TU-DELFT

The Suitability of a High Temperature Aquifer Thermal Energy Storage on the TU-Delft Campus

by

Tim Hacking

4293002

Civil Engineering and Geosciences

May 2017

TU-DELFT

Abstract

Civil Engineering and Geosciences

Bachelor Thesis

by Tim Hacking
4293002

High temperature aquifer thermal energy storage (HT-ATES) is an energy efficient way to store heat in the subsurface, recovery efficiencies of 60-85% have been found in earlier research. The TU-Delft is step by step changing its policies into a more environmental friendly approach and a HT-ATES system could be the next step in this process by functioning as a buffer for geothermal wells. This thesis is the first step in researching if a HT-ATES system is possible on the campus of the TU-Delft. The most efficient situation for a HT-ATES system is described and based on that situation and the demand of the TU-Delft geological Formations are selected for further research. Layers are selected based on information from the DINO-loket and NLOG. The layers that are interesting and seem to be suitable for the use as a HT-ATES are a part of the Maassluis formation starting at a depth of 160 meters, the Formation of Oosterhout, the Berg sand formation at the base of the Breda formation and the Texel greensand. For the Maassluis Formation it is known that 2-3 wells are needed to fulfill the demands. These geological formations where selected based on their general geological description or there lithological description and it looks like these geological formations can fulfill the demands of the TU-Delft.

Acknowledgements

I want to thank my thesis advisor Ir. Martin Bloemendal for his help with this research, he helped when I was stuck and guided the project in the right direction. I also want to thank Ir. Chris Hellinga for his time to answer questions. I would also like to thank Ir. Cees Willems for revising the thesis. I also place on record, my sense of gratitude to one and all, who directly or indirectly, have lent their hand in this venture.

Tim Hacking

Contents

List of Figures

List of Tables

Symbols

Φ	porosity	%
V_P	Volume pores	m^3
V_R	Volume matrix	m^3
t_0	Tilting time	s
H	Thickness of aquifer	m
k^h	Horizontal permeability	m^2
k^v	Vertical permeability	m^2
C_a	Heat capacity aquifer	$(\frac{j}{m^3K})$
C_w	Heat capacity water	$(\frac{j}{m^3K})$
μ_0	Viscosity ambient water	$\frac{kg}{ms}$
μ_1	Viscosity injected water	$\frac{kg}{ms}$
ρ_0	Density ambient water	$\frac{kg}{m^3}$
ρ_1	Density injected water	$\frac{kg}{m^3}$
G	Catalans constant	-
g	Gravitational constant	$\frac{m}{s^2}$
RE	Recovery efficiency	%
V_i	Initial injected volume	m^3
V_u	Not recovered volume	m^3
R^*	Recovery efficient	-
ε	Porosity	-
B	Thickness	m
$r_{0.05,\ bottom}$	Radius warm water bottom	m
V	Volume of water	m^3
Q	Heat	J
c	Volumetric heat capacity	J/(m^3*K)
ΔT	Temperature difference	K
V_{ontw}	Design velocity	m/h
v_v	Specific blockage speed	m/a
u_{eq}	Full load hours	h

A	Area	m^2
Q	Flow rate	m^3/h
h	Height of well	m

Chapter 1

Introduction

1.1 Problem Description

Over the last few years the demand for sustainable and environmental friendly innovations is growing, especially in the energy market. The main source in the European union for energy production is still fossil fuels [5]. The reason the demand for green energy is growing is that people and companies realise that the amount of fossil fuels are not infinite and global warming is an issue. A technical university can be the leader in the process of innovating the energy market, that is why the TU-Delft is changing its policies.

On the campus of the TU-Delft, shown in figure 1.1, the different buildings are relative close by each other. The campus is on this moment still dependent of district heating which is generated on the TU-Delft campus. 75% of this is heat is created using boilers. The TU-Delft had a total CO^2 emission of 15.000 ton [4] in 2016, but the TU-Delft wants to reduce emissions.

Since march 2015 the technological university of Delft started "het Delft plan". This plan is focused on the future of energy and how the Netherlands can be the energy gateway of Europe. One of the main elements of this plan is to convert, store and then trade & transport this energy [6] [7]. High temperature aquifer thermal energy storage, or short HT-ATES, could contribute significantly in reaching this goal.

The TU-Delft has a plan to start exploiting geothermal energy [8]. The organization that promotes this project is called the DAP. With this plan most of the heat demand of the TU-delft campus will be replaced with the warm water exploited via geothermal energy. Geothermal energy can provide a base load energy demand, but the production rate can not be increased or decreased fast to react on fluctuation in the demand. This problem can be solved by using extra gas fueled boilers or by using high temperature aquifer thermal energy storage. The latter option being the more environmental friendly approach.

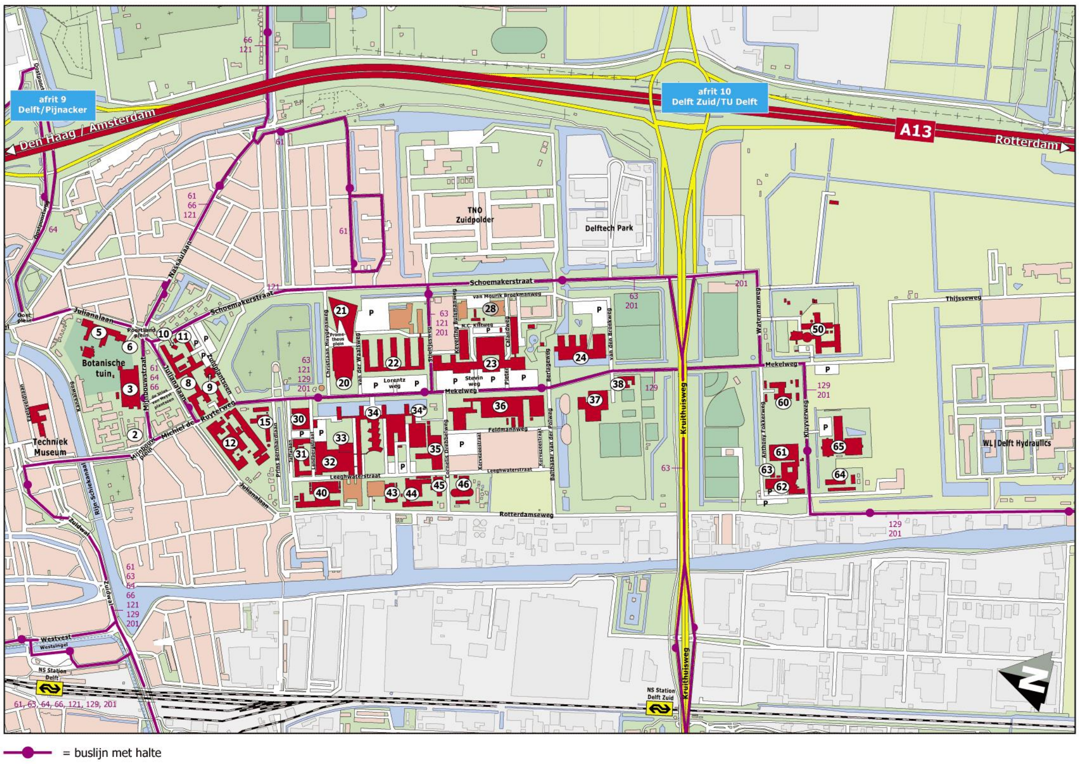

FIGURE 1.1: A map showing the TU-Delft campus (made by Clouter)

1.2 Goal

The goal of this thesis is to determine the suitability of a HT-ATES on the TU-Delft campus. Giving the conditions for the TU-Delft campus. An ideal geological Formation is described and based on that situation the subsurface is evaluated. This thesis can be used as background information and shows suggestions for further research.

1.3 Approach

To achieve this goal first background information is given in chapter two. This chapter explains the concept of a HT-ATES and explains geological terms needed to understand the thesis. Chapter three is about the conditions of the TU-Delft. Explaining what the demands are for extraction and total storage. This chapter also contains information regarding geothermal wells on the TU-Delft. Chapter four describes design challenges of a HT-ATES system. In chapter five the geological setting in the area TU-Delft is described. First step in this is to define an ideal geological formation based on earlier chapters. Then the subsurface is researched. Last part of the chapter is showing which formations are most suitable for HT-ATES. After this the results of the research are discussed. Finally a conclusion about the suitability of an HT-ATES is drawn and recommendations for further research are given.

Chapter 2

Background Information

Aquifer thermal energy storage, or ATES, is already commonly used in the Netherlands, in this chapter there will be an explanation about how an ATES works. Then the definition of a HT-ATES will be explained, and the benefits of an HT-ATES in comparison with an ATES will be discussed. Finally, to get a better understanding of all the different geological definitions a short explanation of basic geology will be given.

2.1 Aquifer Thermal Energy Storage

In different faculties of the TU-Delft a constant ambient temperature of 20 degrees Celsius is desired. But in the winter the average temperature outside will be approximately 3 degrees Celsius [9]. Currently fossil fuels are used to heat the buildings. In the summer the temperature can reach 25 degrees Celsius during the day. This means that the building needs cooling, if electricity used for this process is not green energy the temperature regulation of the building has a strong negative influence on the environment.

Excess heat can be stored in the summer and re-use this in the winter. This can be done above ground and in the subsurface. The disadvantages for above surface storage is that it would take a big storage unit to store large amounts of water. In this thesis the focus will be on the use of the subsurface for the storage of the water. This way of storing energy can reduce the amount of CO^2 emissions and contribute to a sustainable and environmental friendly future. In the subsurface big amounts of water can be stored but there are regulation restrictions

ATES is the process of storing energy in the underground. In figure 2.1 a basic ATES system is shown. In the summer the water in the cold part of the aquifer is pumped up to the heat exchanger. The cold from the subsurface and the heat from the building is exchanged so the cold water gets warmer and is then pumped in the warm part of the aquifer. The result of this exchange is that the building is cooled down. In the winter this warm water is pumped back up to the heat exchanger, loses its heat through the heat exchanger, the building is heated and cold water is pumped into the cold part of the aquifer.

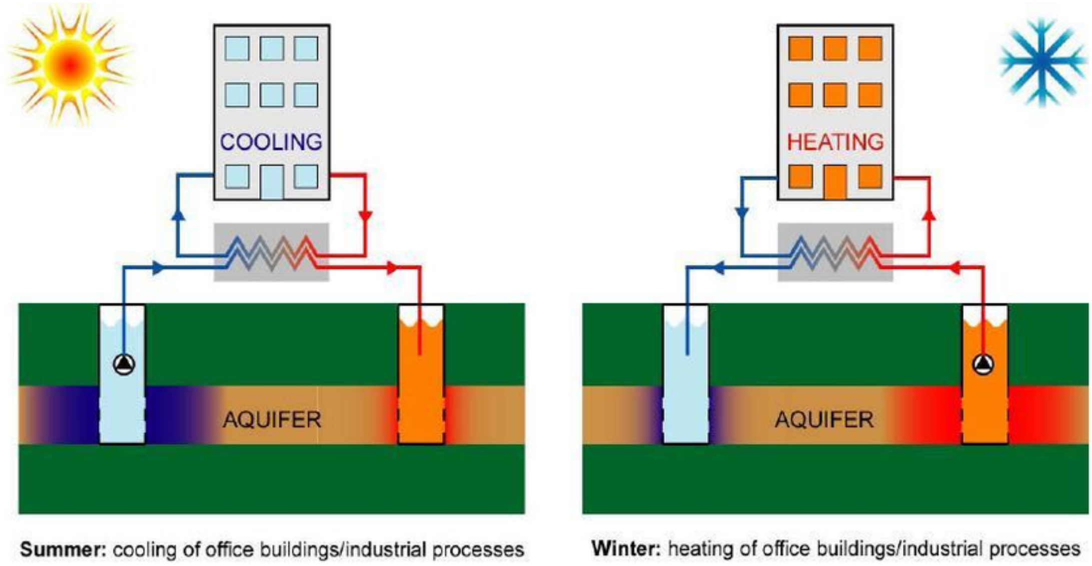

FIGURE 2.1: Systematical figure of an ATES system (Salcedo Rahola et al.)

2.2 High Temperature Aquifer Thermal Energy Storage

In the Netherlands there are approximately 1500 ATES [10] this is because the subsurface of the Netherlands has a high potential for ATES. On the TU-Delft campus alone, already three systems are currently in use [11]. In a typical ATES the temperature difference between the injected or extracted water and the groundwater temperature has a maximum of 15 degrees Celsius [12]. The system of the TU-Delft will inject temperatures of 70 degrees Celsius and this is called a HT-ATES. According to Rapport 6 from Drijver B. [13] 99% of the ATES are low temperature systems there are only a few HT-ATES. Different from a ATES, HT-ATES is that the HT-ATES is not used for cooling the building in the summer but only for heating.

Efficiency of HT-ATES systems ranges from 60% to 85% of the injected energy [14].

2.3 Benefits of a HT-ATES

There are a few benefits of HT-ATES compared to normal ATES. In a normal ATES the heat that is extracted has a lower temperature. Most of the times this heat can only be used for the pre-heating of ventilation air. To use the water as a source for heating in a normal heating system the water needs to be heated using a heat pump. This is, relative to heating colder water with a gas fueled boiler, more energy efficient but compared to a HT-ATES this is less energy efficient. Concluding that a HT-ATES is more efficient then using a ATES because less energy is needed to heat the water used in the regular heating system [13].

Assuming the total amount of injected water is the same, the total storage capacity increases when using a HT-ATES comparing to a ATES. The reason is that the temperature of the water is a lot higher than in a normal ATES. Higher storage temperature means more energy stored using the same volumes.

2.4 Basic Geology

2.4.1 Porosity

The shallow subsurface of the Netherlands contains mostly sands, sandstone and clay formations. Rocks can have permeability and porosity. Porosity is defined as the spaces between the rock particles or expressed in formula:

$$Porosity = \frac{Volume_{pores}}{Volume_{rock}} * 100 \longleftrightarrow \Phi = \frac{V_{\mathrm{P}}}{V_{\mathrm{R}}} * 100 \tag{2.1}$$

As can be seen this is a percentage, also formula (2.1) shows that the grain size does not necessary influence the porosity. The heterogeneity of the layer does influence the porosity, when there are big particles with small particles filling the spaces between the particles this decreases the porosity.

2.4.2 Permeability

Permeability determines how easily fluid can flow through the material [15]. The permeability is linked to the porosity, but can be influenced by shape of particles and heterogeneity in particle size. The SI unit of permeability is m^2 but in practical use it is mostly in described as Darcy or meter/day. Hydraulic conductivity is another way

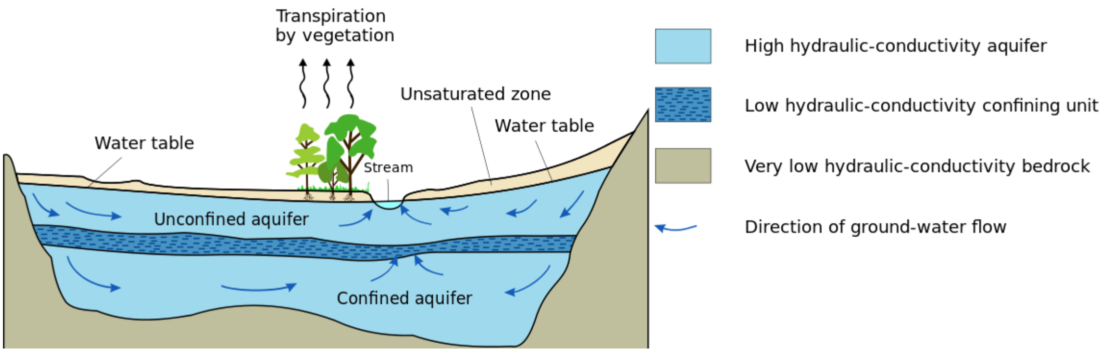

FIGURE 2.2: An example of a unconfined aquifer and a confined aquifer. (©Hans Hillewaert)

of describing the permeability. When the hydraulic conductivity is high the fluid can easily flow through the layer, when the hydraulic conductivity is very low it is almost impossible for water to flow through. [15]

2.4.3 Aquifers

"An aquifer is a water-bearing stratum of permeable rock, sand or gravel"[16]. There are two types of aquifers, confined and unconfined aquifers this is shown in figure 2.2. An unconfined aquifer is a aquifer that is not sealed by a impermeable, or low permeable, layer. A confined aquifer is a aquifer that is sealed by a impermeable, or low permeable, layer.

To confine warm water, a sealing, low permeability is required, this is favourable for a HT-ATES. The reason for this is to prevent up-floating of the warm water to other layers. The confining layers also reduce the amount of energy lost due to conduction between the different layers because there is almost no flow between the hot water and the low permeable layers.

Chapter 3

Conditions HT-ATES

In this chapter the conditions for a HT-ATES system for the TU-Delft are discussed. This is done by first showing the energy demand of the TU-Delft. Including capacity in terms of volume that needs to be stored each year. Pumping rates are calculated based on the demands of the TU-Delft. After this there will be discussed how many wells are needed depending on the capacity. Concluded by explaining a model that calculates amount of wells needed. Concluding the chapter with information about the geothermal wells.

Figure 3.1: TU-Delft campus with the different buildings highlighted in blue (©TU-Delft)

3.1 Current Energy Demand TU-Delft

The heat network of the TU-Delft is not only the different faculties, it also contains some of the student apartments on the TU-Campus. In figure 3.1 all the different buildings that are part of the TU-Delft heating network are shown in blue [4]. The heat is currently still produced by gas boilers. In table 3.1 data is shown regarding the energy use in 2012 of the TU-Delft, numbers are obtained via [4].

3.2 Size & Capacity of Heat Storage

The capacity for the HT-ATES in terms of GJ is between 100.000 and 200.000 GJ. To get an idea of the amount of water that needs to be stored formula (3.1) is used.

TABLE 3.1: Energy use of TU-Delft in 2012 [4]

Gross floor area:	550.000 m^2
Electricity	195.444 GJ
Heat	173.088 GJ
Gas	1.992.000 m^3
Primary energy	204.607.000 kWh

$$V = \frac{Q}{c * \Delta T} \tag{3.1}$$

In this formula the V is the volume of water in m^3, Q is the amount of heat in joules, c is the volumetric heat capacity 4.18 MJ/(m^3*K) [17] and ΔT is the temperature difference between two wells. In this project it is assumed that the volumetric heat capacity is 4.18 MJ/(m^3*K) but this can change because the water injected contains dissolved salts.

A minimum ΔT of 15 degrees Celsius and a maximum ΔT of 25 degrees Celsius is assumed. The volume of the injected water for the two different ΔT's is calculated and shown in 3.2. These numbers are only the injections volumes, this is volume without losses and porosity.

TABLE 3.2: Calculations on injection volume

ΔT	GJ	Volume (m^3)	Volume (liter)
15°	100.000	1,59 * 10^6	1,59 * 10^9
	200.000	3,18 * 10^6	3,18 * 10^9
25°	100.000	9,55 * 10^5	9,55 * 10^8
	200.000	1,91 * 10^6	1,91 * 10^9

These calculations gave the total energy stored, but to fulfill curtain peak demands in the winter and store the amount of residual heat in the summer the power stored needs to be considered as well. The amount of power the wells need to deliver to fulfill peak demands is equal to 2.4 MW. The biggest peaks in the peak demand can not be accomplished with this heating capacity. The amount of full load hours where given in this email conversation also and determined to be 1600 hours. The amount of 2.4 MW is used to identify a pumping rate using the volumetric heat capacity and the difference in temperature following equation (3.1) and shown in table 3.3.

Table 3.3: Calculations on pumping rates

ΔT	pumping rate (m^3/s)	pumping rate (m^3/h)	pumping rate (liter/s)
15°	3,82 * 10^{-}2	138	38,2
25°	2,29 * 10^{-}2	83	22,9

3.3 Amount of Wells

With the calculations given in table 3.2 and table 3.3 a estimation of the amount of wells needed to fulfill the demand can be made. The design pumping velocity can be determined by using equation (3.2) [18]:

$$v_{\text{ontw}} = 1000 * (k/150)^{0,6} * \sqrt{\frac{v_{\text{v}}}{2 * MFI_{\text{mea}} * u_{\text{eq}}}} \tag{3.2}$$

In this formula the v_{ontw} in m/h and is the design velocity of the infiltration well, the k is the permeability in m/d (meters per day), v_{v} is the specific blockage speed in m/a (meters per year), MFI_{mea} is the measured MFI, and the u_{eq} is the amount of full load hours. A few of those values are known or assumed using [18], in this case MFI is assumed to be 2, specific blockage speed is assumed to be 0,1, the amount of full load hours was 1600. Substituting the values and rewriting gives the next formula:

$$v_{\text{ontw}} = 1000 * (k/150)^{0,6} * \sqrt{\frac{0,1}{2 * 2 * 1600}} \rightleftharpoons v_{\text{ontw}} = 3,953 * \frac{k^{0,6}}{150^{0,6}} \tag{3.3}$$

As can be seen the velocity can be calculated when the permeability is known. The design velocity is in meters per hour. So the area of the well needs to be know, this is given by the next formula:

$$A = 2 * \pi * r_{\text{well}} * h \tag{3.4}$$

In this formula A is the area in m^2, the r_{well} is the radius of the well in meters and the h is the height of the extraction part of the well in meters. Knowing the area of the well and the pumping rate the velocity can be calculated using:

$$v = \frac{Q}{A} \tag{3.5}$$

In this formula Q is the flow rate in m^3/h which if the temperature difference is minimum should be 138 m^3/h. With all these values three unknown values remain. These values are the permeability, the radius of the well and the height of the well. For the convenience there is assumed the thickness is 20 or 30 meters and the r_{well} will be divided into two different situations:

One will be an aquifer that is above 500 meters depth, in this case the maximum diameter of the well can be one meter wide. For this case we take two r_{well} that will be 0.5 meters and one will be 0.25 meters.

The second situation is below 500 meters depth this means a blow out preventer will be needed. Also extra regulations apply for this depth. The range of r_{well} will be between 0.05 and 0.015 meters [19].

A model was made to calculate different scenarios. The results of these scenarios are shown in figure 3.2. These graphs show how the amount of wells is dependent of the permeability. Decreasing permeability increases the amount of wells. When the horizontal permeability of a geological formation is known this can be put in the model to estimate the amount of wells needed with the given capacity.

3.4 Combination With DAP

The last condition for a HT-ATES is the geothermal wells. The hot water that will be stored is hot water that is retrieved via geothermal wells. The HT-ATES will then be used as a buffer to help fulfill the demand of heat during cold periods. The plan of DAP is to make a doublet and extract warm water from a reservoir. The depth of these wells will be around 2500 meters deep [8]. For extracting the best option is to produce at a constant rate. A buffer can help with producing at a more constant rate with a high efficiency. When the demand is to low for the geothermal system the excess heat can be stored in a buffer and when the demand is to high the buffer can be used to fullfill the need of warm water. In this way, unfavourable fluctuations in production rate can be avoided. is is better than reducing the production or increasing the production depending on the demand. With such a buffer system the well can produce at a constant rate without losing lots of heat.

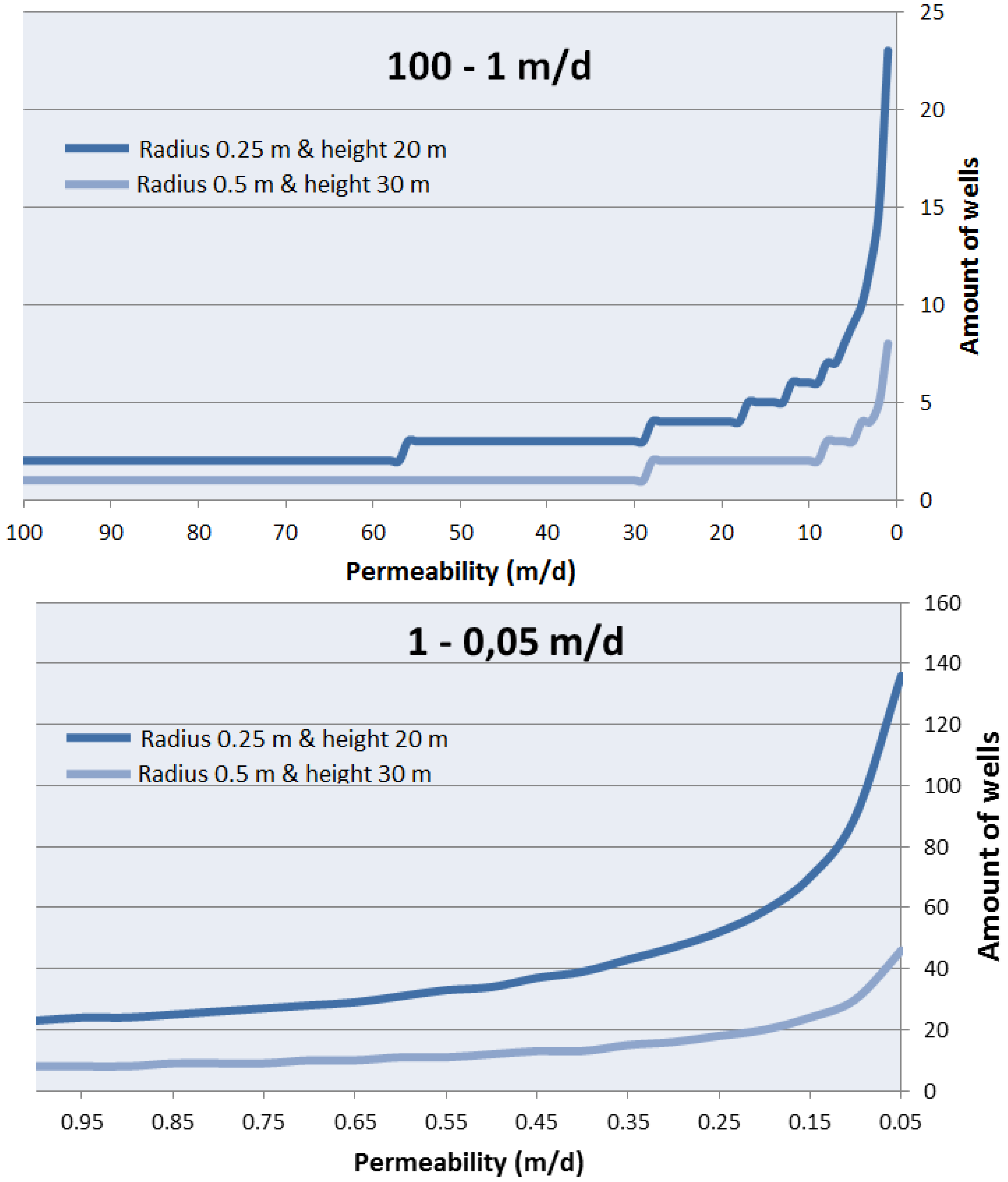

FIGURE 3.2: Figure showing the increase in amount of wells when permeability decrease. Two scenarios are described one with a small area and one with a big area.

Chapter 4

Design Challenges

Density driven flow decreases efficiency and is a phenomena that arises in a HT-ATES. The Density driven flow is a big design challenges and is discussed in the first paragraph. In the next section problems concerning HT-ATES and possible solutions are listed. To conclude the chapter factors that increase efficiency are explained.

4.1 Density Driven Flow

During operation of a HT-ATES there are three different stages, the first stage is the pumping of hot water into the aquifer. The second stage is the storage phase in which the hot water is staying in the aquifer. The third stage is the extraction stage in which the hot water is being retrieved for space heating.

During the first phase the ambient groundwater is colder then the injected water. Figure 4.1 shows that when the temperature increases the density decreases, this means a density difference within the aquifer arises. This leads to a thermal front. This is shown in figure 4.2. The thermal front leads to heat loss. The higher the temperature difference the steeper the front angle. The steeper the angle the more heat loss[20]. So ideally this angle is kept as small as possible.

There are two forms of convection involving the HT-ATES, the first one is forced convection and the second is free convection. Forced convection occurs because water is pumped into a aquifer, according to Ward [21] the least tilting of the thermal front occurs during fast pumping. Tilting is the when the angle of the front is increasing. To keep the thermal front as small as possible during the first phase the pumping rate should be high.

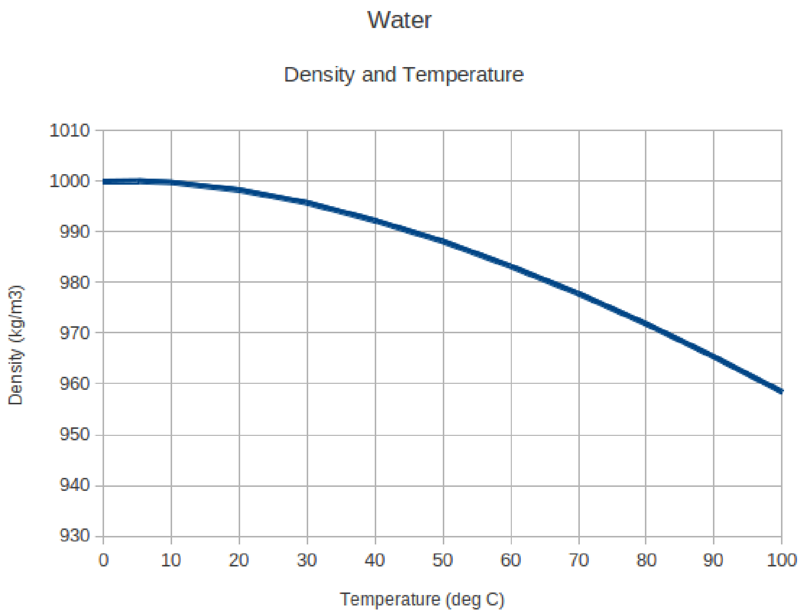

FIGURE 4.1: Density of water plotted against increasing temperature (Engineering-toolbox)

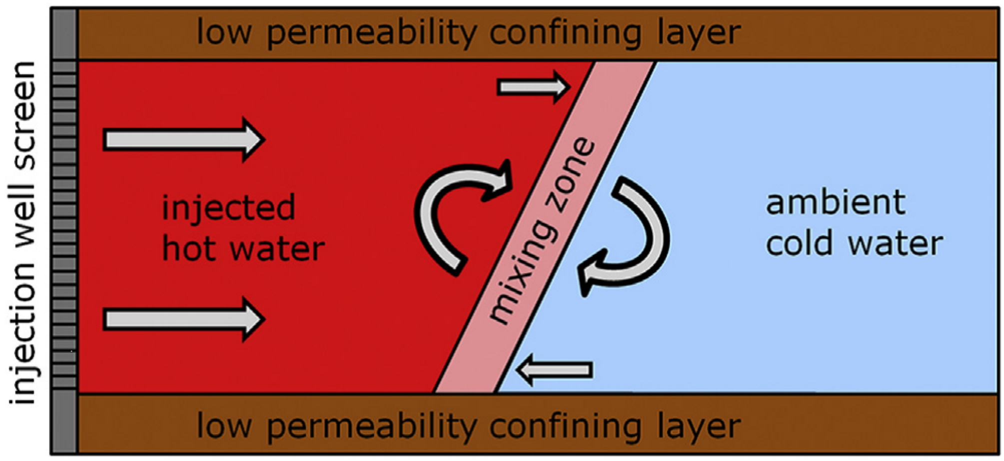

FIGURE 4.2: A picture of a thermal front and how a thermal front causes energy loss. This picture shows the proces of a thermal front during injection. (Schout et al[1])

During the second phase, the storage phase, the water stays still in the aquifer. During this phase the tilting of the thermal front continues. The reason for this is the temperature difference en thus the density difference between the hot injected and colder ambient water. The next formula describes the tilting time of the front and the factors influencing this the next formula is shown [1]:

$$t_0 = \frac{H}{\sqrt{(k^h k^v)}} * \frac{C_a}{C_w} * \frac{(\pi^2(\mu_0 + \mu_1))}{32G(\rho_0 - \rho_1)g} \tag{4.1}$$

In this formula the t_0 is the characteristic tilting time in seconds to reach a tilt of 60 degrees with the horizontal, H the thickness of the aquifer in meters, k^h and k^v are

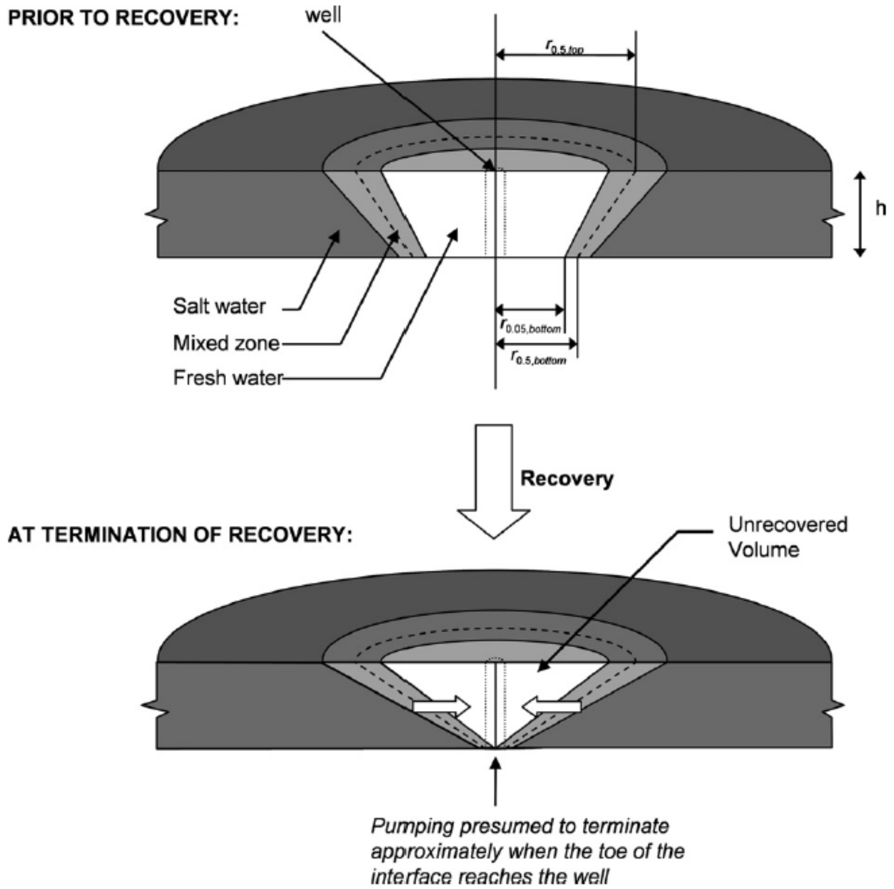

FIGURE 4.3: Figure illustrating loss in recovery efficiency due to tilting (Kimbler et al.)

the permeabilitys in vertical and horizontal direction in m^2. C_a and C_w are the heat capacities of the aquifer and of water ($\frac{j}{m^3K}$), μ_0 and μ_1 ($\frac{kg}{ms}$) are the different viscosity's and ρ_0 ρ_1 ($\frac{kg}{m^3}$)the different densities with the 0 the ambient water and 1 the injected water, G is Catalans constant and g is gravitational constant.

The viscosity also has an influence on this thermal front. The viscosity of water also decreases with increasing temperature [17]. This means that the higher the temperature the more easily the water flows through the aquifer. This increases the tilting speed and decreases the efficiency of the HT-ATES. The reason this decreases the efficiency is because the cold water at the bottom of the layer gets closer to the well. The hot water has a lower viscosity so the flow resistance is reduced.

During extracting the hot water, the front is tilted further and efficiency drops because less warm water can be pumped upwards. This is illustrated in figure 4.3, this pictures shows that a part of the hot water can not be retrieved.

The water that is injected is just normal cubic meters and goes down to the aquifer. In the aquifer the spaces where the water can be stored is only the pores, the porosity.

To get an idea of how much space the cone will take in the subsurface and how that influences the recovery efficiency the next formula is used [21]:

When the porosity of an aquifer is known the amount of volume in the subsurface can be calculated with formula (4.2).

$$R^* = \frac{\pi \varepsilon B {r^2}_{0.05,\text{bottom}}}{V_\text{i}} \tag{4.2}$$

In this formula R^* is the recovery efficient, ε is the porosity of the given rock, B is the thickness of the aquifer and $r_{0.05,\text{bottom}}$ is the radius from the well to the edge of the warm water on the bottom of the reservoir during the storage phase. The numerator is the volume of a cone with a given porosity. This formula only applies under the assumption that the thermal front moves linear through the aquifer.

4.2 Problems Concerning HT-ATES

A few HT-ATES where active in the Netherlands, one in Utrecht on the university campus of Utrecht and one in Zwammerdam. Both where shut down the one. The HT-ATES in Zwammerdam was shut down because financial reasons. The HT-ATES in Utrecht was shut down because of a leak in a valve. [22].

One of the problems is the clogging of the aquifer due to the precipitation of carbonates. The reason for this is that carbonates have, in contradiction to normal minerals, a lower solubility when temperature increase [23] . When the hot water is injected in an aquifer then these carbonates will precipitate and reduce the permeability so more energy needs to be used to pump the water or the carbonates will clog the filter. A solution for this is ion exchange and hydraulic acid. The ion exchange was used in Utrecht but had a clogging still occurred in Zwammerdam the hydraulic acid was used which did prevent the clogging [13]. This does have negative effects on the PH values of the aquifer.

For a HT-ATES another thermal storage system needs to be made if the TU-Delft wants to cool the building by using ATES.

4.3 Factors That Increase Efficiency

The lower the density difference the less loss due to density driven flow occurs. Van Lopik et al. [12] has made a report on the influence of dissolving salt in the injection water. Salt content influences the density of the water. This reduces the loss of energy due to a smaller density difference. Higher salt content in the warm injected water could increase the efficiency.

According to Ward et al [21] rapid injection of the water decreases the amount of tilting of the thermal front during the injection phase. This is because the forced convection exceeds the free convection and the thermal front acts more like vertical line.

The permeability can also have an influence on the efficiency of a HT-ATES. To decrease pumping power needed the horizontal permeability should be high. To decrease the effect of density driven flow the vertical permeability should be low.

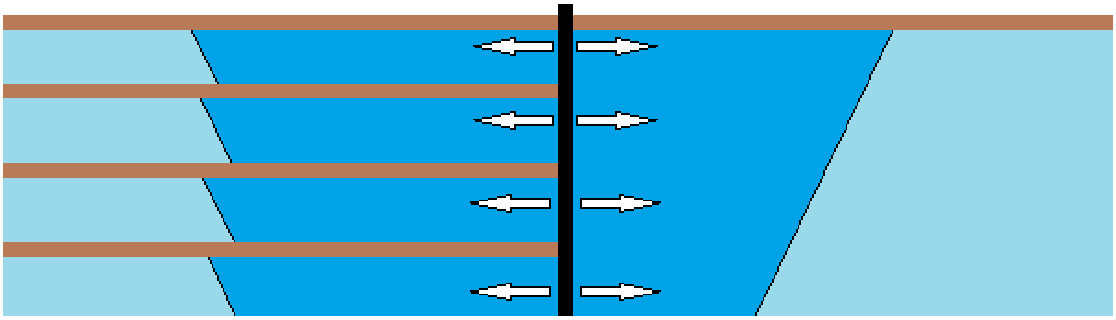

FIGURE 4.4: A schematic overview of what happens when heterogeneity occurs inside a layer. The brown layer has low hydraulic conductivity and the black stripe is the well. The arrows indicate the injection of hot water and the dark blue color shows the warm injected water, the light blue shows the ambient water.

According to a research from Bourbiaux heterogeneity can influences the thermal losses. Small-size impermeable heterogeneity's act like a heat accumulator making it more efficient and large/thick heterogeneity's reduce the thermal efficiency [24]. This principle is shown in figure 4.4. From which can be seen that the efficiency increases due to the presence of the small layers with low permeability. A favourable aquifer has small impermeable heterogeneity's in the form of layers.

Recovery efficiency increases with multiple cycles where one cycle contains the injection storage and extraction of the hot water [12] [21]. This is because the losses from previous cycli reduce losses of current cycle.

Chapter 5

Geological Setting TU-Delft

In this chapter the geological setting below the TU-Delft is described. To do this first the most favourable aquifer is described based on the last chapters. Different sedimentary rocks are explained in appendix A. Different geological units and their characteristics are described in appendix B. The second section of this chapter reports uncertainties related to the available data. Then suitable layers that come close to the favourable aquifer are researched further. As a conclusion of this chapter the most suitable aquifers are listed.

5.1 Favourable Aquifer

Ideal geology

Porosity	The layer has a high porosity.
Vertical permeability	The vertical permeability needs to be low to decrease tilting of the thermal front.
Horizontal permeability	The horizontal permeability needs to be high to increase the pumping capacity
Heterogeneity	The aquifer has small impermeable layers within the aquifer but needs to have a heterogeneous grain size.
Cap-layer	The layer above the aquifer has low permeability.
Heat capacity	The aquifer has a high heat capacity.
Depth	Shallow as possible because greater depth increases drilling costs, decreases maximum bore hole diameter, and permeability & porosity decreases with depth.

Ideal injected water

Density water	Difference in density needs to be as small as possible. This can be done by dissolving salt in the injection water or injecting the water deeper, the deeper the aquifer the warmer the ambient ground water. The disadvantage of a deeper aquifer is that the drilling costs increase and permeability decreases.
Composition water	Dissolving hydraulic acid in the water decreases clogging caused by deposition of calcium-carbonates.

5.2 Difficulties

Dozens of wells are drilled in the area around Delft for hydrocarbon exploration. These hydrocarbons can be found below a depth of approximately 1000 meters[3] [25]. Because of construction in urban areas a lot of information is available of the top layers, from the surface down to around 40 meters. Unfortunately, little is known about the shallower aquifers which are suitable for HT-ATES.

The second point of attention is the porosity decrease. The pressure increases when the depths increases this is because of all the overlaying layers pressing on the lower layers. The porosity and thus the capacity of the aquifer will decrease with depth. The Advantage of the deeper layers is that the ambient temperature is higher and thus less heat will be lost to the surroundings.

The last point is that the well logs located on the TU-Delft campus and nearby the campus all where drilled by the NAM in the 1950's. These drilling's are old en do not give consistent names to the different formation. To solve this problem three well-logs from Pijnacker are used that where drilled around 2010, these wells are located between 4000 and 5000 meters from the TU-Delft campus.

5.3 Different Aquifers

To get an overview of the subsurface four cross section are obtained from the DINO-loket. In figure 5.1 the above ground situation is shown with the two different locations of the cross sections and with the TU-Delft campus shown in red. The cross-section in appendix C.2 is a West to East cross-section and the cross section in appendix C.3 is a North to South cross section. These cross-section are obtained using DGMdiep v4.0 option. This means that only the larger geological structures are shown. The next cross-sections shown are shown in appendix C.4 and appendix C.5. These cross sections give information to a depth of 400 meters. In the appendix C.1 the explanation of the different abbreviations is shown.

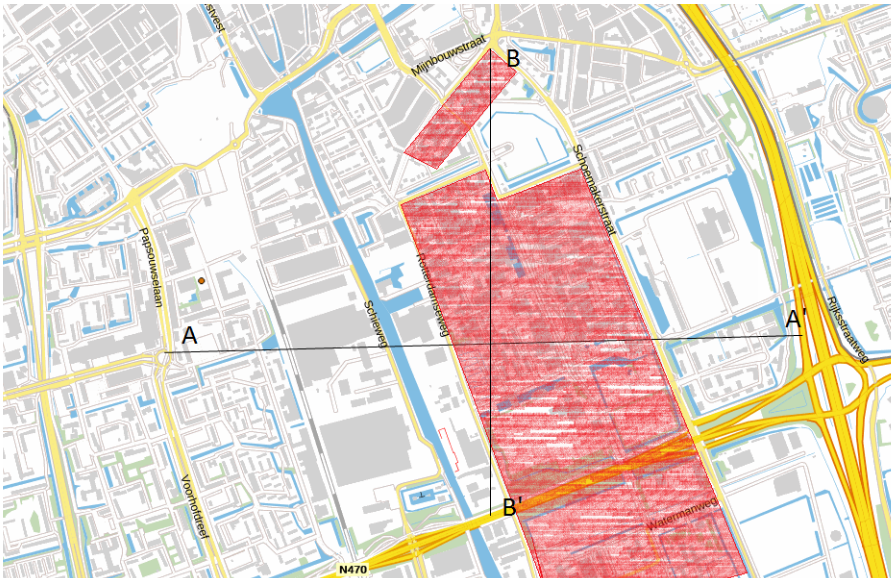

FIGURE 5.1: A map with indicated in red the TU-Delft campus. The lines represent the different locations of cross-sections and the letters indicate the starting and end point of the cross-sections

To get a better idea of the different hydraulic conductivities of different layers figure 5.2 is helpful. In this figure the typical range of hydraulic conductivities of different layers is shown. As an example look at the range for sand that goes from 10^{-1} to $5*10^{2}$, where the loose, well sorted, large particle layers have high hydraulic conductivity and the dense, small particles badly sorted layers have low hydraulic conductivity.

The cross-sections in combination with the nomenclature from appendix A and figure 5.2, aquifers based on there general description and the general characteristics of these aquifers could be chosen for further research. The most important demands were that the layer has the capacity to store enough water, so high enough porosity and thickness, and a seal to prevent losses due to thermal up-floating. The layers that can be suitable and need further research are:

- Formation of Oosterhout (OO). Depth ≈ 245 meters, thickness ≈ 150 meters.
- Texel Greensand Member. Depth ≈ 560 meters, thickness ≈ 20 meters.
- Holland greensand Member. Depth ≈ 910 meters, thickness ≈ 50 meters.
- The Lier Member. Depth ≈ 1140-1150 meters, thickness ≈ 50 meters.

Lithology	Hydraulic conductivity (m/day)
Clay*	5 x 10^{-7} to 10^{-3}
Loess	10^{-2} to 1
Silt	10^{-3} to 10^{-1}
Sand	10^{-1} to 5 x 10^{2}
Gravel	5 x 10^{1} to 5 x 10^{4}
Sand and gravel	5 to 10^{2}
Till	10^{-7} to 5 x 10^{-1}
Halite	5 x 10^{-6} to 5 x 10^{-3}
Limestone, dolomite	5 x 10^{-6} to 10^{0}
Karstic limestone	10^{-1} to 10^{3}
Chalk	Up to 5
Sandstone	5 x 10^{-5} to 2 x 10^{1}
Shale	5 x 10^{-8} to 10^{-4}

FIGURE 5.2: General hydraulic conductivity values used for assuming suitable layers, retrieved and enhanced from [2]

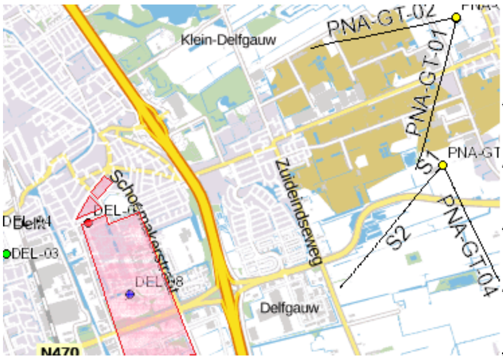

FIGURE 5.3: A map showing the three different well logs used with yellow dots, and the TU-Delft campus shown in red.

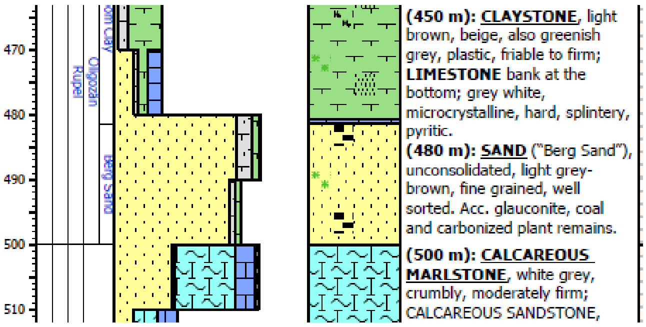

FIGURE 5.4: The lithology found in the well log from Pijnacker of the Berg sand layer.

These layers are all chosen based on their general description which is a big approximation, these layers could deviate from there general description. To find more interesting aquifers the well logs from Pijnacker are used. These logs contain the composition of the layers with colors and symbols, the grains size is also shown and the percentage of different sedimentary components. In figure 5.3 a map is shown with the drilling's of Pijnacker. The well logs from the wells PNA-GT-01, PNA-GT-02 and PNA-GT-04 are used for evaluation. From these wells a new suitable layer was found. The suitability of these layers is discussable because of the fact that the Pijnacker wells are located a few kilometers away from the TU-Delft campus. The layer that seemed to be suitable was the Berg sand layer as is shown in figure 5.4.

The last suitable layer that was found was found using subsurface ground data from the DINO-loket [25]. A figure and place of the drilling is shown in figure 5.5. There are already a few ATES on the TU-Delft campus which are all situated in the layer between

25-40 meters depth and the layer that start at around 45 meters and goes to a depth of 75 meters [26]. Because of the fact of the interference between different wells these layers will not be discussed. One layer that is interesting and can be seen in figure 5.5 is the layer that start at approximately 160 meters and stops at 180 meters depth. This layer is described as a layer that contains fine to medium sized grains. This seems as a good option the reason will be explained in detail later on.There is know these layers have lots of small impermeability's that need to be taken into account.

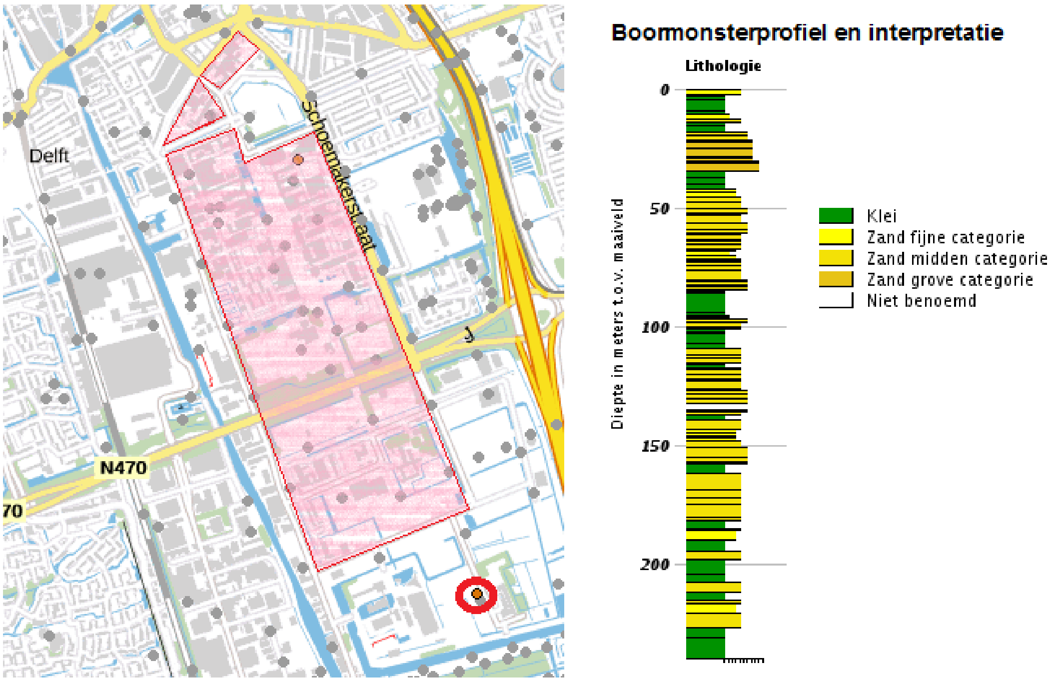

FIGURE 5.5: A figure of the subsurface data with on the left the TU-Delft campus shown in red and the drilling site circled in red. The right part show the lithology with in green clay, yellow fine sand, yellow brownish sand medium fine and in yellow brown coarse sand.

In the next sections the last five different suitable layers discussed earlier in this chapter will be discussed in detail.

5.3.1 Formation of Oosterhout (OO)

This formation is situated below the formation of Maassluis, for the situation of the TU-Delft this layer starts on a depth of 245 meters and has a thickness of around 150 meters. What made this layer interesting for further research was that it was described as a layer that had small layers that had low hydraulic conductivity. The first step in the research is gathering at available data that could be researched, there is known that there are 4 wells close to the campus so this can be used. These wells are shown in appendix D.1, it is important to keep in mind that the wells DEL-07 and DEL-08 are on the TU-Delft campus. The other two wells DEL-04 and DEL-03 are situated approximately

1 kilometer from the campus and the last well DEL-06 almost 2.5 kilometers from the campus.

The old logs are only used to show where the layers start and the thickness beneath the TU-Delft campus and shown in appendices E.6 to E.9. Combining the legend E.1 and the well log in appendix E.2 there can be seen that this layer is mostly made out of sand and siltstone with a little bit of marl stone. Silt decreases the permeability. In the top of the layer the grain size of the sand is bigger but there is a lot of silt present which means heterogeneity of grain-sizes which influence the permeability negatively. There are two wells in Pijnacker also that are being viewed, these do not show silt but show very small grain-size. This aquifer is missing a seal.

The information available shows this layer is not a very suitable layer for storage. To make sure further research should be done because the depth makes it a interesting layer.

5.3.2 Berg Sand Formation

The Berg sand Formation is unconsolidated, sandstone rich and well sorted. The layer on top is limestone and can function as a seal. The only question remaining is if this layer is also situated below the TU-Delft campus. This layer is likely to be situated just below the Breda Formation, which for the situation of the TU-Delft campus had a final depth of 420 meters. The presence of this layer needs to be researched. Also the Breda Formation itself needs to be checked on permeability and porosity, this layer is in general not an ideal layer but could be interesting because it is not situated very deep.

5.3.3 Texel Greensand Member

This formation is situated below the Texel marlstone, at the TU-Delft campus this layer is situated at a depth of 560 meters and is 20 meters thick. This layer is interesting for further research because it contains small layers with low hydraulic conductivity and mostly consist out of sand-stone. The marl-stone is probably a good cap layer because it is made up out of marls and small clay particles. Studying the lithology of this layer shown in figure E.3. The figure shows that it has a seal. It contains mostly out of lime stone and marlstone. Which both have low permeability and that makes the aquifer less interesting. It could be different below the TU-Delft because of the fact that it starts on a a depth of 530 below the TU-Delft and in Pijnacker it starts on a depth of 955 meters. So the pressure is a lot higher and this could influence the permeability in a negative way.

Diepte (m)	Porositeit(%)	Hor.perm (mD)	Korreldichtheid(g/cm3)
922.50	28.00	13.00	2.640
925.50	26.00		2.680
926.50	27.00	7.00	2.630
928.50	29.00	15.00	2.660
930.50	28.00		2.650
936.60	29.00	18.00	2.640

FIGURE 5.6: An overview of results from testing of cores retrieved from NLOG [3], with the horizontal permeability given in miliDarcy and the density given in g/cm^3 for the Holland greensand member.

5.3.4 Holland Greensand Member

This layer is situated below the middle Holland claystone member which looks like a good cap layer. The layer start on a depth of 904 meters in both wells that are situated on the TU-Delft campus. It is 50 meters thick and contains fine grained to very fine grained sandstones with a low permeability. However, permeability could be enhanced by the presence of bio-turbation which could greatly increase the porosity [27]. What is interesting about this layer is that the porosity and permeability are known due to the testing of core samples these values are shown in figure 5.6.

This is a promising layer for the use of storage because of experience from hydrocarbon exploitation which indicate it is good reservoir. In addition to this core samples are available and tested shown in figure 5.6. These are obtained from a borehole that is located on the TU-Delft campus (DEL-07). From the lithology it is clear it contains mostly well sorted fine sandstone. The thickness was found to be around 50 meters below the TU-Delft campus. The layer directly above the Holland greensand Member is a silt stone that has a low hydraulic conductivity and acts like a seal. The only problem that arises is that the permeability is to low and lots of wells should be needed do fulfill demands.

5.3.5 The Liermember

This Layer start around 1140 meters deep and is approximately 50 meters thick. It is located below the lower Holland marl member which could act as a cap layer. The reason this layer is researched further is because this used to be a reservoir for hydrocarbons, so there is porosity and permeability present. The temperature in this layer is also higher but costs of drilling will be higher. Just like the Holland greensand member there were core test done on samples of this layer. The results of these test are shown in figure 5.7. The same as for the Holland greensand member holds for this layer. It used to be an old reservoir and has a cap layer so is a promising layer.

Nummer	Diepte (m)	Porositeit(%)	Hor.perm (mD)	Korreldichtheid(g/cm3)
NM0007	1148.40	21.00	12.00	2.670
NM0008	1148.70	20.00		2.660
NM0009	1149.00	15.00		2.670
NM0010	1177.00	22.00	7.00	2.670
NM0011	1181.00	22.00	1.00	2.670
NM0012	1181.50	15.00	4.00	2.670
NM0013	1182.50	14.00	1.00	2.650
NM0014	1183.50	15.00	2.00	2.660
NM0015	1184.50	15.00	2.00	2.660
NM0016	1185.50	16.00	1.00	2.670
NM0017	1186.50	14.00	2.00	2.650
NM0018	1197.50	16.00	1.00	2.660
NM0019	1197.90	13.00		2.660
NM0020	1198.20	18.00	2.00	2.660

FIGURE 5.7: An overview of results from testing of cores retrieved from NLOG [3], with the horizontal permeability given in miliDarcy and the density given in g/cm^3 for the Liermember samples.

Figure 5.7 shows that in comparison with 5.6 the horizontal permeability and the porosity are less then that of the Holland greensand member. This layer is suitable for storage but is deeper then the Holland green sand member and less permeable. The preference would go to the Holland green sand member.

5.4 Suitable HT-ATES Aquifers Above 500 Meters Depth

The unnamed layer that starts on a depth of 160 meters and is 20 meters high. According the Dino-loket [25] this layer is in the top part of the Maassluis formation and the Maasluis formation is described as a layer with high horizontal permeability ($10 \leq k \leq 100$ m/d) and low vertical permeability ($0.001 \leq k \leq 1$ m/d), this data is retrieved using the Regis II option. This layer is promising and could fulfill the minimum permeability. Using the model the amount of wells needed is calculated to be 2-3 wells assuming a horizontal permeability of 50 m/d.

The Formation of Oosterhout was determined as a semi suitable because of the lithology obtained from the Pijnacker wells, further research should be done because of the fact this layer could have a small layer within the formation made up out of sand in the subsurface of the Delft area. The layer is interesting because it is deep and probably has higher porosity and permeability then layers lower then this.

The Berg sand formation or the bottom section of the Breda formation (depth of 420 meters) is suitable for a HT-ATES. The problem is that it is not found in the outdated wells on the campus. This could be because of the fact of outdated nomenclature. It was found in Pijnacker, core samples of the old drilling's should be studied and tested to make sure this layer is present in the area of TU-Delft.

5.5 Suitable HT-ATES Aquifers Below 500 meters Depth

The permeability and porosity decreases with depth and drillings cost increase with depth. The only advantage of deeper layer is the higher ambient temperature. Because of the mining act drilling below 500 meters give extra regulations and make it harder to reach the pumping demands.

The Texel greensand Member is found in the Pijnacker wells but is more compressed there. There is a change it is in better state below Delft because there the layer is located on 560 meters of the depth as in Pijnacker.

Going deeper makes it less and less interesting for a HT-ATES. The Lier Member is deeper then the Holland greensand member so this is less interesting then the Holland greensand member. The Holland greensand member proofed to be a good reservoir but has a low permeability.

Concluding that only the Texel greensand is interesting for further research.

Chapter 6

Discussion

The wells of Pijnacker where used to study the geological composition. These wells are located 4-5 kilometer away from the campus, the geology is different there then it is beneath the TU-Delft. Some layers like the Texel greensand Member are located twice as deep in Pijnacker as at the TU-Delft this makes them more compressed and because of that the Pijnacker wells do not always show accurate composition. Statements about geological Formations have uncertainty in them because of the distance from the TU-Delft of the wells used.

As was stated earlier there is little information about the subsurface of Delft. The major geological units are known and via well logs the start and end point of those units can be determined with little uncertainty. These are only the major geological units with very limited description and composition. There is not much information about the permeability, porosity and more characteristics available. Only of the shallow subsurface and deeper sub-surface detailed information is available. The reason for this is old oil reservoirs present in the area of the TU-Delft and the interest in shallow subsurface is because of construction buildings and roads. Detail is missing about different layers and still needs to be further examined.

This is the first time the suitability of a HT-ATES is studied. Some layers for further research are listed. Further research could study the boreholes cores that are found in Het Centraal Kernhuis in Zeist. The first step is to study the different layers and examine if they are really present in the drilling's on the TU-Delft campus. If so the next step is to study the presence of seal, or suitable layers within a bigger formation. For example the Oosterhout Formation seems to be suitable but looking at core samples will give a more exact depth of permeable layers within the formation. After this the samples could be tested on vertical and horizontal permeability but also porosity and heat capacity. Better models can be made and the best suitable aquifer can be chosen. When these things are known the amount of wells needed to fulfill demand can be calculated using the model described in this thesis.

Chapter 7

Conclusion

The goal of this thesis was to determine the suitability of a HT-ATES on the TU-Delft campus, and the conditions for the TU-Delft campus. One aquifer can be stated as suitable for HT-ATES. That is Part of the Maassluis Formation. Using this Formation the amount of wells needed to fulfill the conditions of the TU-Delft is between 2-3 Wells. The condition for this situation is that the peak-demand results in a pumping rate of 138 m^3/h.

For the other layers the suitability can not be stated. Further research should be done for the next three aquifers:

- Formation of Oosterhout.
- Berg sand formation or the bottom of the Breda formation.
- Texel greensand.

For these layer the horizontal and vertical permeability should be tested. When these are known a comparison with the Maassluis Formation can be made. And a most favourable scenario can be chosen. In the discussion a plan for further research was described.

Summary

The first part of the thesis is explained what a high temperature aquifer thermal energy storage was and how the efficiency could be as high as possible. The general concept of a HT-ATES is the storage of high temperature water in an aquifer. This water can be used for heating buildings. The advantage of this in comparison with a normal aquifer thermal energy storage is that there is a bigger amount of energy stored. To improve the efficiency of a HT-ATES two different factors play a role. One of the factors is the composition of the water and the other factor is the geology of the aquifer used for storage. The composition of the water is not discussed in detail in this thesis. The Density of the water should be high and dissolving hydraulic acid in the water is favorable.

The most favorable aquifer is a confined aquifer. High porosity leads to a high storage capacity. Horizontal permeability is favourable to be high. To prevent a thermal front and up-floating of warm water it is favourable to have low vertical permeability which could be a result of heterogeneity in the form of small impermeable layers. The heat capacity of the rock should be high. For the depth it is most favourable if this is above 500 meters because of the mining act, decrease in permeability and porosity with depth and cost increase with depth.

The amount of injected water is somewhere between $9{,}55*10^5$ and $2{,}18*10^6$ m^3 depending on the temperature difference between extracted and injected water. The minimum temperature difference leads to a pumping rate of 138 m^3/h and with this pumping rate the minimum permeability needed to fulfill the needs of the TU-Delft could be calculated. A model is made with three variables. That are the height of the well, the radius of the well and the permeability. This model show that when permeability decreases amount of well increase exponential.

Geological formations that are suitable because of the geological characteristics. Studying the local geology and general information given some layers could be described as suitable, these are:

- Maassluis Formation starting at a depth of 160 meters.
- Oosterhout Formation.
- Berg sand Formation or the bottom of the Breda Formation.
- Texel greensand Member.

Further studies in these layer should be done.

A HT-ATES system could be a sustainable way to help the DAP reach its peak demands and make the DAP project more feasible.

Appendix A

Different sedimentary rocks

The definition of a sedimentary rock is a rock that is formed by the deposition of particles that are formed due to the weathering of rocks. another way these sedimentary rocks are formed is due to organic activity[28]. There are different sedimentary rocks but for this research only four will be discussed, these different rocks are clay, sandstone, chalk and marl, because of their presence in the subsurface below the TU-Delft campus.

A.1 Sandstone

Sand-grains are formed by the weathering of and erosion of pre-existing rocks. The definition of sand is that the grain size is between 63 μm and 2 mm. This scale is further divided into five smaller classifications depending on the grain size, these are very fine, fine, medium, coarse and very coarse. One of the most important factors that influences porosity is the heterogeneity in grain-size, when the grain-size is heterogeneous (well sorted) the porosity will be higher. In general the porosity of sandstones is high, most of the aquifers and reservoirs are sandstones [29]. Because of the activity of animals or plants the porosity can change, this process is called **bioturbation** [27]

A.2 clay

Clay-grains have a grain-size that is smaller then 4 μm. One of the most important physical properties of clay is that is has permeability or in other words low permeability. A clay layer can be used as a seal.

A.3 Limestone

Limestones are all the rocks made up out of calcium carbonate ($CaCO_3$). Within this term one other term is important to remember that is **chalk**. Chalk is a variation of limestone and present in the subsurface below the TU-Delft. Chalk consists primarily shells of small creatures that secrete calcium carbonate. Commonly limestone has a small porosity. But because of dissolving of calcium carbonate secondary porosity occurs which could greatly increase the porosity. Primary porosity is the porosity formed during time of deposition and secondary porosity is the porosity formed after deposition, this can be dissolving of calcium carbonates but also bioturbation[29].

A.4 Marl

Marl is an a mixture of two different grain types. It consist out of a calcium carbonate rich rock mixed with clays or silt. Silt are particles classified with a particle size between sand and clay. Marl is a rock with high porosity's. In general marls have low hydraulic conductivity but there are some exceptions.[30]

Appendix B

Appendix

B.1 Basic geological units found beneath Delft

B.1.1 Upper North Sea group (NU)

As seen in the cross-section the Upper North sea group has a quite straight profile with an almost constant bottom depth of 400 meters. Using the nomenclature of the DINO loket there is found that this group is defined as a sequence of clays and fine grained coarse sands with some local deviations[25]. To get a better idea of these layer another function of the DINO-loket called the appelboor a stratigraphy beneath the TU-Delft campus is obtained and shown in figure B.1. As can be seen the Upper North Sea group is divided in different smaller layers. The meaning of the abbreviations can be found in appendix C.1. In appendix D.2 results from nearby wells are shown.

B.1.1.1 Holocene deposits (HL)

These are the deposits that where deposited during the last 12.000 years mostly clay sand or peat in the area of the TU-Delft. This layer is not suitable for storage so will not be discussed further.

B.1.1.2 Formation Kreftenheye (KR)

This is a thicker layers then the Holocene deposits, with dominantly coarse sands and gravel and is around 15 meters thick below the TU-Delft campus. The presence of sands means that this layer is permeable and most likely contains water. This could be a suitable layer for storage but it is a small layer close to the subsurface and probably close to groundwater extractions and also is missing a cap layer.

B.1.1.3 Formation of Peize and of Waalre (PZWA)

The formation van Peize is made up by sand layers with coarse grains but also contains some clay and silt and also smaller sand grains which can decrease permeability. In conclusion there can be said that this layer is suitable for the use of storage but it does misses a cap layer. Below the Peize Formation the Waalre formation is found the exact layer boundary needs to be investigated. The Waalre formation is mostly made up by small grains of sand with some layers of clay.

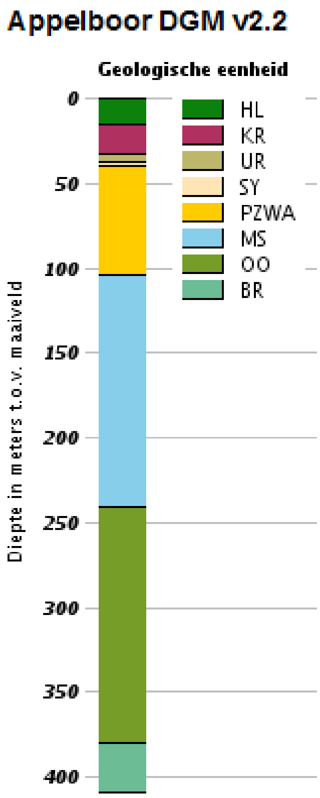

Figure B.1: Picture of the stratigraphy on the location of the TU-Delft campus obtained via DINO-loket.

B.1.1.4 Formation of Maassluis (MS)

This layer has dominantly coarse sand grains and shells, sparsely there are some clay layers. The layer is below delft thick around 150 meters thick. The difference between this layer and the formation of Waalre is that the van Waalre layer does not contain shells adn the Maassluis does contain shells.

B.1.1.5 Formation of Oosterhout (OO)

In the top of the formation there are some clay layers, beneath that the formation is mostly coarse grained sands and middle coarse grains. This is promising for a storage because these small layers with lower hydraulic conductivity can increase the efficiency. The thickness of the formation is about 130 meters thick.

B.1.1.6 Formation of Breda (BR)

This layer is consist of a complex sequence of shallow marine deposits and coastal deposits, or in other words a sequence of clays and sand. In this part of the Netherlands the

Breda formation is not that thick (10-20 meters). This layer could be an interesting cap layer, but is probably too thin to use it as a storage layer. This layer is often described as a heterogeneous layer with small particle as silt and clay so this layer probably has low porosity and permeability.

B.1.2 Lower and middle north sea group(NL_NM)

This is a big group in most of the Netherlands but as can be seen in the cross-sections this layer is only a few meters thick beneath the TU-Delft campus and not interesting for this research

B.1.3 Chalk group (CK)

This group is mostly containing limestones and marly limestones this could possible function as a cap layer. This layer is not as thick below delft as it is in the rest of the Netherlands, it start around 400 meters deep and end around 150 meters deeper.

B.1.3.1 Ommelanden formation

This layer is made up out of limestones that are compressed due to the depth. Also cementation occurred, that process decreases the porosity. To be sure the porosity is low and if this layer can function as a cap layer logs available in this area need to be looked at. The start of this layer is found by looking at data from NLOG [3] and found to be around 420 meters deep and the bottom varies from 490 to 500 meters depth. Below this layer the Texel marlstone follows.

B.1.3.2 Texel marlstone

Mostly limestones and marly limestones, the thickness below delft is around 40-50 meters. For this layer also the logs needs to be viewed to see if it can acts as a cap layer.

B.1.3.3 Texel greensand

According to the the nomenclature these are green sands with small layers of less hydraulic conductive marls between the sandstone. If the porosity is high and the layers above are impermeable or have small permeability this could be a suitable layer for a HT-ATES. According to date form NLOG [3] this layer is 20 meters.

B.1.4 Rijnland Group(KN)

This is the biggest group in size of all the main groups, it start around 600 meters below the surface. The bottom of the layer is around 1700 meters deep, this depth is not going to be researched. This has two reason the first reason is that going to deep makes the drilling costs to high, the second reason is that most of the available boreholes only go to a depth of 1200 meters so limited information is given for the deeper layers. The deepest formation that is researches is the Vlieland claystone formation which begins below 1200 meters depth and is between 200 and 300 meters thick. The geology within this group is very heterogeneous.

B.1.4.1 Upper Holland marl

Below the TU-Delft the thickness of this layer is approximately 200 meters only in the DEL-06 well this layer is thicker but this data is obtained further away from the campus then the other four well, this can be seen in appendix D.1. This whole layer is described as a marl layer. The exact porosity needs to be looked at to determine if this can be a suitable layer for storage.

B.1.4.2 Middle Holland claystone member

This layers start on a depth of about 800 meters and is circa 100 meters thick. This layer has less lime in it and is made up of shaly claystone and is calcium carbonate rich. This could be a good cap layer looking at this description.

B.1.4.3 Holland greensand member

A layer that is 50 meters thick in the area of TU-Delft problem is that in the well DEL-03 this formation was not found, the reason for this is that is was described in this well as a part of the Lower Holland marl member. This layer contains very fine-grained and fine grained sandstones. This layer is characterised by lots of bioturbated nature which means that plants are animals influenced the geology. Bioturbation can increase or decrease the permeability depending on what kind of processes followed after the bioturbation [27]. If the layer was positively affected by the bioturbation this layer could be a suitable layer for storage especially when the middle Holland claystone member is less permeable.

B.1.4.4 Lower Holland marl member

This layer start around 950 meters depth and is circa 180 meters thick. This layer can be determined by low gamma ray values when looking in the logs. Most of the layer is build up out of sand and silty clay stones. Which means this formation has probably a low porosity and permeability.

B.1.4.5 The Liermember

The NAM used to produce hydrocarbons from this layer this mean more information about porosity and permeability is known. When looking in appendix D.2 there is shown that the depth of this layer changes, implying this is not a horizontal layer but a layer with a dip.The layer has a thickness of 50 meters and has a starting depth of circa 1120-1210 meters, in the data available some anomalies are found concerning the thickness. The layer contains very fine and fine grained sandstones.

B.1.4.6 Vlieland claystone formation

This is a thick formation with different layers within the formation. The formation start on a depth of circa 1250 meters and goes down to a depth of 1570 meters which means this is not in the area of interest because drilling below this layer is to expensive. Most of the formation is claystones with some marls and some small layers with fine sandstone.

Appendix C

Appendix

C.1 Cross-sections

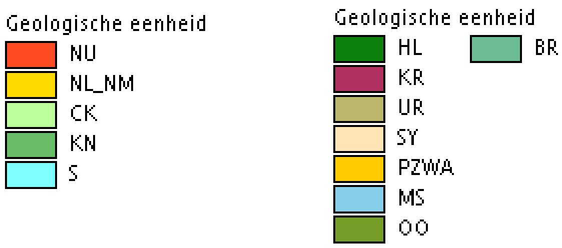

Figure C.1: Abbreviation of the different geological units that can be seen in the different cross-section

Table C.1: Explanation of the different abbreviations

NU	Upper North Sea group	UR	Formation of Urk
NL_NM	Lower and middle North Sea group	SY	Formation of Stramproy
CK	Chalk lime group	PZWA	Formation of Peize and Waalre
KN	Rijnland group	MS	Formation of Maassluis
S	Upper Jura deposits	OO	Formation of Oosterhout
HL	Holocene deposits	BR	Formation of Breda
KR	Formation Kreftenheye		

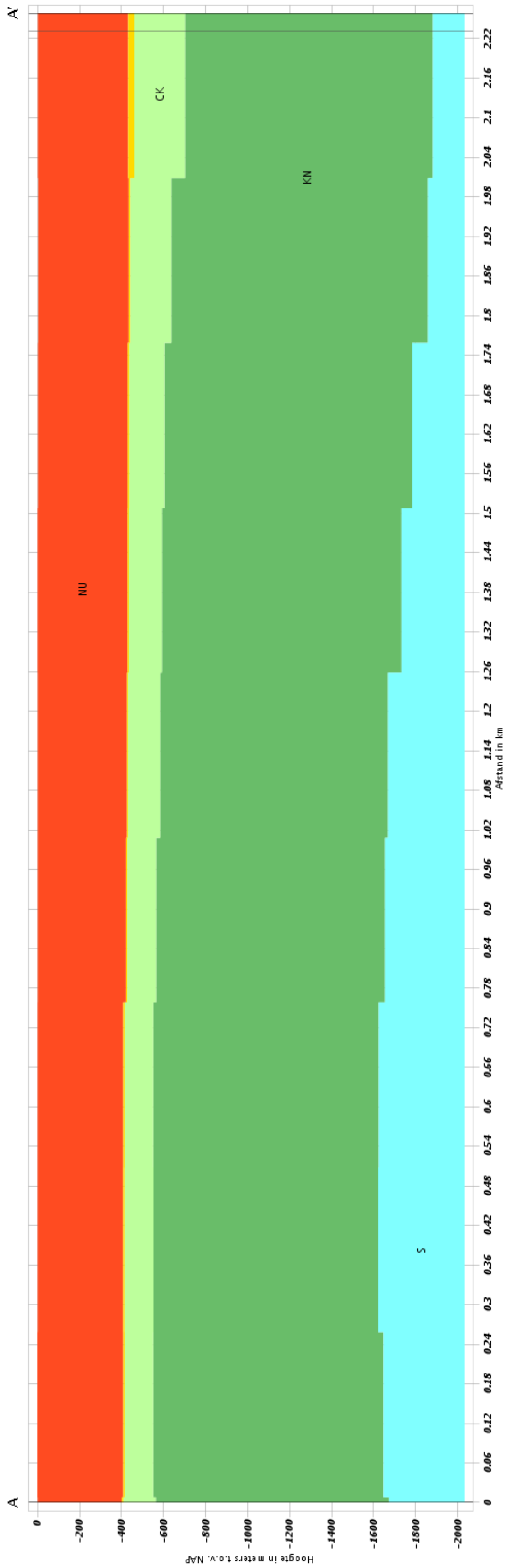

FIGURE C.2: A cross section from point A to A' (West to East) retrieved from DINO-loket. Only major geological units.

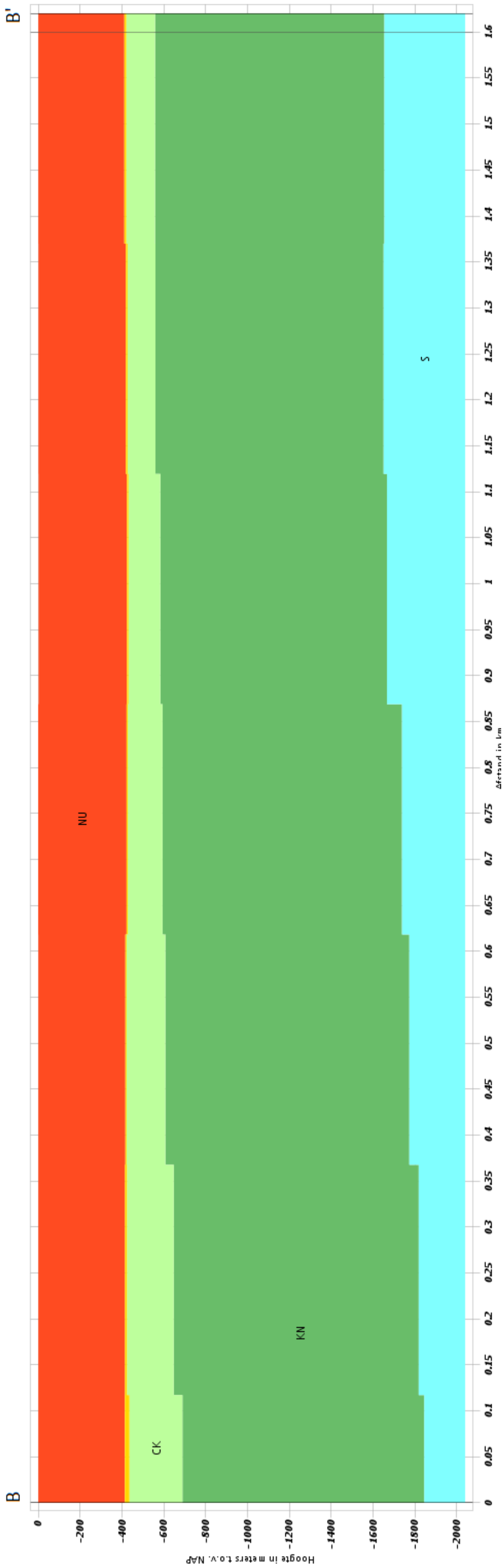

FIGURE C.3: A cross section from point B to B' (North to South) retrieved from DINO-loket. Only major geological units.

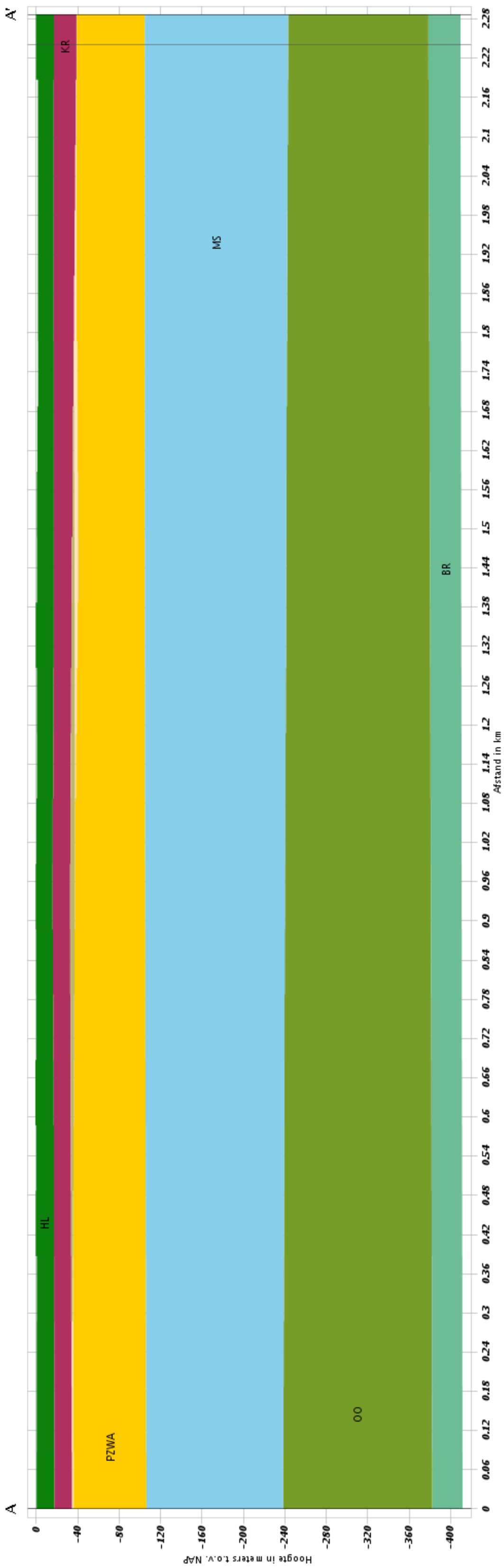

FIGURE C.4: A cross section from point A to A' (West to East) retrieved from DINO-loket, to a depth of 420 meters.

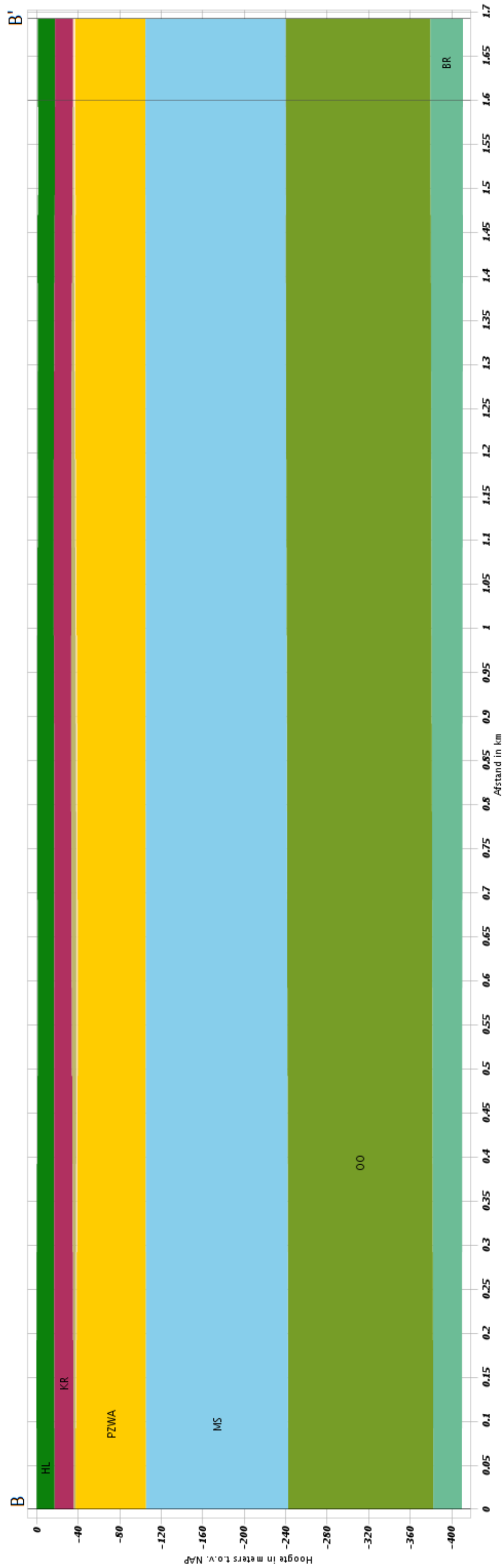

FIGURE C.5: A cross section from point B to B' (North to South) retrieved from DINO-loket, to a depth of 420 meters.

Appendix D

Appendix

D.1 Stratigraphy obtained from wells close to TU-Delft campus

FIGURE D.1: A map with the TU-Delft campus shown in pink and the position of the five boreholes used to create the stratigraphy, retrieved from NLOG and altered.

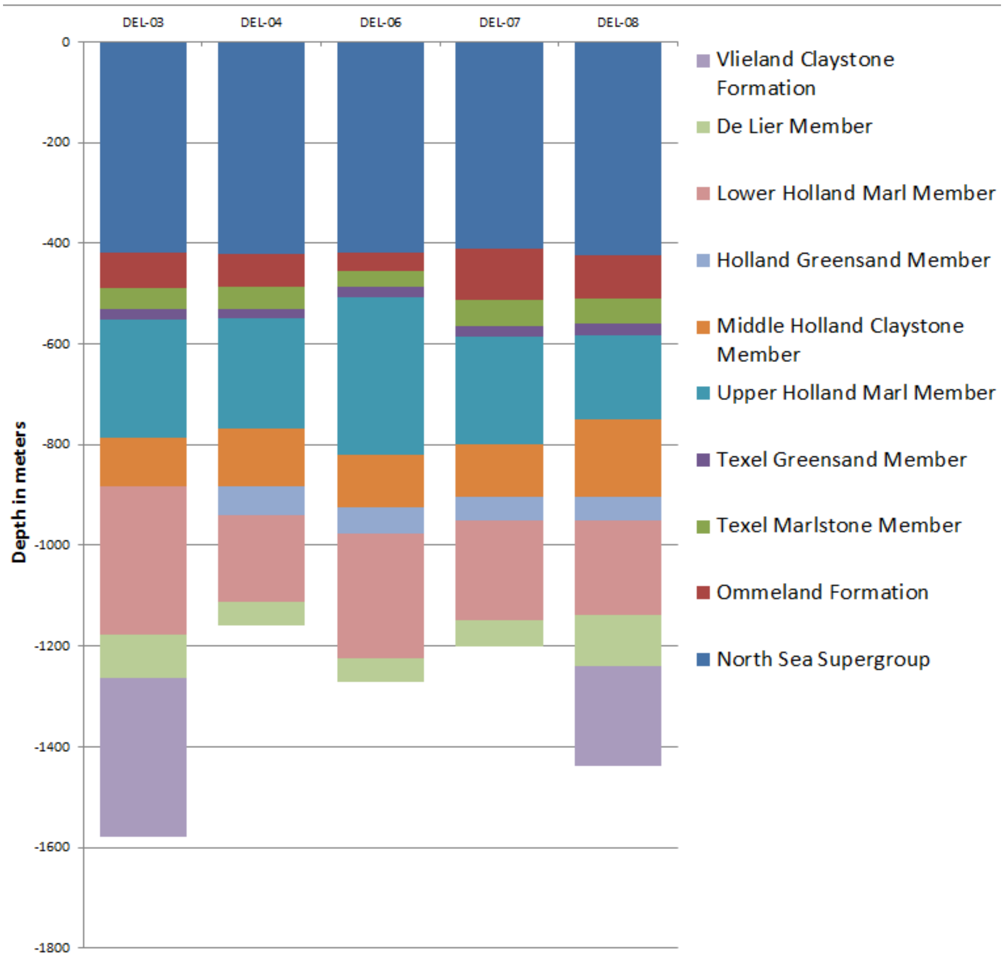

FIGURE D.2: A stratigraphy obtained using data from NLOG.

Appendix E

Appendix

E.1 Overviews of different well logs

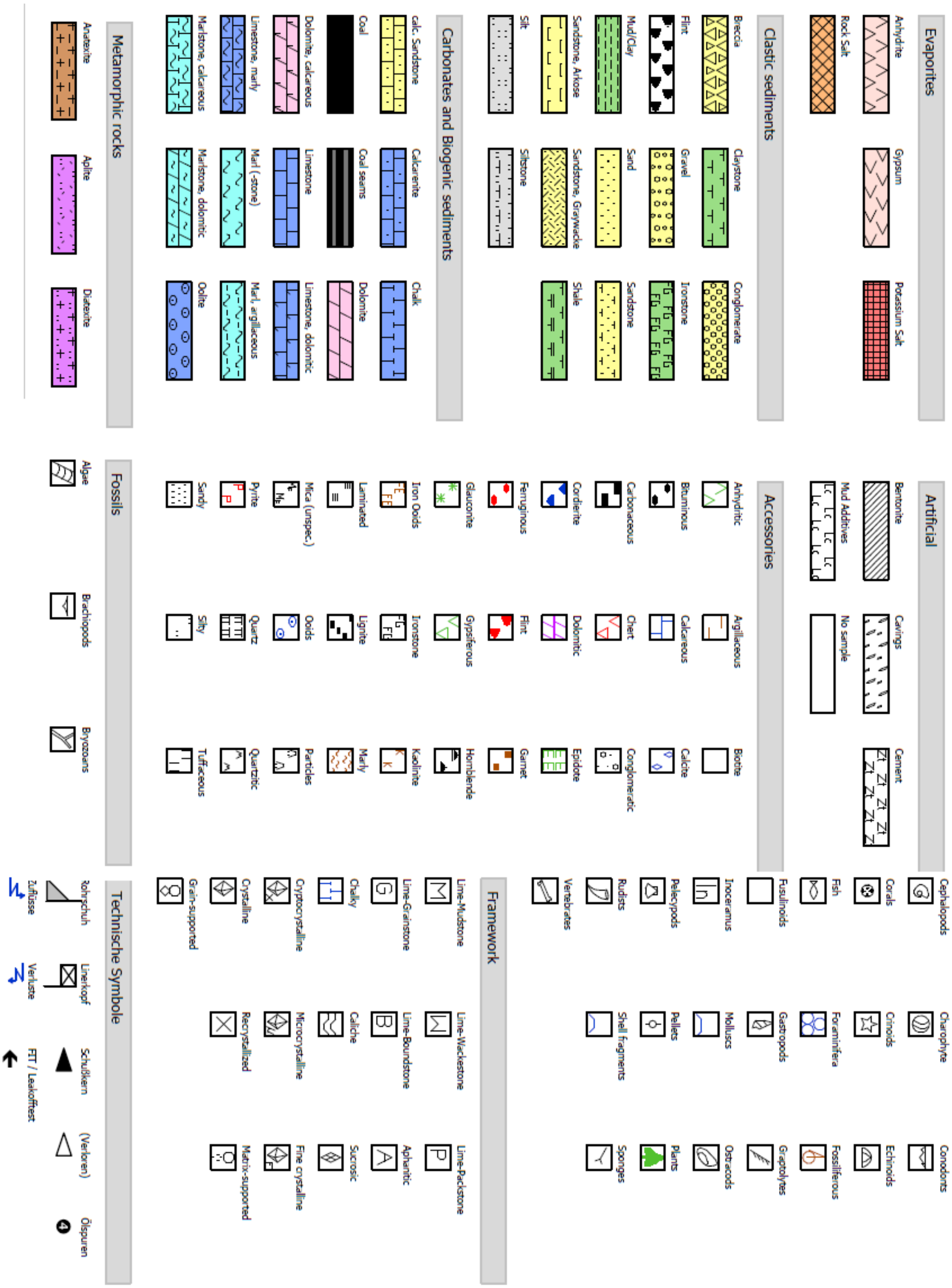

FIGURE E.1: Legend for the lithology in appendices E.2 to E.5

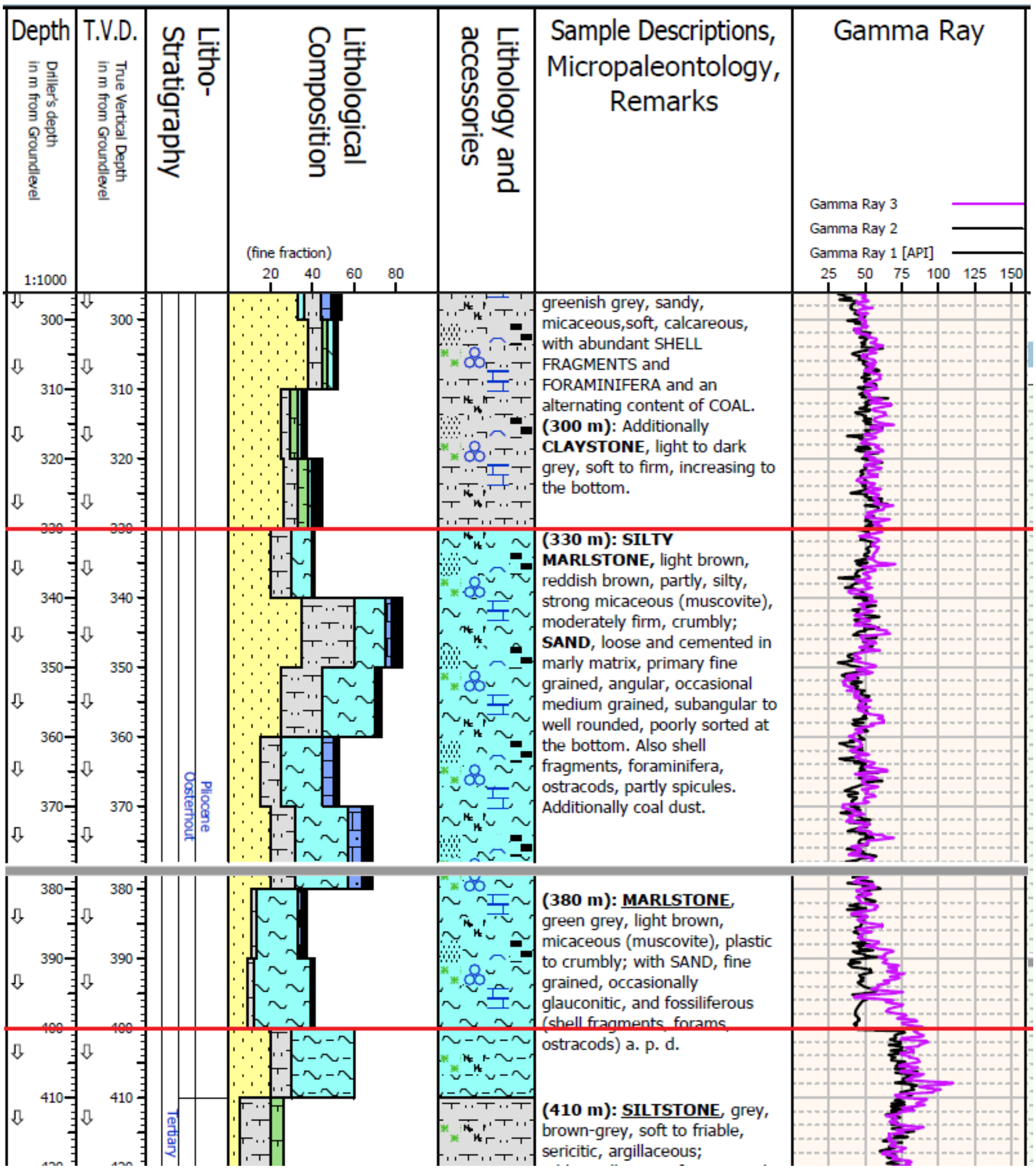

Figure E.2: A Pijnacker well log retrieved form NLOG [3] with the red lines showing where the Oosterhout formation starts.

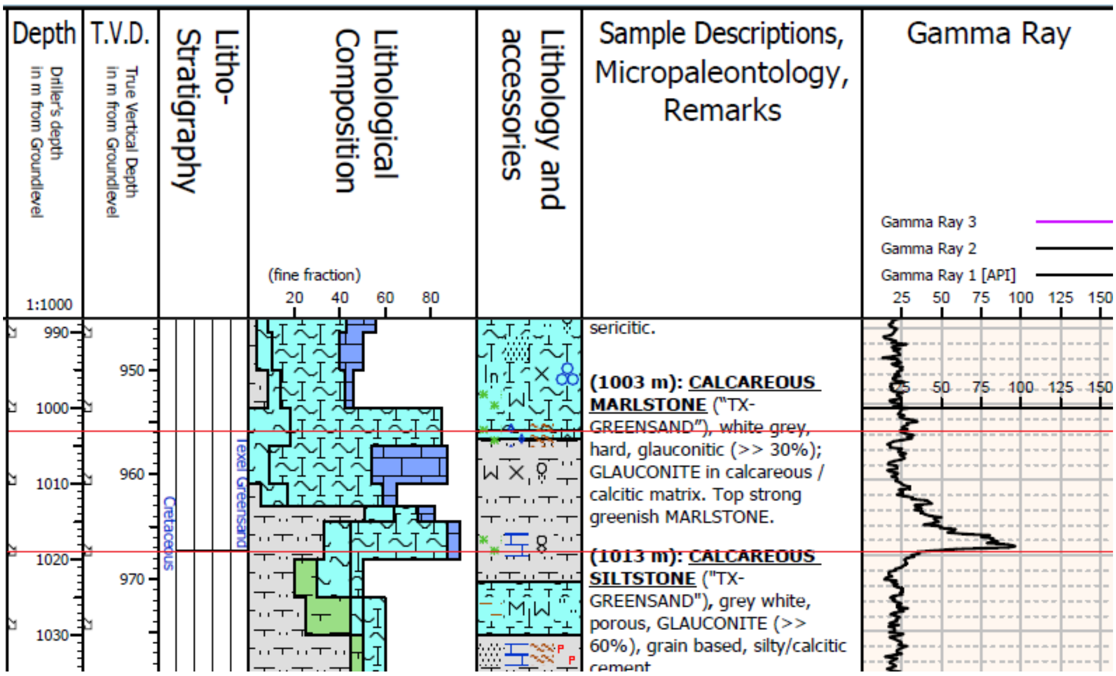

Figure E.3: A Pijnacker well log retrieved form NLOG [3] with the red lines showing where the Texel greensand layer starts.

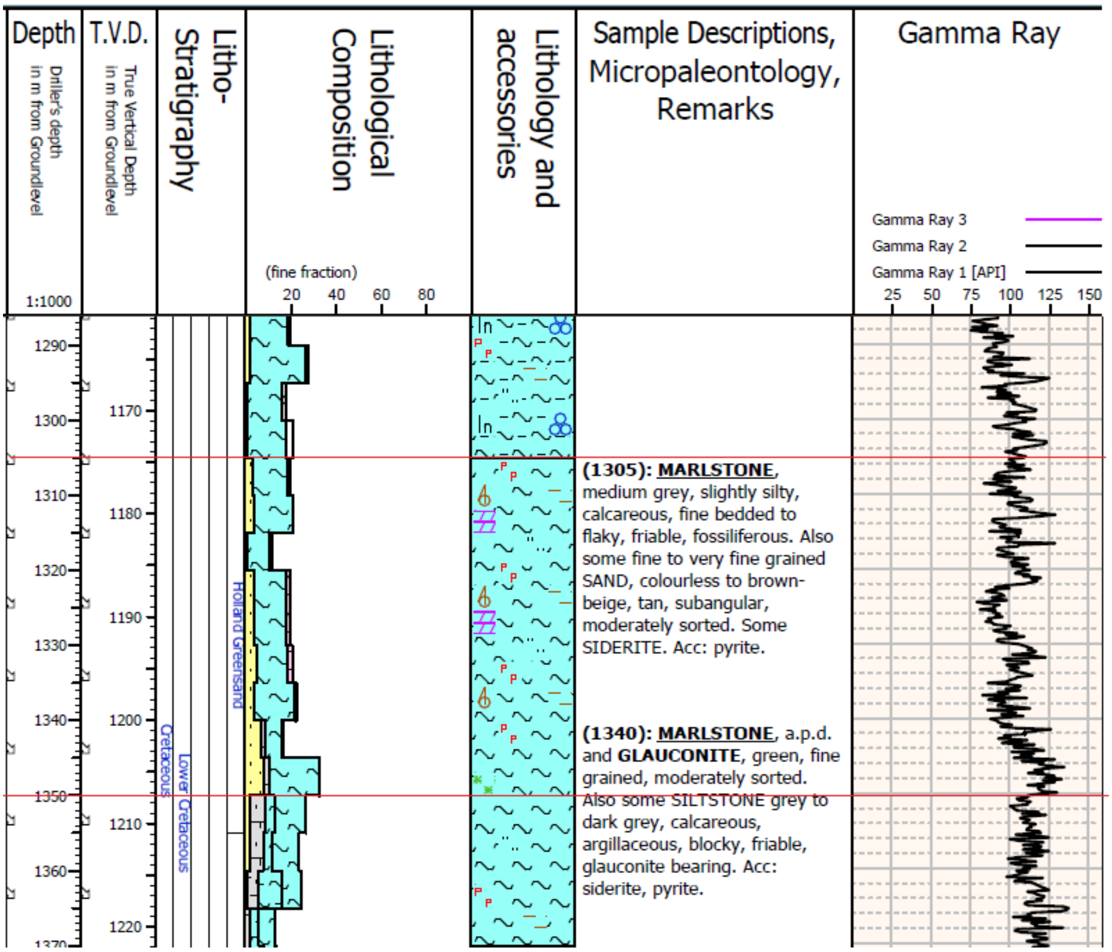

Figure E.4: A Pijnacker well log retrieved form NLOG [3] with the red lines showing where the Holland greensand member starts.

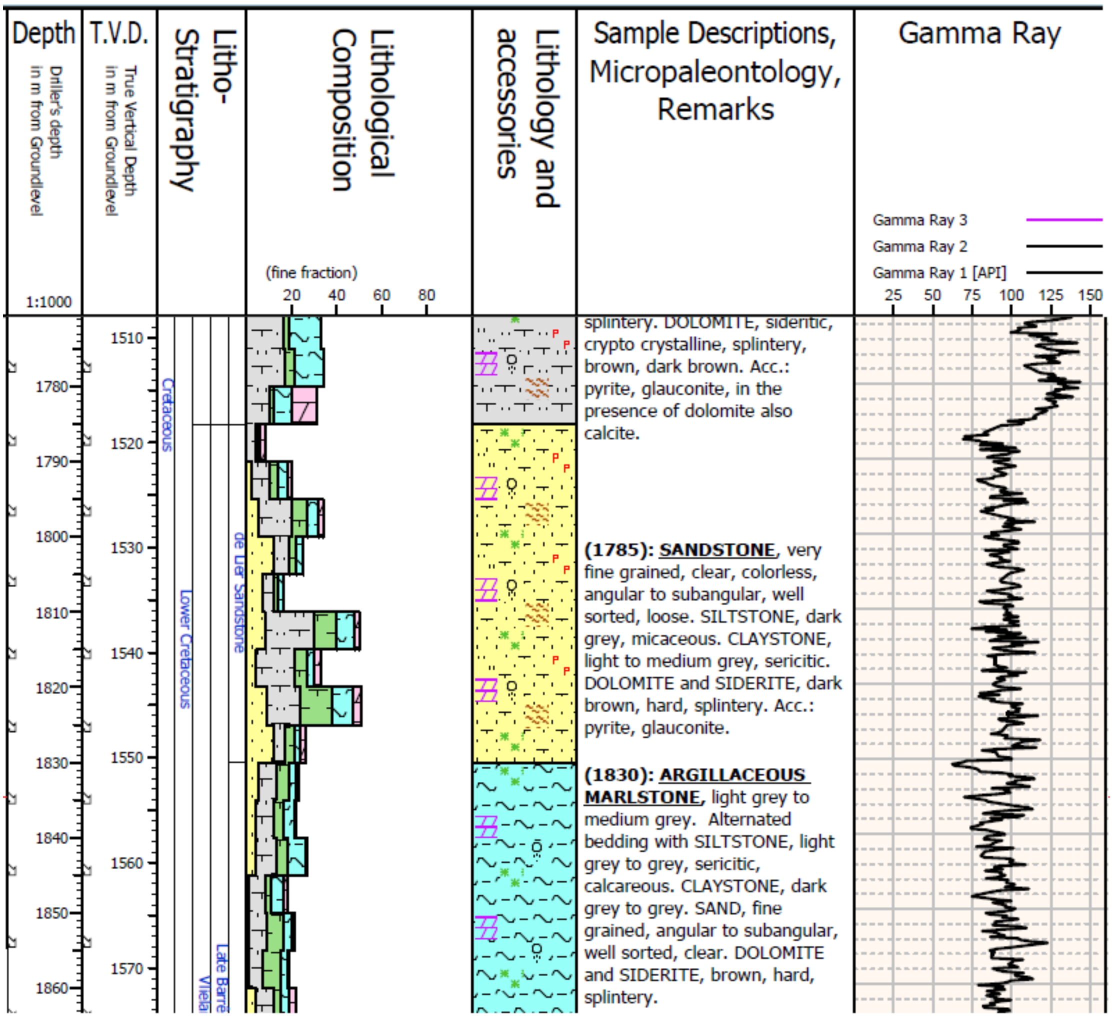

FIGURE E.5: A Pijnacker well log retrieved form NLOG [3] with the red lines showing where the Liermember layer starts.

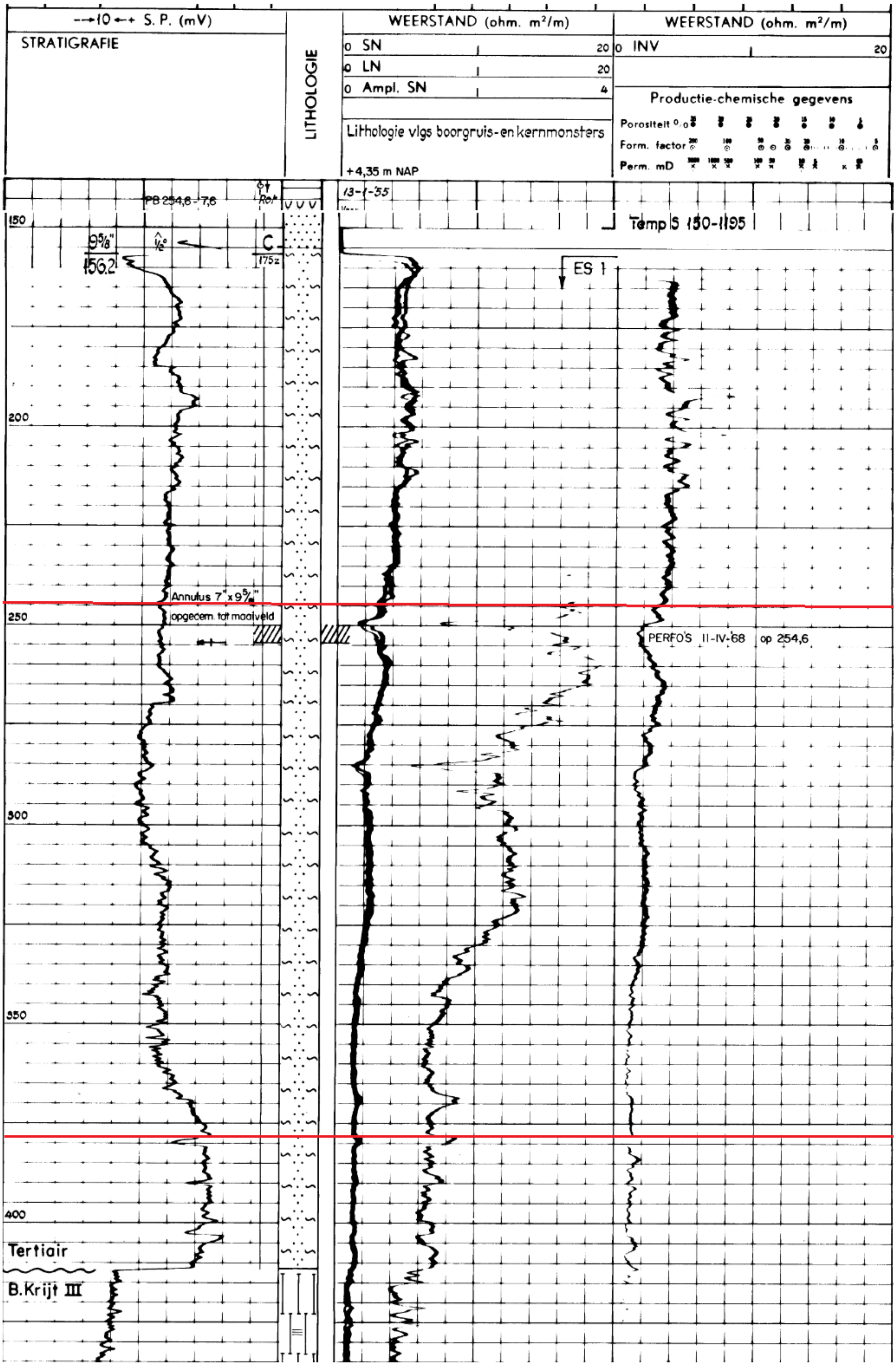

Figure E.6: A Delft well log retrieved form NLOG [3] with the red lines showing where the Oosterhout formation starts.

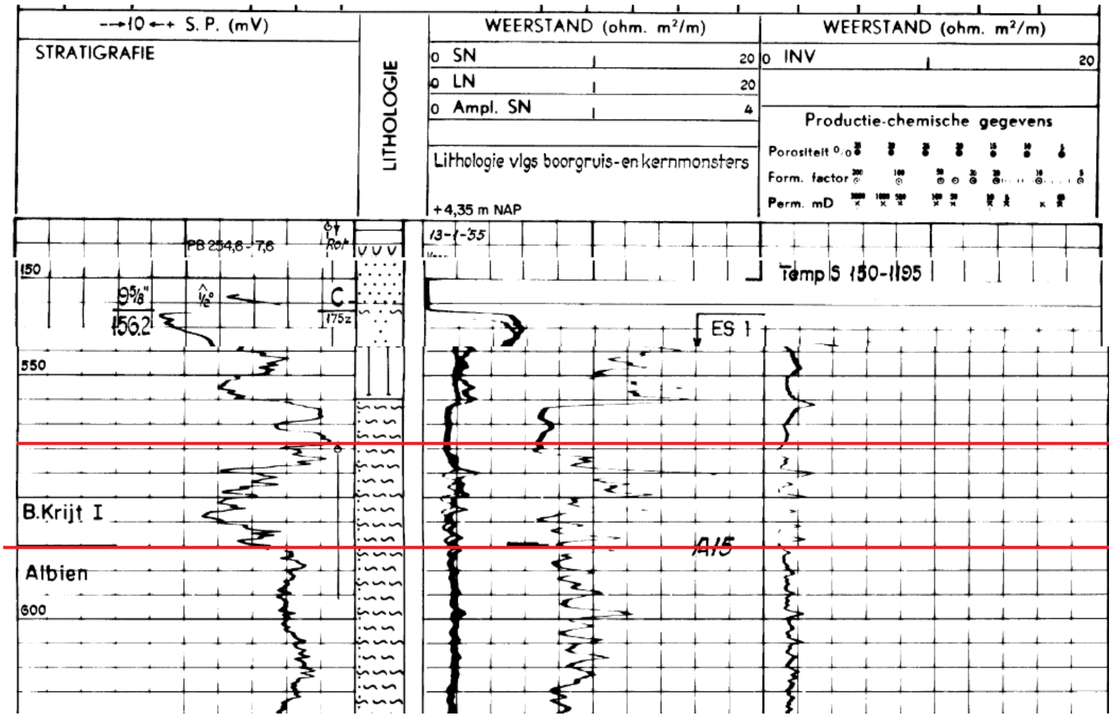

FIGURE E.7: A Delft well log retrieved form NLOG [3] with the red lines showing where the Texel greensand layer starts.

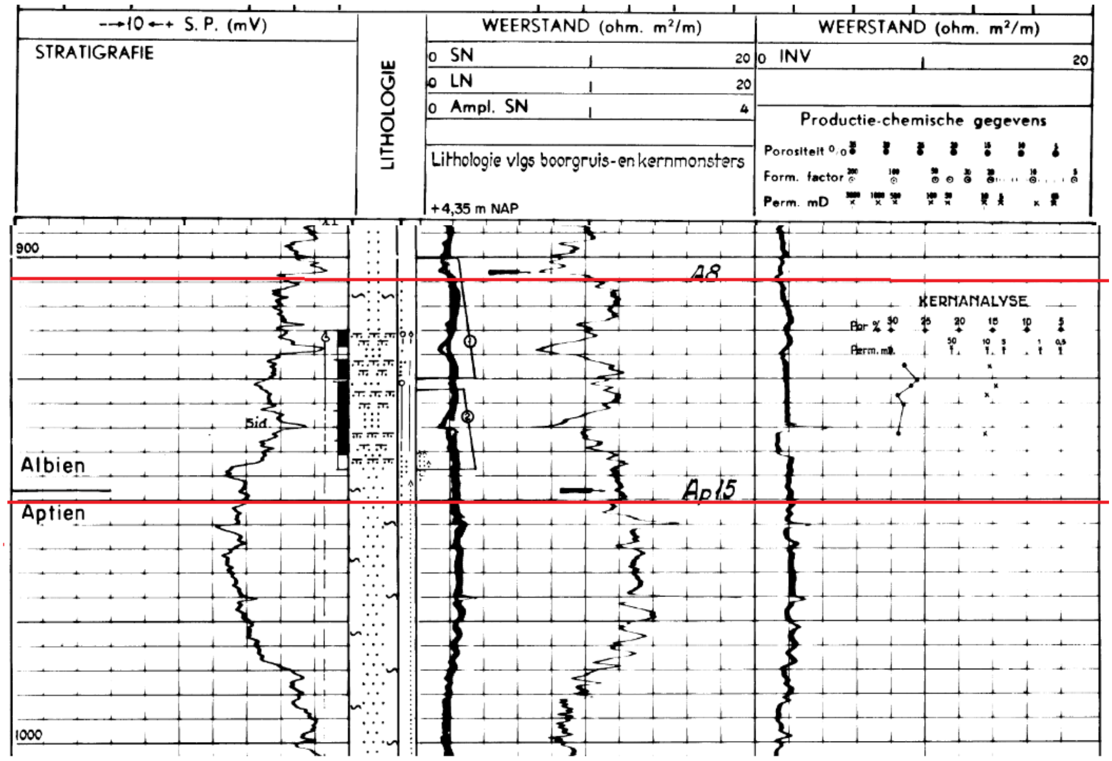

FIGURE E.8: A Delft well log retrieved form NLOG [3] with the red lines showing where the Holland greensand member starts. The points that are shown in these logs correspond with the core testing results in figure 5.6

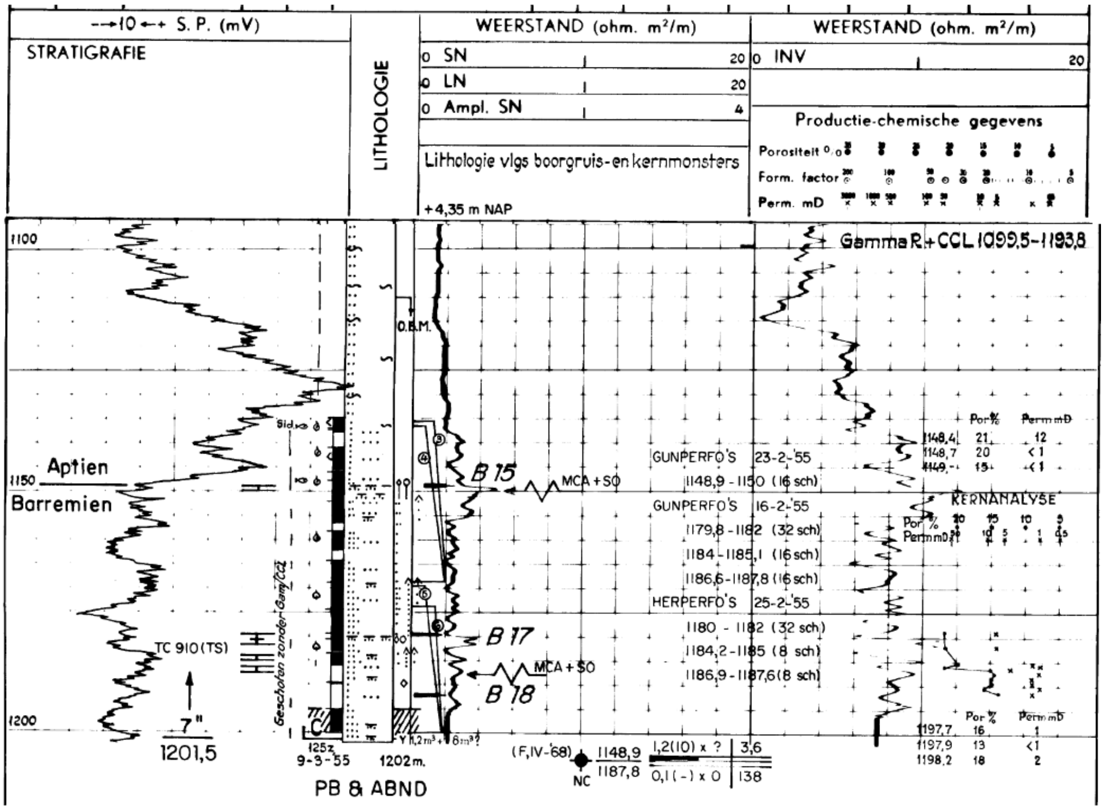

FIGURE E.9: A Delft well log retrieved form NLOG [3] with the red lines showing where the Liermember layer starts.The points that are shown in these logs correspond with the core testing results in figure 5.7

Bibliography

[1] Drijver B. & Schotting R. Schout, G. the influence of the injection temperature on the recovery efficiency of high temperature aquifer thermal energy storage: Comment on jeon et al. *Energy*, 103:107–109, 2016.

[2] Cheney C.S. & Dochartaigh B.. Lewis, M.A. *Guide to Permeability Indices.* Natural Environment Research Council, ©NERC, 2006.

[3] NLOG. Nlog, 03-2017. URL http://www.nlog.nl.

[4] TU Delft Energy Monitor. Campus, 20-02-2017. URL http://www.energymonitor.tudelft.nl/Campus.

[5] Eurostat. Eurostat: Production of primary energy, 17-02-2017. URL http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Production_of_primary_energy,_EU-28,%28%25_of_total,_based_on_tonnes_of_oil_equivalent%29_YB16.png.

[6] Delft Energy Initiative. Het delft plan, 14-02-2017. URL http://www.tudelft.nl/onderzoek/thematische-samenwerking/delft-research-based-initiatives/delft-energy-initiative/het-delft-plan/.

[7] Tu-Delft. Nederland kan regierol nemen in europese energiemarkt :, 14-02-2017. URL http://www.tudelft.nl/nl/actueel/laatste-nieuws/artikel/detail/nederland-kan-regierol-nemen-in-europese-energiemarkt/.

[8] DAP. Het delfts aardwarmte project, 17-02-2017. URL http://www.delftaardwarmteproject.nl/.

[9] KNMI. Winter door de jaren heen, 15-02-2017. URL https://www.knmi.nl/kennis-en-datacentrum/uitleg/winter-door-de-jaren-heen.

[10] Energievastgoed. Dossier: Warmte en koudeopslag (wko), 01-05-2017. URL http://www.energievastgoed.nl/dossiers/dossier-warmte-en-koude/.

[11] TU-Delft. *Energieoplsag TU Delft.* TU Delft, Delft, 2010.

[12] Hartog N. & Zaadnoordijk W.J. Van Lopik, J.H. The use of salinity contrast for density differnce compensation to improve the thermal recovery efficiency in high-temperature aquifer thermal energy storage systems. *Hydrogeology journal*, pages 1–17, 2016.

[13] Drijver B. Rapport 6 hogetemperatuuropslag. kennisoverzicht en praktijkmetingen rondom hogetemperatuuropslagsystemen. *Eindrapport. Bioclear, Deltares, IF Technology en Wageningen Universiteit in het kader van het project meer met bodemenergie.*, 2012.

[14] M. Wesselink. *Prospect for HT-ATES in the Dutch energy system. Potentials, applications and business cases of High-Temperature aquifer thermal storage systems.* TNO, Utrecht University, Utrecht, 2016.

[15] Schlumberger. Defining permeability, 20-02-2017. URL `http://www.slb.com/news/inside_news/2015/2015_0130_defining_permeability.aspx`.

[16] Merriam-webester. Aquifer, 28-02-2017. URL `https://www.merriam-webster.com/dictionary/aquifer`.

[17] Engineering Toolbox. Water-thermal-properties, 21-02-2017. URL `http://www.engineeringtoolbox.com/water-thermal-properties-d_162.html`.

[18] NVOE. *NVOE Richtlijnen Ondergrondse Energieopslag.* NVOE, 2006.

[19] Wika. Deep bore well, 28-03-2017. URL `http://en-co.wika.de/newscontentgeneric_ms.WIKA?AxID=471`.

[20] van Aarssen M. & Zwart B. Drijver, B. *High-temperature aquifer thermal energy storage (HT-ATES): sustainable and multi-usable.* University of Lleida, Spain: Lleida, 2012.

[21] Simmons C.T. & Dillon P.J. Ward, J.D. A theoretical analysis of mixed convection in aquifer storage and recovery: How important are denisty effects? *Journal of Hydrology*, 343:169–186, May 2007. URL `www.elsevier.com/locate/jhydrol`.

[22] Lennart Brokx. *Problems encountererd with the and future possibilities for medium and high temperature aquifer thermal energy storage in the netherlands.* Utrecht University, Utrecht, 2016.

[23] uark. Carbonate geochemistry, 21-02-2017. URL `comp.uark.edu/~ksteele/gochemfiles/SteeleCarbonatePC-762.html`.

[24] b. Bourbiaux. Ates contribution to the housing energy balance: a simple assessment methodology. *Oil & gas science and technology rev. IFP energies nouvelles*, 1(66): 21–36, 2011.

[25] DINO-Loket. Dino-loket, 03-2017. URL `https://www.dinoloket.nl`.

[26] van Beek H.J.M. Koenders, M.J.B. *Bodemenergieplan TU Delft en omgeving, DEFINITIEF*. IF Technology, Arnhem, 2011.

[27] George Pemberton S. & Smith M. Murray, K. Bioturbation: Reworking sediment for better or worse. *Oilfield Reviews ©Schlumberger*, 26, winter 2015.

[28] Science daily. Sedimentary rocks, 27-03-2017. URL `https://www.sciencedaily.com/terms/sedimentary_rock.html`.

[29] G. Nichols. *Sedimentology and stratigraphy*. Wiley-Blackwell, Oxford, 2009.

[30] Palcu M. & Scradeanu D. Boian, V. *Hydraulic conductivity assessment of aquifer structures from Southern Suhard Mountains*. University of Bucharest, Bucharest, 2015.