbody>
</table>

Fine grain laminae:
The fine grain laminae composes for 50 percent of monocrystalline quartz. The dominant pore-filling cement is Calcite/Dolomite.

Coarse grain laminae:
Monocrystalline quartz is also the most frequently observed mineral in the coarse grain laminae. The pore spaces are predominantly occupied with Anhydrite cement.
3.3.6. Porosity and Permeability data

Table 8: Porosity and permeability measurements from core plugs (Nederlandse olie- en gasportaal, 2013)

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Porosity(%)</th>
<th>Hor.perm (mD)</th>
<th>Depth (m)</th>
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<td>7.9</td>
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</table>

Back when the KAM-01-S1 well was drilled in 1969 the NAM also performed core measurements to determine the porosity and permeability. Table 8 shows the results of lab experiments performed in 1969. This data is available at the "Nederlands olie- en gasportaal". Coreplugs were
taken in horizontal orientation every 30 cm and the porosity and permeability was measured in the lab.

**Figure 45: Porosity and permeability values at given depths of the Kampen core**

Figure 45 shows the porosity and permeability at given depths. There is not a wide spread in values for both the permeability and porosity. These measurements emphasize the observations.
made in the macroscopic and microscopic analysis that the Kampen core is one of little lithological variation.

To illustrate the spread of the porosity and permeability values histograms are made (Figure 46-47). The porosity measured with lab experiments show mean values of around 16-17% and varies between 10% and 20%.

![Porosity distribution](image)

**Figure 46: Porosity distribution KAM-01-S1**

The permeability values are log-normally distributed as is shown in Figure 47. There is a peak in values around 4-10 mD and can reach up to 32 mD

![Permeability distribution](image)

**Figure 47: Permeability distribution KAM-01-S1**
3.3.6.1. Porosity-Permeability relation

![Porosity-Permeability crossplot](image)

\[ y = 1.863e^{0.0789x} \]
\[ R^2 = 0.028 \]

**Figure 48: Porosity-Permeability crossplot Kampen core**

\[ K = 1.863e^{0.0789\phi} \]
\[ K = \text{permeability} \]
\[ \phi = \text{porosity} \]

Poro-Perm relations are used as a petrophysical guideline to determine permeability of similar reservoir units in nearby wells that have no cores available. This relation is based on the properties determined from laboratorial experiments. By plotting the permeability on log-scale against the porosity (normal scale) usually a linear relation can be found. Implementing this relation where the porosity is known from well logs a permeability can be calculated. A prerequisite however is that a useful relation can be determined from the data set. Figure 48 shows a dataset that has no trend. Fitting of a trend line through these data points is therefore not a useful method to predict permeabilities for similar rocks.
3.3.7. Interpretation Kampen core

3.3.7.1. Facies

Horizontal and low-angle lamination in Aeolian setting have been interpreted as Sand-sheet deposits by studies carried out by Fryberger in 1979. He studied the transitional facies (sand-sheet) between high angle Aeolian dunes and non-aeolian facies in Colorado. His studies showed that low-angle sand-sheet deposits originate mainly by gentle deceleration of wind. This can be the case if the area is in the lee of small topographic features. Low to moderate velocities generally remove fine sand from exposed areas and deposits the sand in topographically sheltered places resulting in texturally homogeneous sets of laminae (Fryberger, 1979).

The horizontal and low-angle lamination observed in the Kampen core have strong similarities with the facies that Fryberger described during his studies in 1979. The finer particles have been deposited under normal wind conditions while the coarse grains were transported during higher intensity regimes for example storms.

The low angle and wavy lamination are attributed to the existence of wind-ripples during time of deposition.

The conclusion of the of the macroscopic lithology description is that the sandstone is an Aeolian sand-sheet deposit.

3.3.7.2. Provenance sediment

The Kampen core comprises mainly quartz grains that underwent at least two cycles of transportation and deposition. The evidence supporting this theory is given in Figure 43. Eroded grain boundaries imply that the grains were already once transported and deposited. Studies (Gaupp, 2011) have shown that sediment deposited in the Southern Permian Basin in the Netherlands were derived from the Rhenish massif and London Brabant massif South-South-East of the Basin. This theory is confirmed by the evidence observed in the thin sections. The lack of Feldspar also supports the theory that the sediments are reworked. Feldspar are minerals more easily degraded, compared to quartz.
3.3.7.3. Diagenesis

A range of authigenic minerals are observed during the microscopic analysis. Most prominent is the Anhydrite pore-filling cement in the coarse grained laminae. The occurrence of this type of cement predominantly in the coarse grain laminae can be contributed to the deposition of detrital gypsum. This theory is based on the following facts:

- The presence of detrital gypsum grains in the coarse grained laminae (Figure 37). The red oxidation rim around this milky white soft grain suggests a detrital heritage. The oxidation coating which is common for Aeolian sediments is formed during or shortly after deposition.

- Oversized pores present in the coarse grain laminae suggests recrystallization of detrital gypsum into Anhydrite pore-filling cement. The space formerly occupied by detrital gypsum is replaced by Anhydrite thus creating oversized pores. This Anhydrite is actually a pseudo-cement which was a gypsum grain.

- The absence of Anhydrite-pseudo cement in the finer grained laminae can be contributed to the non-deposition of detrital gypsum with the fines. Gypsum has a higher material density and transportation of the grains is dependent on wind energy. Storms and gusts have probably enough energy to transport gypsum grains together with other coarse grains to form coarse grain laminae.

- Inclusions of calcite/carbonate cement in the Anhydrite pseudo-cement indicate early diagenesis of Gypsum/Anhydrite followed by precipitation of carbonate cements (Gaupp, 2011).
4. SEISMIC INTERPRETATION

4.1. Introduction

This chapter is devoted to the processing of the seismic data of the area. Seismic data is needed to construct a structural framework for the aquifer (top and bottom) which will then be converted to depth. The reflection seismic dataset (Two Way Traveltime) is evaluated in the seismic platform Petrel from Schlumberger. The first step is a well to seismic tie which is needed to align seismic responses from the dataset with horizons interpreted from well logs from the wells. After the well-tie process is completed horizon interpretation in the seismic cube follows. Fault interpretation and building a velocity model are necessary to complete the final step which is time-depth conversion.

4.2. Seismic data

A 3D seismic survey covers the Southern part of the area and is integrated with a previously taken 2D seismic survey to complete the North-Western part (Figure 51). The 3D seismic dataset (TWT) is a survey that was carried out by NAM in 1997. The coordinate system is “Rijks Driehoekstelsel” and the units are metric. Figure 50 gives an overview of the SEG conventions regarding polarity and responses on seismic trace recordings.

The 3D dataset L3NAM1997A contains 1190 inlines (IL) and 614 crosslines (XL). This dataset has been made public in 2007. It is available at the “Netherlands Oil and Gas portal” (NLOG). Table 9 gives the geometric properties of this 3D dataset.
The 2D data lines (TWT) have not been acquired in the same survey as the 3D data. These lines had to be loaded into Petrel individually. There are some differences in alignment of these two data sets. Therefore the 2D seismic lines have been discarded in overlapping areas where they do not match the 3D data. In the North-Western part, that is covered by the 2D seismic, the resolution of the interpretation is lower. Some processing attributes that require 3D seismic were also not used in areas the 3D seismic survey did not cover.

The 2D data is also non-SEG zero phase that lines up with the 3D survey.

Table 10: List of 2D seismic lines

<table>
<thead>
<tr>
<th>Name</th>
<th>number Inlines</th>
<th>number xlines</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3NAM1997A</td>
<td>1190</td>
<td>614</td>
</tr>
</tbody>
</table>

<table>
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</tr>
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<tbody>
<tr>
<td></td>
<td>6211</td>
<td>7400</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>End line</th>
<th>inline</th>
<th>xline</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4937</td>
<td>5550</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>space between inline</th>
<th>25 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>space between xline</td>
<td>25 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Length inline</th>
<th>29725 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length xline</td>
<td>15325 m</td>
</tr>
</tbody>
</table>
4.3. Well to seismic tie

Checkshot data is available for the wells KAM-01-S1 and LNH-01. Checkshot data would make it possible to match the wells, which are given in depth, with TWT from the Seismic data. The well LNH-01 is located in the realm of the 3D seismic survey. Therefore the well to seismic tie could be established for this well. The Kampen well is located on the edge of the study area where the 3D seismic is unavailable and therefore no well to seismic tie was possible for this well.

For wells that do not have checkshot data (see Table 1) there will be a manual conversion to match the wells with TWT from the seismic data. The LNH-01 well (checkshot data) will then serve as a reference to guide the process of well to seismic tie.

Based on well log signature the distinctive transition surfaces (Formation boundaries or ‘well tops’) in the well LNH-01 were interpreted. This interpretation was already done in previous evaluations from which the results will be used for this study. The distinctive surfaces recognized in the well are marked by well tops (Figure 52) and are often transitions of rocks with different properties. The well tops can be tied to seismic responses. Figure 52 shows the well LNH-01 with a GR log and the well tops which are tied to the seismic log. Figure 52 also includes the Koekoekspolder doublet wells which have been manually tied to the seismic data.
Figure 52: Well to seismic tie of LNH-01. Manual conversion of the KKP-GT01 and KKP-GT02 from depth to TWT.

The wells of the doublet KKP do not have checkshot data. The process of tying the KKP wells to TWT was to manually pick the seismic responses in TWT and connecting it to stratigraphic markers in the wells (well tops). This is an iterative process that requires constant adjustment.

Figure 53: The distinctive layers in the subsurface. These bounding surfaces mark the end or the beginning of rocks deposited during different geological times.
4.4. Horizon interpretation

The well to seismic tie was the first step to horizon interpretation. By using the markers (well tops) in the wells a guided picking of seismic reflectors can be established. These horizons are also useful for the time to depth conversion and will be elaborated later on in this chapter. The focus of this study is the Rotliegend. This formation is bounded by rocks of Carboniferous age below and of Zechstein age on top. The bounding surface of the Carboniferous to the Rotliegend is known as the Base Permian Unconformity. The end of the Rotliegend is marked by the presence of a shale layer called the “Coppershale” (ZEZ1K in Figure 55).

4.4.1. Base Rotliegend

The Base Rotliegend is recognisable as an angular unconformity in the seismic data. The Rotliegend discordantly overlies slightly to steeply dipping rocks of the older Carboniferous (Figure 54). In the seismic section this unconformity is clearly visible and is also known as the Base Permian Unconformity (BPU). Figure 54 and Figure 55 show the Rotliegend bounded by the Coppershale (ZEZ1K) and the Carboniferous. Confirmation of this boundary has been done in wells through well logs were this transition is also visible. The BPU is more easily recognized when the seismic dataset is flattened at the base Zeckstein (ZEZ1K).

Figure 54 shows a seismic section flattened at the base of the Zechstein. This is to illustrate the inclined Carboniferous and the BPU. Also notice the varying thickness of the Rotliegend which as explained in Chapter 3 is influenced by the palaeotopography, accommodation space and sediment influx.

![Figure 54: Seismic section flattened at the Base Zechstein to illustrate the BPU](image-url)
4.4.2. **Base Zechstein**

The base Zechstein is formed by the Coppershale and is an important layer in the subsurface of the Netherlands. It marks the end of the Rotliegend rocks and the beginning the Zechstein. On the seismic section it is visible as a positive (blue) reflector due to the difference in acoustic impedance with the overlaying evaporates of the Zechstein (Figure 55). The anhydrite/salt has a higher acoustic impedance compared to the underlying Shale/sand which causes the soft kick.

**Figure 55: ZEZ1K “Coppershale” (Base Zechstein) and Base Rotliegend. The angular unconformity of the Carboniferous and the Rotliegend also known as the BPU**
4.5. Fault modelling

4.5.1. Fault interpretation

Figure 56 represents a composite line that includes the wells KKP-GT01 and KKP-GT02. The Rotliegend is visible between the dashed horizons. Faults can be manually picked for each composite, in- and cross-line. As we move along these cross sections faults can be drawn systematically.

Figure 56: The yellow box is the cross section being displayed in Figure 57

![Figure 57: Manually picking faults in an interpretation window. The dashed horizons indicate the Rotliegend. Yellow arrows indicate compressional direction during the Alpine Inversion phase](image)
As noticed from Figure 57 it is sometimes difficult to pick the faults and see to what extend the faults are present in the subsurface. To aid with the interpretation there is a seismic attribute called Ant tracking which can be useful to track faults. The Ant tracking attribute is a coherent signal tracking based on “swarm intelligence” to find optimal connectivity for fault features using an edge detection volume. This principle is used to highlight lines that are likely to be faults. The result is given in Figure 58. Displayed is a time slice (z-direction) so the view is an aerial one. The box in the upper left corner is the Koekoekspolder concession where dark blue lines can be observed. These lines may represent fault surfaces and together with the manual picked faults a fault network can be established.

The manually picking of faults was restricted to the Koekoekspolder concession. Figure 59 shows the interpreted faults and fault-names that have been assigned to each fault. The majority of the faults are oriented NW to SE. This orientation corresponds to the main NW-SE fault systems that were already established before the Permian. The latest tectonic phase also known as the Alpine Inversion caused compressional deformation in the subsurface of the Netherlands (Ligtenberg, 2011). The faults interpreted in the KKP area related to this Alpine inversion. This inversion of pre-existing NW-SE faults are visible in Figure 57. The compression was from the South and the North and resulted in inverted fault blocks.
4.5.2. Fault model

The final fault model consists of 2 large faults (arrows) in the centre of the Koekoekspolder concession. The 12 remaining faults interpreted in the model are either connected faults of the SE-NW trending faults in the Koekoekspolder concession.
2 large faults or smaller separate faults. For the scope of this research the faults were modelled with linear pillars to simplify the model. In between the KKP-GT-01 and KKP-GT02 there is a set of smaller faults interpreted.

<table>
<thead>
<tr>
<th>Fault name</th>
<th>Fault name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Fault E-W</td>
<td>Fault E-W 1</td>
</tr>
<tr>
<td>Connecting Fault E-W 1</td>
<td>Fault E-W 2</td>
</tr>
<tr>
<td>Main Fault SE-NW</td>
<td>Fault E-W 3</td>
</tr>
<tr>
<td>Connecting Fault SE-NW 1</td>
<td>Fault E-W 4</td>
</tr>
<tr>
<td>Connecting Fault SE-NW 2</td>
<td>Connecting Fault E-W 4-1</td>
</tr>
<tr>
<td>Fault SE-NW 1</td>
<td>Connecting Fault E-W 4-2</td>
</tr>
<tr>
<td>Fault KKP 1</td>
<td>Connecting Fault E-W 4-3</td>
</tr>
<tr>
<td>Fault KKP2</td>
<td></td>
</tr>
</tbody>
</table>

4.6. Time-depth conversion

The time-depth conversion process is necessary to convert the aquifer that has been interpreted in the seismic (TWT) to depth. This process starts with creating a grid, with the use of pillar sticks (Figure 61), and applying a layer cake velocity model to convert the aquifer to depth. In the end it is important to be able to quantify the aquifer in terms of volume. Therefore the dimensions of the aquifer should be one that gives information about the thickness and depth.

4.6.1. Building 3D grid

For the Petrel software to be able to construct a grid it needs reference pillars across the thickness of the aquifer. These pillars are subtracted from the fault model. The process of building the 3D grid is called pillar gridding.

The default size for a grid block is 100 by 100 meters in the Petrel software. For this project the grid size is set to 50 by 50 meters to create a more detailed aquifer model.

The I-direction for the gridding process is along main fault East to West. The J-direction will automatically be perpendicular in N-S direction (Figure 61).
4.6.2. Layer cake model

A velocity model is needed as input for the time-depth conversion. This model holds information about the acoustic velocities in the subsurface. For this project it was sufficient to see the earth as a layer cake with the layers possessing different properties. The earth can be seen as layers stacked on top of each other (Velasquez, 2012). With this in mind a division is made and given in Figure 52. In Figure 62 there is an explanation of the different geological times in which the layers are deposited. The velocity model used for this study counts 7 layers to the base of the Rotliegend.

According to Dalfsen et al. (2007) the subsurface of the Netherlands has been devided in a much more detailed layer cake as given in Figure 62. For the specific area however not all layers are present in the subsurface and a layer cake model of 7 layers was sufficient. The overburden layers on top of the Rotliegend can be seen as layers that each have specific acoustic properties.

![Layer cake model by Dalfsen et al. 2007](image-url)
4.6.3. V0-K velocity models

Each layer in the velocity model can be described with the relation given in formula (1) when considering the layers to be dominated by burial compaction. This model is suited for basin sediments where burial compaction plays an important role.

\[ V(Z) = V_0 + K \cdot Z \]  

\( V(Z) \): Velocity of layer at depth \( Z \)

\( V_0 \): normalized velocity

\( K \): constant

\( Z \): depth

The \( V_0 \) and \( K \) are values that can be derived from sonic logs taken from wells in the surrounding area. The Velmod-2 model by Dalfsen et al. (2007) is a regional model derived from well logs in the Netherlands. The parameters will serve as an initial estimate of the values \( V_0 \) and \( K \). For each formation the \( V_0 \) can be variable depending on the location of the formation. The \( K \) value is assumed to be constant for the same formation.
With Petrel it is possible to run a time-depth conversion and to compare the horizon depths of the converted model to the known depths of the horizons in the wells. If the difference between the depths in the model and the wells is within acceptable range (0-30 m) the operation can be called successful. This time-depth conversion is an iterative process with constantly tweaking the values to reach an optimum result.

Table 12 shows the position and depth of the top and bottom of the aquifer in the 3 wells used for time-depth conversion. In the last Column (Difference after) the residuals are given which indicate the accuracy of the time-depth conversion process. To match the depths of the top and bottom in the wells a correction was applied which reduced the residuals to zero.

<table>
<thead>
<tr>
<th>ZE_Base</th>
<th>Well</th>
<th>X-value</th>
<th>Y-value</th>
<th>Z-value</th>
<th>Horizon after</th>
<th>Difference after</th>
</tr>
</thead>
<tbody>
<tr>
<td>KKP-GT-01</td>
<td>193946</td>
<td>510414.6</td>
<td>-1858.79</td>
<td>-1831.38</td>
<td>-27.41</td>
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</tr>
<tr>
<td>KKP-GT-02</td>
<td>192398.4</td>
<td>510855.7</td>
<td>-1849.47</td>
<td>-1862.66</td>
<td>13.19</td>
<td></td>
</tr>
<tr>
<td>KAM-01-S1</td>
<td>194125</td>
<td>511775</td>
<td>-1789.45</td>
<td>-1815.96</td>
<td>26.52</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RO_Base</th>
<th>Well</th>
<th>X-value</th>
<th>Y-value</th>
<th>Z-value</th>
<th>Horizon after</th>
<th>Difference after</th>
</tr>
</thead>
<tbody>
<tr>
<td>KKP-GT-01</td>
<td>194026.3</td>
<td>510393.5</td>
<td>-1958.8</td>
<td>-1920.79</td>
<td>-38.01</td>
<td></td>
</tr>
<tr>
<td>KKP-GT-02</td>
<td>192344.3</td>
<td>510899.7</td>
<td>-1937.33</td>
<td>-1920.81</td>
<td>-16.52</td>
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</tr>
<tr>
<td>KAM-01-S1</td>
<td>194125</td>
<td>511775</td>
<td>-1912.59</td>
<td>-1936.61</td>
<td>24.03</td>
<td></td>
</tr>
</tbody>
</table>
4.6.4. Aquifer model in depth

The time-depth conversion is a process that uses the V0-K relation form the layers above the base Rotliegend to convert the aquifer from TWT to depth. The interval between the base Zechstein and base Rotliegend is the focal point of this research. The faults and horizons that were interpreted in the time domain will now be displayed in the depth domain. The continuing modelling will now also take place in the depth domain. That includes the Facies and Properties modelling in chapter 6.

Figure 65: Aquifer model is now displayed at depth [m]

Figure 65 shows the Rotliegend aquifer now converted to depth. The result is an aquifer situated around 1800-1900 meters depth.

To have an idea of the thickness of the Rotliegend aquifer in the Koekoekspolder concession there a thickness map created and given in Figure 66. The aquifer increases in thickness to the northern part of the Koekoekspolder concession. Outside the concession in the South Western and North Western part the aquifer seems to be missing.
Figure 66: Thickness map of the Rotliegend (meters)
5. PETROPHYSICAL EVALUATION

5.1. Introduction

The petrophysical evaluation has been carried out by TNO. In this paragraph the results of the evaluation will be discussed. Important for the area of interest are three wells, KAM-01-S1, KKP-GT01 and KKP-GT02. These wells will be used in further modelling of the aquifer. Other wells like Dronten, Kraggenburg and Langenholte are located outside the area and are therefore considered less relevant.

5.1.1. Gamma Ray, Bulk Density, Porosity and Permeability

The GR, RHOB, NPHI and DT are well logs that are directly measured with logging tools in the borehole. The well panel of these logs (Figure 67) shows slight variation on the GR log which was already concluded in paragraph 3.1. The RHOB and NPHI logs however show more variation in rock properties which were not detectable on the GR. Examining the cuttings for the wells (KKP) showed the presence of anhydrite/gypsum zones that have been deposited either as nodular gypsum growth or as detrital gypsum dunes. The extent of these zones is not known. Therefore lateral correlation of these zones between wells is uncertain if not impossible.

Figure 67: GR, Bulk density, Neutron porosity
5.1.2. Effective porosity

The effective porosity log can be created by combining the directly measurable logs RHOB and NPHI. The result is given in Figure 68. The porosity logs show zones of very low porosity which coincide with the anhydrite/gypsum zones found in chapter 3.2.1. The conclusion can be drawn that a low or zero porosity value can be assigned to zones of anhydrite/gypsum. The thickness of the anhydrite/gypsum zones in the Koekoekspolder concessions appears to be variable between the three wells.

The aquifer in the Kampen well shows the best vertical continuation and highest porosity values of all three wells. The lower 20 meters of the Rotliegend in the Kampen well has an effective porosity of 15 to 25 percent. There is a 5 meter zone that has low porosity values but above that almost a 50 meter interval of porosity between 20 and 30 percent. The porosity in the upper part of the Rotliegend gradually decreases. This is also the interval where the Kampen well has been cored. There is no evidence available to comment on the increase of the effective porosity in the middle part of the aquifer. The assumption is therefore made that the facies encountered in the core is representative for entire Rotliegend. There is however an exception for the 5 meter interval in the lower part that shows lower porosity values.

In the KKP-GT-01 well there is no substantial evidence that the Carboniferous is reached. In this research there is no information about lower part (10-20 meters) of the aquifer in this well. The logging tools have started at 1950 meters TVD. The effective porosity is between 0 and 15 percent in the lower 50 meters. This part of the aquifer also includes the zones that have the anhydrite/gypsum accumulations. The upper 35 meters in the KKP-GT01 well has fairly good porosity between 10 and 25 percent.
The KKP-GT-02 well shows similar trend as the KKP-GT-01. It is also assumed that the carboniferous was also not reached in this well. The effective porosity in the lower part of the aquifer is very low and it seems that there is even an even longer part of the aquifer not logged compared to the KKP-GT-01 well. The upper 45 meters of the aquifer along KKP-GT-02 has porosities of 15 to 25 percent and is in that respect better than KKP-GT-01.

5.1.3. Permeability

\[ K = 1.1978e^{27.093\phi} \]

\( K = \text{permeability} \)
\( \phi = \text{porosity} \)

Figure 69: GR, porosity and Permeability logs

The permeability is calculated by evaluating core data retrieved from wells in the area. As in paragraph 3.3.6, samples were taken from the cores from different wells. These sample core plugs were used for porosity and permeability measurements in the laboratory. Figure 70 shows a cross-plot of the average permeability and the average porosity. The empirical relation that arises from this plot can be implemented to calculate the permeability where cores have not been taken in wells.
Figure 70: Porosity-Permeability cross plot of the Rotliegend near the KKP

\[ y = 1.1978e^{27.093x} \]
6. STATIC MODELLING

Facies modelling uses information from well logs, core data and literature to create a spatial distribution of the facies interpreted. The facies will be populated within the boundaries of the Rotliegend which is obtained from seismic interpretation.

6.1. Facies definition

Figure 71: Interpretation of the facies
Figure 71 shows the facies interpretation made for the wells in the Koekoekspolder concession. As seen in the figure there is mainly sandstone in the aquifer with some anhydrite/gypsum zones. The Facies interpretation is a combination of cuttings analysis, core analysis en log interpretation. Table 13: Facies distribution parameters shows the criteria that were used to define the facies types in the wells. The Bulk density and porosity log were chosen as primary indicator. For the detection of shale use was made of the gamma ray but this log was less effective to differentiate between Sand and Anhydrite/Gypsum.

<table>
<thead>
<tr>
<th>Log</th>
<th>Facies distribution parameters</th>
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</thead>
<tbody>
<tr>
<td>GR [API]</td>
<td>Porosity [fractions]</td>
</tr>
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<td>&gt; 0,1</td>
<td>&lt; 2,7</td>
</tr>
<tr>
<td>&lt; 0,1</td>
<td>&gt; 2,7</td>
</tr>
<tr>
<td>&gt;80</td>
<td></td>
</tr>
</tbody>
</table>

6.1.1. Facies modeling

The facies modeling is object based with as background sandstone. The objects modeled are the gypsum zones. To have an indication what the geometries of these zones/bodies are an effort was made to seismically identify these. Shown in Figure 72: Surface in the Rotliegend with seismic amplitudes projected. is a surface that was interpreted parallel to a reflector observed in the Rotliegend. This reflective event may be the result of the anhydrite/gypsum zones. On the surface of Figure 72 and 73 the amplitudes are projected. The blue colors indicate positive amplitudes. These amplitude surfaces do not show any trend. This is not conclusive evidence to control the modeling of the anhydrite/gypsum bodies.

Figure 72: Surface in the Rotliegend with seismic amplitudes projected.
Facies modelling parameters

Facies modelling has been done as an object based distribution. In this case Aeolian sandstone shall be used as background where anhydrite/gypsum bodies shall be modelled in. The only control points of this modelling process are near the wells where interpretation is done.

The choice is made to model the gypsum accumulations as Enterolithic gypsum bodies. The occurrence of selenite gypsum favours that scenario over detrital gypsum dune sediments. With the information at hand there is no conclusive evidence to prove that the zones are of detrital origin.

Modelling of Enterolithic gypsum

The object based modelling process requires geometry distribution for the objects that will be modelled. Seismic evaluation as well as previous studies done by other researchers have not shed light in this area. Therefore the objects shall be modelled in a wide range of possibilities.

The size, orientation of objects depends on factors like accommodation space, water table fluctuations. These factors are unknown and shall therefore lead to a range of possibilities.

An ellipse has been used as object geometry with no specific orientation. The maximum length of these objects is set at 1500 meters which coincide with small scale sabkha type environment. The thicknesses of these objects is derived from well logs and set between 1-15 meters. The well logs showed a vertical net to gross of 10% of anhydrite/gypsum. For the aquifer a total net to gross of 1% is taken. The other 99% is Aeolian sand.

The result of such a realisation is given in Figure 74. The ellipsoid bodies are populated through the entire Rotliegend aquifer. Figure 75 shows an intersection window of the KKP wells. The anhydrite bodies match the zones interpreted in the wells which means that the simulation honoured the well data.
Figure 74: Gypsum enterolithic bodies in the aquifer. The figure only shows the modelled bodies. The Aeolian sand background is made transparent.

Figure 75: Intersection window between the wells in the KKP concession.
6.1.2. Property modelling

To complete the aquifer modelling there is also a porosity and permeability distribution modelled for the aquifer. Aeolian sands are known to have continuous facies stretched out over large areas. This gives the properties distribution a large correlation length.

6.1.3. Porosity modelling

The porosity values at well locations are acquired through well logs. The area in the Koekoekspolder is assumed to be of the same facies as described in the Kampen core. Sandsheet facies can extend over a large areas. There is no information available that could suggest the aeolian sand is of different facies. As seen in the previous paragraph the gypsum enterolithics are bodies which have very low porosity and are present in the KKP wells. The result of porosity modelling is given in Figure 77. Figure 78 shows a cross section between the wells in the KKP. Many of the low porosity zones coincide with the gypsum/anhydrite zones which was expected.
Figure 77: Effective porosity distribution aquifer KKP

Figure 78: Porosity distribution between wells KKP-GT01 and KKP-GT02 and KAM-01-S1
6.1.4. Permeability modelling

To complete the static aquifer a permeability distribution is created honouring the porosity thus the facies of the model. The permeability-porosity relation in the petrophysical evaluation was implemented to create the permeability model. This model has strong resemblance with the porosity model.

To what extend these faults influence the transmissivity cannot be determined from the seismic data.
The results of the static model can be used as input to simulate the flow of warm water from the aquifer and injection of cooled water back into the aquifer. Simulation programs like Eclipse need input parameters like Porosity, Permeability and Saturation to be able to match the real production data to simulated data. By improving the static model with more detail it is possible to do a history match as an iterative method.
7. CONCLUSIONS AND RECOMMENDATIONS

Aeolian sandstones North-East of the Texel-IJsselmeer high were deposited under East or North-East wind direction (Glennie, 1985). The mainly sand-sheet deposits suggest constant wind direction. The presence of bimodal distributed sand and anhydrite cementation in the coarser lamina may indicate detrital gypsum particles during early deposition. Oversized pores observed in the coarser grain lamina may also indicate the recrystallization of detrital gypsum into anhydrite pseudo cement during burial of the sediments. The detrital gypsum was probably blown simultaneously with the coarser particles during periods of increasing wind strength (storms). This would explain the absence of anhydrite cement in the finer grained red intervals.

Average porosity measured from core-plugs from the Kampen well range between 15%-18% for the sandstones. The permeability is around 4-10 mD.

Study of well log data, seismic and cuttings have shown that the Aeolian sands of the Upper Slochteren in the Koekoekspolder concession are fairly homogeneous throughout the area except for the occasional presence of gypsum enterolithics and or gypsum sand dunes. Enterolithics are displacive early diagenetic gypsum nodules that have grown in a host sediment just above the water table near the surface. These gypsum enterolithics observed can reach up to 15 meters thick. There is minimum control in modelling the spatial distribution of the enterolithics. It can be modelled as object based in a wide range of possibilities.
Recommendations:

Acquiring more data is always a benefit for modelling subsurface aquifers/reservoirs. This information will help construct the model in more detail. Ideally a core of the Rotliegend aquifer would shed more light on the origin of the layers. There is however a financial restraint that makes such an acquisition difficult. Other methods of gathering more information would be via logs.

- Sonic density logs would give more detail to the acoustic properties.
- FMI logs are useful to identify any layering and dip-directions of layers inside the aquifer.
- NMR (Nuclear Magnetic Resonance) logs will determine the pore content thus giving information on porosity and permeability.

Further research can be done in the presence of continental gypsum/anhydrite deposits in the Rotliegend to characterize these phenomena. Knowing the geometries of these bodies will be useful for modelling.

History matching is the next step to evaluate if the model built fits the reality. Production data would then be iteratively matched with simulated results. If the results do not match perhaps the static model should be revised.
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APPENDIX A: CORE PHOTO’S

Appendix A 1
Appendix A 2
Appendix C 1: Photo of a possible detrital gypsum grain
APPENDIX C: GYPSUM DUNES

Barchanoid gypsum dune. The crestlines show the migration of the dune over the years. (Szynkiewicz 2009)
Appendix D 1: Gypsum dunes

Appendix D 2: Gypsum dunes surrounded by other Aeolian sand facies
APPENDIX D: PROPERTY MODELLING