The Delft Sandstone in the West Netherlands Basin.

TA 3006: BSc Thesis Applied Earth Sciences

C.J.I. Wiggers
t119264
April 2009
# Table of contents

Table of contents .......................................................................................................................... 2  
Abstract......................................................................................................................................... 3  
1. Introduction ............................................................................................................................... 4  
2. Regional geology of the West Netherlands Basin ................................................................. 6  
3. Stratigraphy West Netherlands Basin ..................................................................................... 10  
   Alblasserdam Member ................................................................................................................. 10  
   Delft Sandstone Member ........................................................................................................... 11  
   Rodenrijs Claystone Member .................................................................................................... 11  
   Rijswijk Member ....................................................................................................................... 11  
4. Depositional models .................................................................................................................. 14  
   Den Hartog Jager .................................................................................................................... 14  
   DeVault & Jeremiah ................................................................................................................. 17  
5. The Delft Sandstone Member in the MKP 11 core and the Del 03 logs ...................... 19  
   The MKP 11 core ..................................................................................................................... 20  
   The Del 03 logs ........................................................................................................................ 21  
   The MKP 11 core versus the Del 03 logs .............................................................................. 24  
   A thickness model of the Delfland Subgroup ........................................................................ 25  
6. Conclusions and Recommendations ..................................................................................... 27  
   Conclusions .............................................................................................................................. 27  
   Recommendations .................................................................................................................. 27  
Acknowledgments ......................................................................................................................... 29  
References ...................................................................................................................................... 30  
Appendices ....................................................................................................................................... 32
Abstract

The Delft Sandstone Member (Late Valanginian, Early Cretaceous) is part of the Delfland Subgroup that is deposited in the West Netherlands Basin, in the southwestern part of the Netherlands. It is the target sandstone for the Delft Aardwarmte Project, that is planning to produce hot water from this sandstone. A detailed reservoir-geological model is an important step in assessing the spatial distribution of lithofacies- and fault-related heterogeneities in this sandstone, because these are of influence on the fluid flow properties of the sandstone. The Delft Sandstone Member consists of fluvial deposits in a syn-rift tectonic setting. The thickness, stacking, and lateral connectivity of the fluvial sandstones determine the overall reservoir communication.

The present study comprises an analysis of available literature about the West Netherlands Basin and the Delft Sandstone Member in particular. Furthermore the core of the Moerkapelle 11 (MKP 11) well is described and compared to the logs of the Delft 03 (Del 03) well, with the aim to get a better understanding of the Delft Sandstone Member and make a comparison between the two Delft Sandstone Member packages.

The Delft Sandstone Member is approximately twice as thick in the Delft area compared to the Moerkapelle area, probably because of the location of the MKP 11 near the boundary of the basin, where the Del 03 is located near the middle of the graben where more subsidence has resulted in more accommodation space. Both packages show loosely stacked sandstone bodies in the bottom of the Member and thicker stacked sandstone bodies in the top. The vertical connectivity is best in the stacked sandstones in the top of the Member, the lateral connectivity is difficult to establish only on the basis of correlation of wide-spaced well logs. Due to extensive faulting in the West Netherlands Basin, thickness modelling of the Delft Sandstone Member is almost impossible.
1. Introduction

The West Netherlands Basin is an area in the southwestern part of the Netherlands where extensive research has taken place in the search for oil and gas (Figure 1). Many wells were drilled and there is basinwide three-dimensional seismic data available. Many oil and gas fields are found up till now, but the subsurface can also be used for other purposes.

The Delft Aardwarmte Project (DAP) is planning to use the subsurface of Delft for the extraction of geothermal energy. The objective of DAP is to create sustainable, CO₂ neutral heating for the TU Delft campus, using innovative solutions while integrating research and education. To achieve this objective a plan is proposed to drill a geothermal doublet in the TU Delft premises. This doublet produces hot water from one well and cooled-down water, possibly including CO₂, is reinjected into the same sandstone layer at some distance from the production well. The innovative part will be drilling with a composite casing. Several people have taken part in the research for this project, among which Smits (2008) who has made a first simple dynamic model and Den Boer (2008) who has calculated the underground well spacing, needed for a reasonable lifetime of 30 years.

The target sandstone layer of DAP is the Delft Sandstone Member of Late Valanginian (Early Cretaceous) age. Smits (2008) concluded that this is the most favourable sandstone for geothermal exploitation at the TU Delft campus area, because it is known for its potentially good reservoir properties and it is the deepest potential reservoir within the Lower Cretaceous succession in the area, which will give the highest water temperature. Furthermore, the Delft Sandstone Member is the main reservoir layer in the Moerkapelle field, some 12 km to the northeast of Delft. Many wells were drilled in this field and therefore there is a relatively good understanding of the Delft Sandstone Member.

In the West Netherlands Basin, most wells are drilled in horst blocks and structural highs, and therefore the reservoir distribution within the grabens and the structural lows is still poorly understood. (DeVault & Jeremiah, 2002). The target of DAP is situated in such a structural low. A detailed reservoir-geological model is an important step in assessing the spatial distribution of lithofacies- and fault-related heterogeneities. These are of influence on the fluid flow properties of the sandstone. The Delft Sandstone is identified as syn-rift fluvial deposits (e.g. Den Hartog Jager, 1996; Van Adrichem Boogaert & Kouwe, 1993). The thickness, width, stacking, and lateral connectivity of the fluvial sandstones determine the
overall reservoir communication. The connectivity of the layers is very important because the reinjected water is supposed to uphold the pressure in the sandstone over a distance of approximately 1500 meters (Den Boer, 2008). The geometry and correlation of particular sandstone bodies depend on their depositional setting and nature of syn-sedimentary tectonics (Den Hartog Jager, 1996).

This paper will be the basis for a dynamic model that is to be constructed for the Delft Sandstone Member in the TU Delft area. It describes the geological history of the West Netherlands Basin based on a literature study. The core of a well in the Moerkapelle field (MKP 11) is described in detail by Gilding et al. (2009) and in this paper the logs of a well near the TU Delft campus (Del 03) are looked at and compared to the core of MKP 11.

First the regional geology of the West Netherlands Basin is described in chapter 2, then the stratigraphy of the Delfland Subgroup in the West Netherlands Basin is given in chapter 3, after which existing depositional models are described in chapter 4. The relation between the Delft Sandstone Member in the core of MKP 11 and the logs of Del 03 is given in chapter 5, the conclusions and recommendations are given in the last chapter of this paper.
2. Regional geology of the West Netherlands Basin.

The West Netherlands Basin is a basin in the southwestern part of the Netherlands, on- and offshore (Figure 1). This basin is bounded by structural features on the south and north. In the north, the NW-SE striking Mid Netherlands Fault Zone, which comprises among others the Zandvoort Ridge and the offshore IJmuiden High, forms the boundary with the Central Netherlands Basin and the offshore Broad Fourteens Basin. (Van Adrichem Boogaert & Kouwe, 1993-1997). In the south the London-Brabant Massif forms the boundary, to the southeast the basin merges with the Roer Valley Graben (Van Balen et al, 2000).

![Figure 1: Left: The structural element of the Netherlands during the Late Jurassic to Early Cretaceous. The white colour indicates the basin, the light brown a platform and the dark brown a structural high. (Wong, 2007). Right: The west of the Netherlands, with known oil and gas fields and all drilled wells indicated. The oil fields are indicated in red, the gas fields in green (Nlog, 2009).]
The West Netherlands Basin is situated on top of an area where tectonic deformation has played a role from the Late Carboniferous onwards. Many faults are present in the basin, and these divide the basin into several elements that are bounded by long NW-SE trending faults.

Van Balen et al. (2000) have divided the history of the West Netherlands Basin into four stages from the Late Carboniferous to the Tertiary.

**Late Carboniferous-Early Permian stage**
During the Variscan Orogeny the axis of the Campine Basin was situated at the place where now the southwestern part of the West Netherlands Basin is. First subsidence took place in this basin, but from the Westphalian to the Early Permian uplift and erosion occurred because of the Variscan orogeny.

**Late Permian – Middle Jurassic ‘prerift’ stage**
From the Late Permian onwards, the West Netherlands Basin formed a stable block. During the Late Permian rift pulse, the basin was uplifted followed by regional thermal subsidence in the Early Triassic. The West Netherlands Basin was part of a gentle, northward dipping basin, where lacustrine sediments were deposited, followed by a sandy fluvial and aeolian succession. During the Early Kimmerian tectonic phase (Middle to Late Triassic) the West Netherlands Basin formed a structurally simple, large-scale half-graben. Igneous activity accompanied the rifting, as is evidenced by the occurrence of volcanic rocks and intrusive sills (De Jager, 2007).

**Late Jurassic – Early Cretaceous ‘synrift’ stage**
From the Late Jurassic to the Early Cretaceous, strong rifting caused the breaking up of the West Netherlands Basin into subunits. A differentiation was caused between rapidly subsiding basins and more quiescent platform areas. (Wong, 2007) The highs in the basin were uplifted and eroded during the Middle Jurassic and Early Cretaceous rifting phases, while the basins accumulated very thick syn-rift sediment packages (De Jager, 2007). Large thickness variations occurred due to the syn-rift sedimentation with continuous shifting of depocenters because of oblique-slip effects in the extensional basin. As a result, the distribution patterns are very complex (Van Adrichem Boogaert & Kouwe, 1993).

Although the rifting gradually ceased during the Aptian-Albian, the subsidence of the West Netherlands Basin continued into the Late Cretaceous.
Late Cretaceous – Quaternary ‘postrift’ and inversion stages
After the rifting had ceased, compressive forces during the Alpine orogeny caused the inversion of the West Netherlands Basin (De Jager, 2007). This inversion resulted in the uplift of depocenters. Only in marginal troughs that formed to the north and south of the basin sedimentation still took place. The whole basin was covered by sediments during the Maastrichtian-Danian, when inversion movement temporarily ceased. Movement during the Paleogene caused more uplift in the basin and therefore hardly any sedimentation took place from that time onwards. The uplift was followed in the Neogene by again a subsidence (Van Balen et al., 2000).

During the syn-rift stage, the West Netherlands Basin filled with sediment from fluvial systems that came from the southeast and followed the southeast-northwestern trend of the basin. In the northwest the sea had an entrance into the basin, and in this part of the basin, there was an interfingering of fluvial and marine sediments (Wong, 2007).

The West Netherlands Basin is an oil and gas province in the Netherlands and hydrocarbon accumulations are mainly found in structural traps, formed by the reactivated faults, so called flower structures (De Jager, 2007) (Figure 2).

Present-day fault trends cannot be directly interpreted in terms of paleo-stress directions. Although it can be assumed that regional extension en compression in the Netherlands during the various stages in time was not only NW-SE oriented, but also N-S and W-E, the NW-SE trending West Netherlands Basin follows the older underlying structural trends. These different stress-regimes imply that
most of the faults not only have moved vertically, but also oblique. This is however not clearly shown in the faults because of the reactivation under the different stress regimes. Because of this, it is almost impossible to unravel the sense and amount of displacement during the various evolutionary phases of individual faults. (De Jager, 2007).
3. Stratigraphy West Netherlands Basin

In the West Netherlands Basin, different formations were deposited in time. The target sandstone for the Delft Aardwarmte Project is the Delft Sandstone Member. This sandstone is part of the Nieuwerkerk Formation (SLDN, Portlandian/Ryazanian – mid Hauterivian/Valanginian age) a formation that is part of the Delfland Subgroup (SLD) in the Schieland Group (SL, Late Portlandian – Early Barremian age). The Nieuwerkerk formation is the only formation in the Delfland Subgroup in the West Netherlands Basin and consists of three Members: The Alblasserdam Member (SLDNA), the Delft Sandstone Member (SLDND) and the Rodenrijs Claystone Member (SLDNR) (Figure 3).

The three members of the Nieuwerkerk formation will be described here, because they generally conformably overly each other and the boundaries between the members are therefore not always clear in logs, cores and seismics. The overlying Rijswijk Member is also described.

Alblasserdam Member

The Alblasserdam Member is described by Van Adrichem Boogaert & Kouwe (1993) as fluvial-plain deposits, with sand concentrated in mostly channels and crevasse-splays and with swamps and soils on the floodplains. The main transport direction was from southeast to northwest. Sediments are found of Portlandian to Hauterivian age. It contains typically dark to light grey, red and variegated (coloured zones) clay-and siltstones, fine to medium grained sandstones with bed thicknesses up to a few meters, and massive, thick-bedded, coarse-grained sandstones. Coal and lignite beds are associated with the grey claystones. Dispersed lignite matter, siderite spherulites and concretions are common. Cored sections show extensive mottling of the variegated claystones. Sandstone occurs in sheets, isolated or stacked channel fills.

The thickness of the Alblasserdam Member is variable between less than 100 meters to more than 1300 meters, controlled by the syn-rift deposition and a rapid pinch-out in a south-westerly direction towards the London Brabant Massif.
Delft Sandstone Member
The Delft Sandstone Member is of Valanginian age and defined as a light-grey massive sandstone sequence, fine to coarse-gravelly, fining upward, lignitic. The Member is interpreted as stacked distributary-channel deposits in a lower coastal plain setting and its occurrence is in the western and central parts of the West Netherlands Basin. In line with the Alblasserdam Member, the thickness of the Delft Sandstone Member is also influenced by the syn-rift deposition of the sediments and varies between 0 and 130 meters (Smits, 2008).

Rodenrijs Claystone Member
The Rodenrijs Claystone Member consists of medium to dark-grey, silty to sandy lignitic claystones in which laminated bedding, and lignite/coal beds are common. Locally mollusk shell remains are present. Siderite spherulites and concretions are common. It is interpreted as a lower coastal plain to lagoonal depositional setting and is distributed in the western and central parts of the West Netherlands Basin. The member is normally recognized on wire-line logs by a characteristic serrate (saw toothed-shaped) pattern. It is deposited from Late Valanginian to Early Hauteverian times. The thickness of this member varies from 20 to 115 meters along hole.

Rijswijk Member
The Rijswijk Member (KNNSR) from the Vlieland Sandstone Formation (KNNS) in the Rijnland Group (KN) conformably overlies the Rodenrijs Claystone Member in most of the West Netherlands Basin. This Rijswijk Member represents a marine transgressive systems tract that gradually, from the north and northwest, flooded the West Netherlands Basin from the Valanginian onwards.

The Nieuwerkerk Formation contains limited geochemical marker events. This indicates little variability in the provenance areas for the fluvial deposits. (DeVault & Jeremiah, 2002).

The lack of alluvial fans observed on seismic or encountered in wells in the hanging walls of major faults, suggests that the horst blocks rarely had a large amount of topographic relief from which fans could be shed (DeVault & Jeremiah, 2002). The source of the rivers which deposited the fluvial deposits in the Alblasserdam Member and the Delft Sandstone Member was from the southeast and the rivers flowed through the newly formed grabens towards the northwest. The most probable source of the clastic deposits is therefore the Ardennes and the Rhenish Massif, some 150 km to the southeast (Den Hartog Jager, 1996). Higher areas in Germany are another possible source.
Figure 3: Litho-Chronostratigraphic section through the West Netherlands Basin, where the stacking and stratigraphy of the different Members is shown (after Van Adrichem Boogaert & Kouwe, 1993). The Delft area is indicated by the rectangle. The location of this cross-section is indicated in Figure 4.
Figure 4: the locations of the cross sections of Figure 3 (black), Figure 6 (purple), and Figure 7 (blue) (Nlog, 2009).
4. Depositional models

Several papers have been written about the deposition of the Delfland Subgroup and the Nieuwerkerk Formation in the West Netherlands Basin. The models proposed by Den Hartog Jager (1996) and DeVault & Jeremiah (2002) are presented here.

**Den Hartog Jager**

Den Hartog Jager (1996) has described the Delfland Subgroup as characterized by fluvial deposits. This because of the lack of marine flora and fauna, the presence of channels sands, in situ coal beds and paleosols, cross-bedding and erosional bases. The fluvial channel type changed from braided river to meandering river in time due to the fact that the climate became more humid and because of the continuously changing tectonic movements in the basin. When going through the basin from southeast to northwest (Figure 5) the sand/shale ratio decreases, this means that there is relatively more shale in the northwest compared to the southeast. Furthermore, the sand/shale ratio increases towards the horst blocks next to the grabens. This is due to the fact that the fluvial systems followed the lowest point of the graben, which is typically next to the horstblock in a half-graben as is shown in Figure 5. In this lowest point, lateral movement of the fluvial system will be small and therefore not many shales are deposited. In the southeastern part of the basin, the grabens are relatively narrow and deep compared to the grabens in the northwestern part of the basin. This has resulted in a thicker stack of fluvial sediments in the southeast. In the lowest part of the Delfland formation, the Alblasserdam Member, very rapid lateral variation in thickness and sand/shale ratios are found with very sand-rich deposits probably concentrated in the graben centres. The Delft Sandstone Member is deposited in a similar type of environment, but the active faulting had decreased and an extensive coastal plain began to form in the northwest.
Figure 5: Model for the deposition of the Delfland Subgroup in the West Netherlands Basin. The source of the fluvial sands is further southeast (Den Hartog Jager, 1996). The figures 7a to 7c that are referred to can be found in Appendix A as figures 4 to 6. The location of this cross-section is indicated in Figure 4.
Den Hartog Jager (1996) has divided the Delfland Subgroup into six sequences. The subdivision is based on biostratigraphic data, sequence stratigraphy concepts, seismic facies, and depositional facies, where the lithofacies were of greatest influence. The cross section with the sequences indicated, is shown in Figure 6. The sequences NRL, NRU and NVA consist of fluvial synrift deposits, while the NVH, NHB and NBR have increasing marine influences. More information about the sequences can be found in the paper by Den Hartog Jager (1996).

In Figure 6 it is visualized how the coastal Rijswijk Member and the marine Vlieland Claystone gradually move land inward during a transgression. By the end of the Barremian, the whole West Netherlands Basin was flooded by the sea.

Figure 6: Sequence stratigraphic scheme for the Lower Cretaceous of the West Netherlands Basin (Den Hartog Jager, 1996). The location of the cross section is shown in Figure 4.
DeVault & Jeremiah

DeVault & Jeremiah (2002) have made a different model in which they no longer define the Delft Sandstone Member as a separate member. This, because the Delft Sandstone Member is defined by Van Adrichem Boogaert & Kouwe (1993) as stacked distributary-channel deposits and these occur, according to the authors, throughout the Nieuwerkerk Formation. The Rodenrijs Claystone Member is extended to encompass all coastal-plain sediments, including channel sandstones. According to DeVault & Jeremiah (2002) the fluvial origin of the formation is evidenced by an abundance of stacked, fining-upwards fluvial channel sandstone bodies capped by flood-plain siltstone and ponds and the predominance of fining-upward gamma-ray log signatures in wells. They interpret the depositional environment as a meandering fluvial system because of the thick flood-plain deposits that are unusual for braided systems. Their model is based on recognition of characteristic log shapes, and the use of stratigraphic concepts. Log facies analysis also has been applied in the recognition of stacked/amalgamated channel systems and fining/coarsening-upward cycles. DeVault & Jeremiah (2002) state that the base-level changes and their A/S ratio (Accommodation space/Sediment supply ratio) expression are as likely to be caused by tectonic episodes as by distal eustatic fluctuations, but that it is hard to distinguish without additional information.

Although it is very difficult to correlate layers within the syn-rift deposits, DeVault and Jeremiah (2002) have found cycles to be reasonably correlatable on a subregional (i.e., 10–20 km) scale within individual intrabasinal provinces defined by major rifting faults.

By looking at the influence of tectonics on sedimentation, DeVault & Jeremiah (2002) show that sand has been trapped in the grabens adjacent to the major rift faults in the basin. A shadow effect can be seen in the vicinity of the Berkel and Delft fields, where generally the net/gross values are low. This might indicate that the major faults to the south of the IJsselmonde area acted as sand traps. The thickness of the layers is shown in Figure 7. The total net thickness of the sandstone bodies at the production location of DAP is approximately 80 meters. Assuming (partial) connectivity between different sandstone bodies, this is thick enough for DAP to produce from.
Figure 7: Seismostratigraphic relative net sand thickness of the Alblasserdam Member from Early Valanginian to Early Hauterivian with net/gross values overlain as line contours. The Delft Sandstone Member is deposited in the Late Valanginian and therefore part of the sandstone shown in this picture. (DeVault & Jeremiah, 2002). The approximate location where DAP is planning to produce its hot water from is indicated in the figure with the red star. The black star represents the location of the injection well.
5. The Delft Sandstone Member in the MKP 11 core and the Del 03 logs.

The Delft Sandstone Member is found in the western and central part of the West Netherlands Basin. The sandstones are however not deposited equally everywhere. Most information about the Delft Sandstone Member is gathered at the Moerkapelle field. By looking at a core from a well there and from a well in the vicinity of the TU Delft, a comparison can be made between the two Members in the different areas. Since there are no cored sections with the Delft Sandstone Member near the TU Delft area, the logs of well Del 03, a well near the TU Delft campus, were looked at (Figure 8).

Figure 8: location of the Del 03 well (yellow star) and the MKP 11 well (blue star). These two wells are approximately 12 km apart.
The MKP 11 core
To get a better understanding of the Delft Sandstone Member, the core of the well Moerkapelle 11 (MKP 11) is described. Gilding et al, (2009) give a detailed description of their observation on this core. It is concluded that the Delft Sandstone Member consists of seven sandstone bodies that are partly stacked and contain multiple reactivation surfaces, where clay pebbles are found within the sandstone bodies. The deposits mostly consist of medium to coarse grained sands, with pebbles at the base of the bodies. Finer deposits are present in the top of the sandstone bodies and coal layers and coal clasts are found throughout the core. The sandstone bodies are characterised as fluvial channel deposits, probably meandering channels. Although no distinct cross-bedding is found in the core the coal clasts suggest a depositional environment that changed its position in time and cut into its own floodplains and swamps. The position of the Moerkapelle field during the time of deposition of the Delft Sandstone Member is in the distal part of the fluvial system, approximately at the location of the middle block of the interpretation by Den Hartog Jager, where meandering rivers are found (Figure 5).

Appendix B shows the log of this core with the different sandstone bodies and reactivation surfaces indicated. The total thickness of the Delft Sandstone Member is approximately 50 meters along hole. The thickness of individual sandstone bodies varies from 2.5 to 13.5 meters in the core, with an average thickness of 7 meters. The deviation of the well varies in the core from 41 to 45°. When applying a dip of 45° on the whole log, the result is a conservatively calculated vertical thickness. The calculated vertical thicknesses of the sandstone bodies in the core vary from 1.8 to 9.5 meters with an average thickness of 5 meters. The tectonic dip of the area varies from place to place in the basin, and therefore it is not taken into account at this point. Loerakker (2009) will give exact thicknesses of the sandstones in the MKP11 with the tectonic dip being taken into account.
Figure 10 shows the Gamma Ray (GR) log of the MKP 11, unfortunately there is no Spontaneous Potential (SP) log available.

The net/gross value of the Delft Sandstone Member in the MKP 11 is approximately 75%, based on the core and the GR log, assuming that the missing parts of the core mostly consists of sandstones.
The vertical connectivity in the core seems reasonably well, with the stacked sands and the reactivation surfaces. There are siltstone layers found inside the Delft Sandstone Member, but since there are oil stains found above and below these siltstones, they are no big threat to connectivity.

**The Del 03 logs**

In the logs of the well Del 03, the Delft Sandstone Member can be recognized on the SP log. The SP curve is a recording versus depth of the difference between the electrical potential of a movable electrode in the borehole and the electrical potential of a fixed surface electrode (Schlumberger, 1989). Low SP readings indicate the most permeable layers, which are the sandstone layers and high SP readings indicate layers that contain clays and are less permeable.

The Del 03 well is a vertically drilled well. The interpretation of the SP-log shows a thickness of the Delft Sandstone Member of approximately 110 meters with the cleanest sandstone bodies in the top of the Member (Figure 10). Here the sandstone bodies have a thickness of 12, 10 and 8 meters respectively and because of the low SP reading, a good permeability is expected. Below this nice sandstone, more sandstone bodies are found, but these have higher shale contents, hence the higher SP reading.

The three highest sandstone bodies probably consist of several fluvial channel deposits that are stacked and therefore give the continuous SP pattern and thicknesses as shown on the log. These sandstones will be the main target for DAP.

The net/gross value of the Delft Sandstone Member in the Del 03 is approximately 60% based on the SP log, assuming that the clay content of the lower sandstone bodies is 50%.

The vertical connectivity between the different sandstone bodies seems reasonably well in the top of the Del 03 well; in the top of the Member, the layers between the sandstone bodies seem to not only consist of clays, but they probably contain fine sands and clays of a floodplain deposit. The deep resistivity (RESD) log however shows high values at the layers between the sandstone bodies. This might indicate that there is more clay present than the SP log shows. In the lower part more clay is present between the different sandstone bodies that might have an influence on the vertical connectivity. These layers with more clay are possibly floodplains on top of a channel deposit or a point bar.
The sandstone bodies, which contain about 50% clays, have thicknesses between 2 and 8 meters and seem to be deposited on top of each other, instead of being amalgamated as has happened in the top of the Member.

Davies et al (1992), state that the principal reservoir sand bodies in meandering systems originate as point bars that are developed on the inner bank of meander loops in response to lateral sand accretion (Figure 9). Donselaar & Overeem (2008) have shown that there is a preservation of coarse sandy bed forms on channel floors of mixed load fluvial channels. The cross-bedded channel-floor deposits are directly connected to the lowest part of the sandy point-bar sequence and are also preserved as sandstone lenses in the crossover reach between meander bends. These channelfloor sandstone lenses play an important role in connecting pointbar units in an along-stream direction. (Donselaar & Overeem, 2008). This means that the lateral connectivity is higher in the direction of the flow then it is in the direction perpendicular to the stream.

Richardson et al (1987) warn that permeabilities and porosities usually do not correlate from well to well at equivalent stratigraphic depths because they represent different positions in a bed. These two things are very important to keep in mind when modelling the properties in a later stage.

Figure 9: block diagram of a high-sinuosity fluvial system illustrating the facies associations, channel belt and flood-plain subenvironments. The point bar accretion is indicated. (Emery & Myers, 1996)
Figure 10: Spontaneous Potential (SP) and Deep Resistivity (RESD) log of Del 03 and the Gamma Ray (GR) and RESD log of MKP 11. SLDND_T and SLDNA_T are top and bottom of the Delft Sandstone Member respectively, interpreted by the NAM. The yellow colour indicates low SP and GR values, which are the most permeable layers, the sandstone layers. The grey colour indicates parts with high SP and GR values, this are less permeable layers that contain more clays.
The MKP 11 core versus the Del 03 logs

The depth of the Delft Sandstone Member is about 1000 meters deeper in the TU Delft area than it is in the Moerkapelle field. Since both intervals are identified as Delft Sandstone Member both are in the same chronostratigraphic interval, which means that they have been deposited in the same time period. The fact that there is now a 1000 meters difference between the Delft Sandstone Member in the two locations shows the influence of the tectonics in the area. Smits (2008) has shown that the two locations have been buried to approximately the same depth, and because of this, the Moerkapelle field can be used as an analogue for the Delft area with respect to the properties of the sandstone.

The Delft Sandstone Member is approximately twice as thick in the Delft area as in the Moerkapelle field. This thickness difference can be explained by the position of the two areas in the basin. The Delft area is located near the middle of the West Netherlands Basin, where the Moerkapelle field is located near the border. Most accommodation space was available in the middle of the basin due to the highest subsidence rate, and therefore more sediment is deposited there. Another interpretation could be that the model of Den Hartog Jager (1996) is applicable in this case, but with the model mirrored. This would mean that the Del 03 is closest to the horst and the MKP 11 is further away from it. This interpretation does not seem plausible, because of the many faults that are found between the Del 03 and the MKP 11.

The two areas are approximately 12 km apart and the two sandstone packages were deposited by different branches of a river. The presence of active faults during the time of deposition also plays an important role in the accommodation space. If there were faults between the two areas at the time of deposition, the resulting blocks might have behaved different in time due to tectonics and the thickness differences can be a result of that.

In both wells, the stacking pattern of the sandstone bodies changes within the Delft Sandstone Member. At the bottom, the different sandstone bodies are loosely stacked, with more clayey layers in between, whereas the sandstone bodies on top seem to be vertically stacked and laterally amalgamated.

The stacking pattern of fluvial channel sandstones may indicate changes in rate of accommodation space increase. Multilateral, multistory channel units for example, represent low rates of accommodation increase. Widespread, laterally amalgamated fluvial sandstones that are overlain by more isolated meander-belt sand bodies and an increasing proportion of mud may reflect increasing rates at which accommodation space is created (Shanley & McCabe 1994).
The more loosely stacked sandstone bodies in the bottom of the Delft Sandstone Member suggest that there a rapid relative rise of base level and therefore a rapid accommodation space increase during the time of deposition. This resulted in layers that were deposited on top of each other and were not cross-cutting other sandstone bodies. The rapid increase is due to the rifting that occurred during deposition. The stacked sandstone bodies in the top of the Member correspond to a decrease in accommodation space, and with that a decrease in subsidence due to rifting. Due to the decrease in accommodation space increase, channels cut into older sandstone bodies and this has resulted in the stacked sandstone bodies.

The lateral connectivity and extent of the sandstone bodies are difficult to establish by only the correlation of the logs and core. Seismic data might give more information on this.

**A thickness model of the Delfland Subgroup**

The thickness of the Delfland Subgroup and specifically the Delft Sandstone Member varies throughout the West Netherlands Basin. This is illustrated by the different cross sections that can be found in the literature and go through the basin, which are shown in Appendix A. Within the Moerkapelle field for example, the thickness of the Delft Sandstone Member varies from 22 to 128 meters, according to log descriptions made by the NAM. In three wells that are located close to each other, but on different sides of faults, (MKP 10, 11 and 12, Figure 11) the thickness difference is up to 70 meters. In all three wells, there is a Rodenrijs Claystone Member identified on top of the Delft Sandstone Member. The difference is therefore probably caused by the many faults that are present in the field and the way they have reacted to the different tectonic forces in time. It proves that the tectonic activity had an active role in the distribution of the channels and therefore their deposits, and that not only the sea level was of influence.

Because of the faults it is very difficult to make a thickness model of the Delft Sandstone Member in the Moerkapelle field. Without a proper fault model of this field and the rest of the West Netherlands Basin, it is impossible to make a model for the thickness of the Delft Sandstone Member in the basin at this stage.
Figure 11: Countour map of the top of the Nieuwerkerk Formation and the location of the Moerkapelle wells. (Bartlema, 2002). Wells MKP 10, 11 and 12 are situated inside the blue circle
6. Conclusions and Recommendations

Conclusions
The depositional history of the Delfland Subgroup and the members in it, is described in this paper. The main target of DAP, the Delft Sandstone Member, is deposited during an active phase of rifting by meandering rivers that were flowing through the basin from the southeast to the northwest, following the lowest parts of the basin. This has resulted in large thickness variations in the sandstone. Modelling this is a challenge.
When comparing the core of well MKP 11 with the logs of the well Del 03 it is found that:
The net/gross of the Delft Sandstone Member is 75% in the MKP 11 and 60% in the Del 03. This is mainly due to the fact that the bottom part of the Delft Sandstone Member does not contain clean sands, but sands that contain about 50% clays.
The Delft Sandstone Member is approximately twice as thick in the Delft area compared to the Moerkapelle area. This is probably due to the fact that the Moerkapelle field is located near the horst, on the northern boundary of the basin, while Delft is located more in the middle of the basin where a higher subsidence rate created more accommodation space.
Both the MKP 11 core as the Del 03 logs show loosely stacked sandstone bodies in the bottom of the Member and thicker stacked sandstone bodies in the top.
The vertical connectivity is best in the stacked sandstones in the top of the Member, the lateral connectivity is difficult to establish by only the correlation of the logs and the core. The extensive amount of faults in the West Netherlands Basin makes it difficult to correlate different sections of the Delft Sandstone Member. This is already evident at relatively small distances in for example the Moerkapelle field.

Recommendations
With the information in this paper, a geological model of the Delft Sandstone Member can be build, which is an important step for modelling the lithofacies- and fault-related heterogeneities. Besides the information described here there is more information that can be used for the modelling of the Delft Sandstone Member.
- Seismic data can give information about the lateral connectivity of different sandstone packages and their thickness. The seismic data that is
available now is not processed for the Delft Sandstone Member. Reprocessing the data should improve the thickness and connectivity determination.

- Several faults are present in the West Netherlands Basin and it is crucial to know exactly where these are and what has happened with them during the geological history of the area. It is impossible to model the thickness of the deposits during the time of deposition for the different members in the Delfland Subgroup when it is not clear how much movement occurred across the faults. Special software makes it possible to invert movement across faults, which is an important step to modelling the thicknesses of the Delfland Subgroup.

- A detailed geological model can be build when the facies in the Delft wells and the Moerkapelle wells are recognised. By combining the information from the core of the MKP11 with its logs, the facies can be recognised on logs. It is then possible to compare the logsignature of the facies from MKP 11 with the logs of the TU Delft area and in that way build a facies model of the Delft area.

- A study on the cuttings of the Del 03 well can be performed to get a better understanding of the Delft Sandstone Member and its overburden in the TU Delft area. With that information a link can be made between the logs and the rocks that are present in the well. Although this is already done for the MKP 11 well, where the core is compared to the logs (Loerakker, 2009), it would give extra information for the model and more certainty about the subsurface of Delft.

- As was mentioned, the base-level changes and their A/S ratio expression are as likely to be caused by tectonic episodes as by distal eustatic fluctuations, but it is hard to distinguish without additional information. Information that might be used to distinguish between these two influences might be found by looking at the global sea level changes during the time of deposition and by looking at fossil traces that might be found in wells that are closer to the edge of the basin. In that way, the influence of the sea level can be assessed.

- When modelling the properties of the Delft Sandstone Member in a dynamic model, it is important to keep in mind that the permeabilities and porosities usually do not correlate from well to well at equivalent stratigraphic depths because they represent different positions in a bed.
Acknowledgments

I would like to thank my supervisor Rick Donselaar for his input in the project and for assisting Douglas Gilding, Mark Loerakker and myself, with the core description at the NAM in Assen. Karl-Heinz Wolf has given useful input during the presentation that was given halfway the BSc thesis work. The NAM has kindly provided their core-shed in Assen for our research on the MKP 11 core. With Mark and especially with Douglas, I spend many hours discussing the geology of the West Netherlands Basin. Thank you for your input! It was a good experience to be part of a team working on the research for the Delft Aardwarmte Project.
References

Bartlema, H., 2002, 3-D Geological modelling and a SAGD production forecast of the Moerkapelle Field (volume 1), MSc Thesis, Delft University of Technology, Delft, the Netherlands.


Loerakker, M., 2009, In progress, BSc Thesis, Delft University of Technology, Delft, the Netherlands.


Appendices

Appendix A: Cross sections through the West Netherlands Basin.

Appendix B: The log of the MKP 11 well made by Gilding et al. (2009)
Appendix A.

Cross sections through the West Netherlands Basin.

Cross sections through the West Netherlands Basin that show the Delfland Subgroup or the Delft Sandstone Member from literature are listed here. Figure 1 shows the positions of the first 10 cross sections in Figure 13 to Figure 22. After this, the lines are not always straight, and from Figure 23 to Figure 16, the position of the cross section is shown in the figure itself. Figure 13 and Figure 14 give the schematic stratigraphies of the Netherlands Basin made by respectively Den Hartog Jager (1996) and Racero-Baena & Drake (1996).

Figure 12: The West Netherlands Basin in current times with the position of figures 2 to 11 indicated. Oil (red) and gas (green) fields are also indicated. (www.Nlog.nl)
Figure 13: Cross section of the West Netherlands Basin with indicated sequences (Den Hartog Jager, 1996). See figure 1 for the exact location.
Figure 14: Schematic Lower Cretaceous stratigraphy of the Rijswijk Concession. The diagram illustrates the stratigraphic position and geometry of the oil-bearing reservoirs in the West Netherlands Basin. The Unzelmonde and Bedelf Sandstone Members are barrier complexes, whilst the Rijswijk Member is a transgressive deposit. The De Lier and Holland Greensand Members represent shelf deposits of poor reservoir quality. See Fig. 6 for the location of this conceptual section. Blue symbols below Delfland indicate Podosoro Shale.

Figure 15: Cross section through the West Netherlands Basin (Den Hartog Jager, 1996). See figure 1 for the exact location.
Figure 16: Cross section through the West Netherlands Basin (Den Hartog Jager, 1996). See figure 1 for the exact location.

Figure 17: Cross section through the West Netherlands Basin (Den Hartog Jager, 1996). See figure 1 for the exact location.
Figure 18: Well-log correlation of the Nieuwerkerk Formation of in the West Netherlands Basin (Wong, 2007). In figure 1 the location is indicated.

Figure 19: Regional seismic line through the West Netherlands Basin. (Racero-Baena & Drake, 1996). The red dots indicate oil fields; the green dots indicate gas fields. See figure 1 for the exact location.
Figure 20: Seismic line across the inverted Wassenaar Graben (Racero-Baena & Drake, 1996). See figure 1 for the exact location.
Figure 21: Seismic line across the Pijnacker field (Racero-Baena & Drake, 1996). See figure 1 for the exact location.
Figure 22: Schematic SW-NE cross section through the West Netherlands Basin. (De Jager et al., 1996) see figure 1 for the exact location.

Figure 23: Southwest-northwest oriented seismic line through the central West Netherlands Basin, showing rift-generated horst and graben structures, synrift thickness variations in the
Nieuwerkerk Formation, and compressional structures formed by later basin inversion. (DeVault & Jermiah, 2002).

Figure 24: South-north transect through several wells. Not the relatively constant thickness of the postrift strata (above the Speetonesis MFS) compared to the underlying synrift sequence. (DeVault & Jermiah, 2002).
Figure 25: West-east strike well-log cross section through the West Netherlands Basin Lower Cretaceous interval. (DeVault & Jermiah, 2002).
Figure 26: North-south dip well-log cross section through the West Netherlands Basin Lower Cretaceous interval. (DeVault & Jermiah, 2002).
Figure 27: Northwest-southeast dip well-log cross section through the West Netherlands Basin Lower Cretaceous interval. (DeVault & Jeremia, 2002).
Average deviation of the well over cored section is 45 degrees

Core description made by Gilding, Wiggers and Loerakker

Appendix B