Early Cenozoic stratigraphy in the Vrijenban syncline – compilation of current information

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Abstract
We here report on the early Cenozoic stratigraphy of the Vrijenban syncline in the West Netherlands Basin, between the cities of Delft and Pijnacker. These formations are a target of coring within the frame of the DAPwell geothermal project, where representative cores of the overburden will be taken. At Delftse Hout, a monitoring well of DAPwell is planned and this well seem suited for coring the more shallow formations, due to reduced costs, rather than coring these in the DAPwell drilling sites at TU Delft campus. In addition, at Delftse Hout, the Vrijenban synclinal structure produces a slightly thicker Cenozoic stratigraphy. This is important as previously TNO reported the thickness of the Rupelian Clays to be 'uncertain' in the area and seismic lines and offset well data show limited thicknesses.

In order to better understand and predict early Cenozoic stratigraphy in the Vrijenban syncline, we asked TNO to do a biostratigraphic analysis of cutting samples from wells in the area. The selected wells are PNA-GT-01 and PNA-GT-04, both drilled for geothermal purposes, approximately 2 to 3 km to the south-southeast of the Delftse Hout area. We here provide the full TNO report (Appendix B) and discuss the findings in view of the lateral continuation of the stratigraphy to below Delftse Hout where the coring is anticipated. For that, we use well-log data for 5 older PNA wells in that area, while the other PNA wells in the area have no well-logs in the upper 500 meters.

Stratigraphies of well-logs in PNA wells few hundreds of meters around Delftse Hout can be correlated seemingly straightforwardly. Spontaneous Potential logs show very similar trends above the Chalk Formation and below the sandy Miocene formations. This is interpreted to be indicating very laterally constant thickness of sedimentary units in the area of Delftse Hout. There is a stable 65m thick interval of fine clastics above the Chalk and below the Miocene. Within this interval, we interpret a fine clastic intervals of around 20 m of Eocene at the base of the interval and around 30-35 m as Oligocene at the top of the interval, separated by a condensed and more heterolithic, possibly glauconitic interval of around 10m. Comparing these Delftse Hout records with the PNA-GT wells drilled more recently few kilometres further south and studied here biostratigraphically by TNO, shows that the Eocene interval thins and the Oligocene interval thickens northward.

With high certainty, the current data demonstrate there will be an early Cenozoic package of clays and silts of around 65 meters in the Delftse Hout area of which 10 meters will be more sandy, possibly glauconitic. Further detailed stratigraphy cannot be assured until biostratigraphic analysis of cores is undertaken, which are currently unavailable for the area. For coring the early Cenozoic in the Delftse Hout, the data indicate that the full 65 m should be targeted including the transition from the Miocene and into the Chalk. A note should be made that the caliper log of PNA-GT-01 well indicates serious borehole calving of the well in the sandy intercalation of what is interpreted to be in between Eocene and Oligocene and in the earliest Miocene. This points to very loose materials that may be hard to core, contaminate cuttings, and fill the borehole after drilling. The caliper log does not indicate swelling of clays to the extent of making a smaller borehole than initially drilled.

Introduction

The coring of subsurface formations is prime target of the science component of Delft Aardwarmte Project (DAPwell) by TU Delft. EPOS-NL has supplied funds to core considerable intervals of the subsurface in, below and above the geothermal reservoir sandstone. Rock cores serve to groundtruth the indirect estimates of flow, thermal and geomechanical parameters of the subsurface rocks using well-logs and nearby wells. That allows improved models for risk assessment of earthquakes and of geothermal production and cold-front breakthrough, and validation when combined with monitoring. This makes this geothermal project a unique research facility of geothermal energy production in an economically optimal and environmentally and societally safe manner.

The overburden rocks of a geothermal reservoir are important to understand their geomechanical properties. Young's modulus and Poisson's ratios are best measured directly on rocks rather than indirectly using well-logs. However, no suitable and undisturbed rock cores are available from depth between 200 m and 1500m of many of the formations in the Dutch subsurface making geomechanical and geophysical models more uncertain. Therefore, in DAPwell, we target some of the end-member lithologies in the overburden of the targeted Delft sandstone reservoir. A specific target is the lithification transition between unconsolidated to consolidated rocks anticipated around 400-500 m depth. Additionally, heat storage in the shallow subsurface is important for seasonal storage of geothermal heat, allowing a more efficient use of the geothermal project. Rock cores will help to further quantify the flow and geomechanical character of the potential target rocks in the shallower subsurface including the heterogeneity. Moreover, this area of the West Netherlands Basin has little direct data such as biostratigraphic analysis on rock cores, therefore little is known about the evolution of the area during the Cenozoic. This is interesting from engineering point of view, to further predict character of the subsurface, but also for paleoenvironmental and paleoclimatic studies that try to explain Earth system evolution through time. Finally, radioactive waste disposal in the subsurface needs accurate knowledge of geomechanical properties of the target formations. For that, undisturbed rock cores are indispensable.

Coring in the DAPwell injector and producer wells will occur across the reservoir zone interval and the direct over- and underburden. Higher in the overburden, intervals of end-member lithofacies are selected for core retrieval. The Cenozoic sequence including the Paleogene clays and Neogene sands were also selected as coring targets in the DAPwell doublet. However, these unconsolidated sediments have to be cored with specialistic techniques and in the DAPwell doublet, one of the main costs is the presence of the drilling rig (which is able to drill to several km). In the search for alternatives, coring the Cenozoic in one of the nearby monitoring wells is seen as advantageous. TU Delft could arrange the coring without interrupting the logistics of DAPwell. Additionally, seismic lines indicate that towards one of the monitoring wells in Delftse Hout the Cenozoic sequence is thicker than at the drill site of the DAPwell doublet.

To further investigate the stratigraphy of the Cenozoic sequence below Delftse Hout, TU Delft asked TNO to perform a biostratigraphic analysis on cuttings of wells nearby Delftse Hout. The report (Munsterman, 2020) is presented as Appendix B of this report and materials are used within this report. TNO reported to be only able to use cuttings from PNA-GT-01 and PNA-GT-04 wells; these were recently drilled and had cuttings available. The current report briefly discusses the TNO results and then extends those findings into the nearby Delftse Hout area using well log data of wells in that area.

Approach

We use PNA-well data from nlog.nl. Well logs are given for the upper 500 m for PNA-03, 05, 06, 08, 11, and PNA-14. See figure 1 for the overview of the area and the location of the wells.

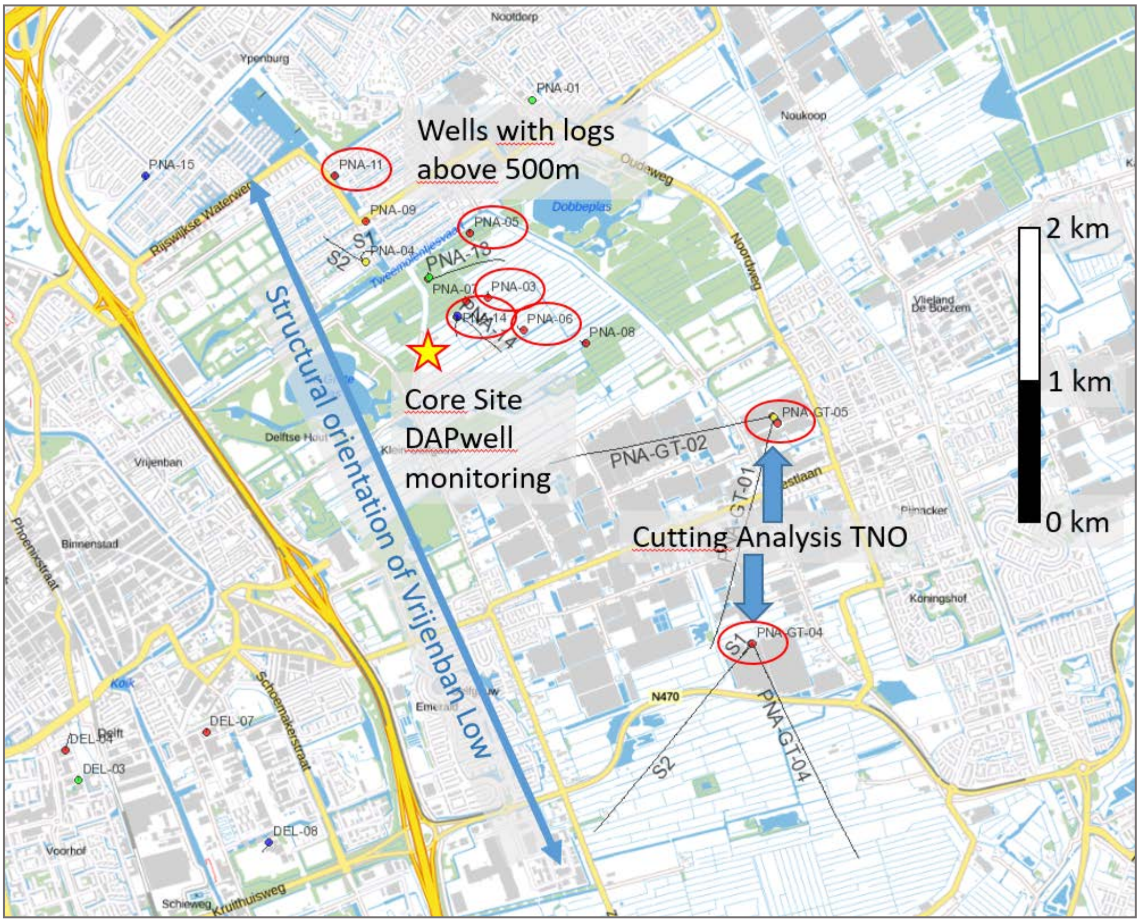

Figure 1. *Map of area between Delft campus to the left (Del-07 and Del-08) and Pijnacker to the right with existing wells given. PNA-GT-01 and PNA-GT-04 wells are used for cutting analysis by TNO, whole PNA-11, PNA-05, PNA-03, PNA-14 and PNA-06 are used for correlations as these wells display well logging in their upper 500 meter. The proposed drill site for the DAPwell monitoring in Delftse Hout is given with the yellow star. Map modified from nlog.nl.*

Well log stratigraphy of the Delftse Hout wells are correlated to each other and then to the well logs of PNA-GT-01 and 04 wells. This allows the biostratigraphic observations and interpretations to be imported into the Cenozoic stratigraphies at Delftse Hout and general stratigraphic interpretation to be made of the stratigraphy at the Delftse Hout. Minor reinterpretations were made to the TNO interpretation of PNA-GT well stratigraphies based on well-log stratigraphy within the margins of the biostratigraphy. Conclusions are summarised and discussion of expected Cenozoic stratigraphies at Delftse Hout including considerations of uncertainty is provided.

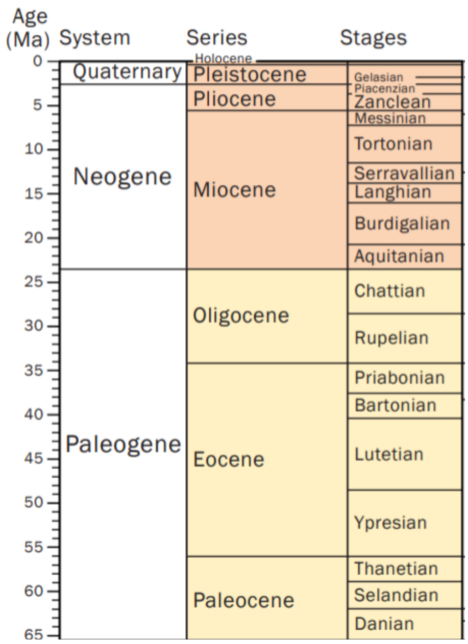

Figure 2. *Cenozoic stratigraphic column (TNO, 2011).*

Results

Most wells with well logs above 500 m at Delftse Hout have a Spontaneous Potential (SP) log and Resistivity (RES) log, see Figure 3 for an example from the PNA-06 well and all results in Appendix A. SP provides a measure of the electric potential between the formation material including its fluids and the surface. There is no straightforward relation between formation porosity and SP as formation fluids may result in very different responses. One well, PNA-14, has a Gamma Ray (GR) log and no other logs for the upper 500 m.

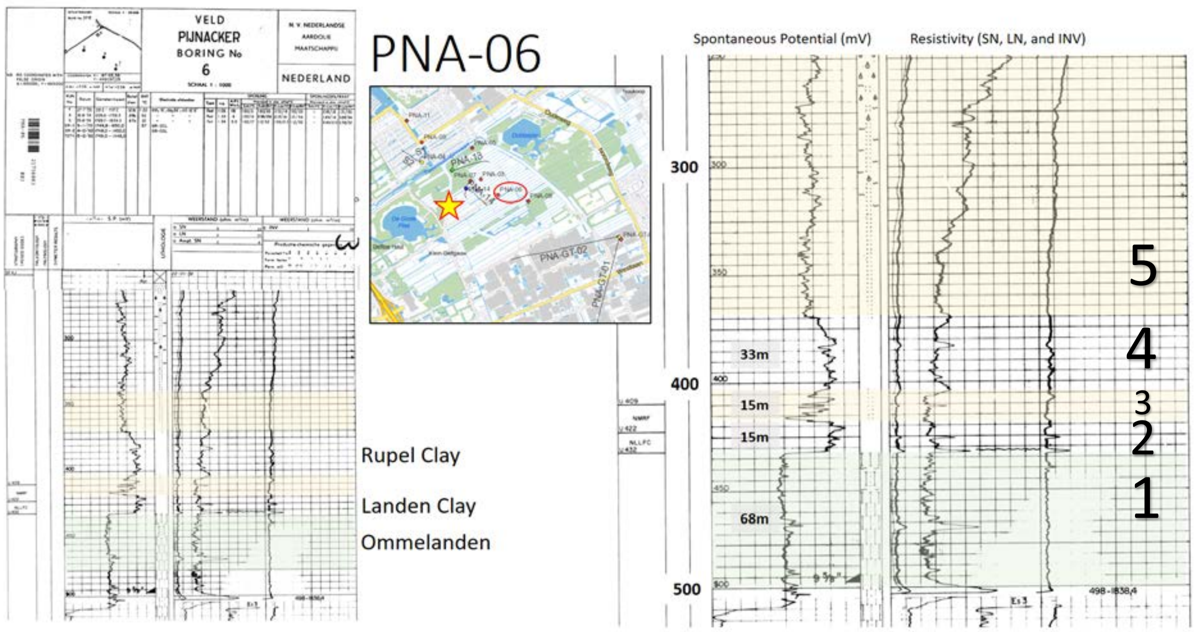

Figure 3. *Well logs of PNA-06 from nlog.nl. Similar figures for the other wells are supplied in Appendix A. The tentative relation of well-log stratigraphy to Rupel, Landen and Ommelanden is based on correlations between the wells, available lithological descriptions and the biostratigraphic analysis of the PNA-GT wells by TNO presented further in this report.*

Remarkably, PNA-11, PNA-05, PNA-03, and PNA-06 all reveal very similar SP and Resistivity (RES) stratigraphies (Fig. 4). Correlation of these wells can be considered very certain. Interval1 shows low SP and RES and is reported to be rich in limestone or marl lithologies. Interval 2 starts with a sudden increase in SP and RES at around 435 to 425 m depth. Interval 2 is between 15m and 21 m thick and is reported to be marly. Overlying is interval 3 that is 10-15 m thick and shows lower and variable SP and somewhat lower RES. Interval 3 is reported to be a little less marly or a little more sandy in some wells. Next is interval 4 that is 30 to 36m thick and slightly more marly with higher SP and RES. Comparing interval 4 and interval 2, shows that RES is generally higher and SP is generally lower in interval 4. Again moving upwards, interval 5 gradually moves into a long interval of lower SP and an initially lower and increasing RES. Interval 5 is mostly reported to be more sandy.

The thicknesses, log responses, and stratigraphic depths at which the intervals occur are very similar between the 4 sites that could be analyses (Fig. 4). Despite that the lithologies behind the log responses and the detailed age labelling remains uncertain, this makes the correlation highly certain.

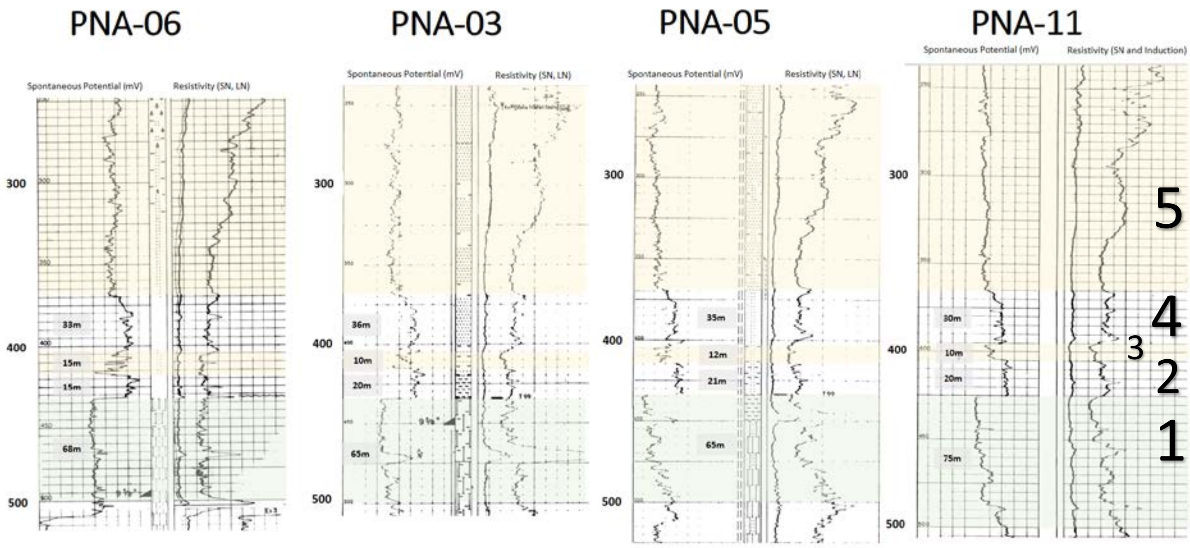

Figure 4. *Correlation of downhole Spontaneous Potential and Resistivity logs in PNA-06, 03, 05, and 11, from right to left in increasing order of proximity to the proposed Delftse Hout monitoring well. Note the remarkable common log stratigraphy between these wells. Green color shade suggest the Chalk of the Ommelanden Fm, the lower, thin yellow shade could be the sandy transition between Eocene and Oligocene clays and the upper yellow the Miocene sandy formations.*

The Gamma Ray record of PNA-14 (Fig. 5), that is in the near vicinity of the previously discussed wells (Fig. 1), shows not very pronounced trends in the same interval. Placing the correlative SP and RES stratigraphy of the nearby wells along the GR log of PNA-14 indicates that the GR changes at the same depths. Interval 2 with increasing SP and RES shows increasing GR. The intermediate interval 3 shows decreasing GR while Interval 4 shows increasing and then decreasing GR. The upper sandy interval 5 has stable low GR values in PNA-14. The strong consistency of log stratigraphy in the nearby PNA wells in terms of well-log patterns, thicknesses and depth of these intervals makes the correlation of these intervals into GR stratigraphy of PNA-14 very likely (Fig. 5).

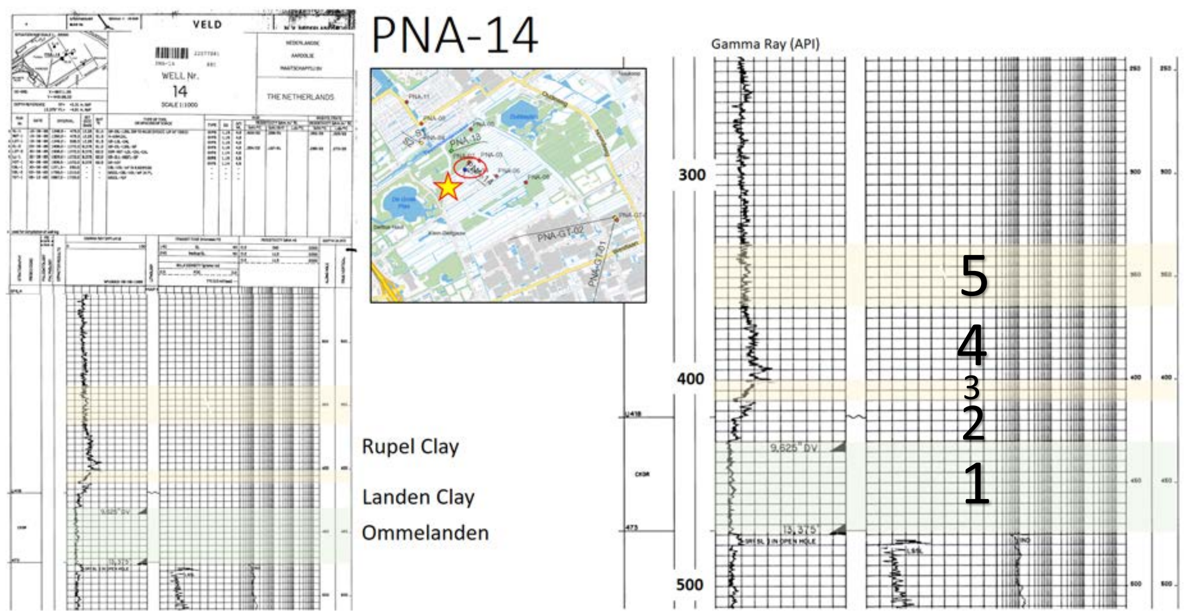

Figure 5. *Gamma Ray log of PNA-14, the well most near-by the proposed drillsite of the monitoring well in Delftse Hout. Color shades and interpretations are imported from the other near-by PNA wells.*

TNO has produced biostratigraphic analysis of cuttings of PNA-GT-01 and PNA-GT-04 (Munsterman, 2020). Both wells are approximately 2 to 3 km southeast of the study area with the other PNA wells just discussed (Fig. 1). Cuttings are sampled during drilling by sieving the drilling mud and thus are a mix of materials from the drilling depth but also from upwards in the borehole, as discussed in the TNO-report (Munsterman, 2020). Cuttings are therefore by definition contaminated samples and results have to be taken with caution. The depth reporting of specific cutting samples should be good to reasonably good. Both wells have cutting samples at 5 meter intervals in PNA-GT-01 and 10 m intervals in PNA-GT-04. Cores are absent for the interval of study, so, clearly, cuttings are the most optimal way to come to more accurate stratigraphy for the Vrijenban syncline infill.

The results are promising as a fairly detailed stratigraphy of Paleogene intervals is resolved in both wells. We refer to the TNO report for the details and discussion of these (Munsterman, 2020). In Fig. 6, results for PNA-GT-01 and in Fig. 7, results for PNA-GT-04 are given along the well data.

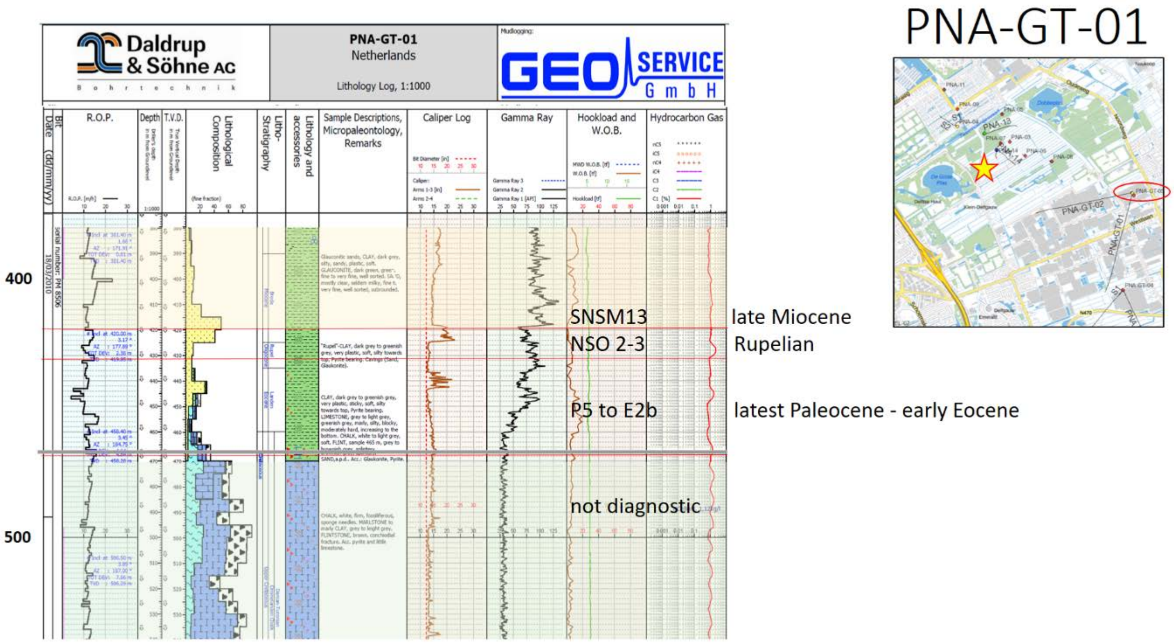

Figure 6. *Stratigraphy in PNA-GT-01 as concluded by TNO from detailed biostratigraphic cutting analysis at 5m resolution. Figure modified after nlog.nl.*

The biostratigraphic results indicate the presence of earliest Eocene sediments in the PNA-GT area. Upwards, lower Oligocene strata are seen followed rapidly by Miocene sediments. In PNA-GT-04, the southernmost well of the two, the Rupelian stratigraphy is split into two intervals, a Rupelian and a Chattian interval. In the northernmost well, PNA-GT-01, there is only Rupelian strata. This indicates that the early Cenozoic sedimentation is not continuous over the area. In the more northern Delftse Hout area, a relative stable stratigraphy seems present following the very straightforward well-log correlation between those wells (Fig. 4 and discussion above). This despite that sedimentation was not continuous. In the more southern area of the PNA-GT wells, the same stratigraphy is not present and both PNA-GT-01 and PNA-GT-04 show different patterns. In this part and between this part and the Delftse Hout area, which is not very far, different pulses of sedimentation and non-deposition or erosion apparently occurred resulting in different detailed stratigraphies.

The locations of stratigraphic changes following biostratigraphic analysis in PNA-GT wells is not always easily visible in the well logs of these wells. The transition from Eocene to Oligocene, from

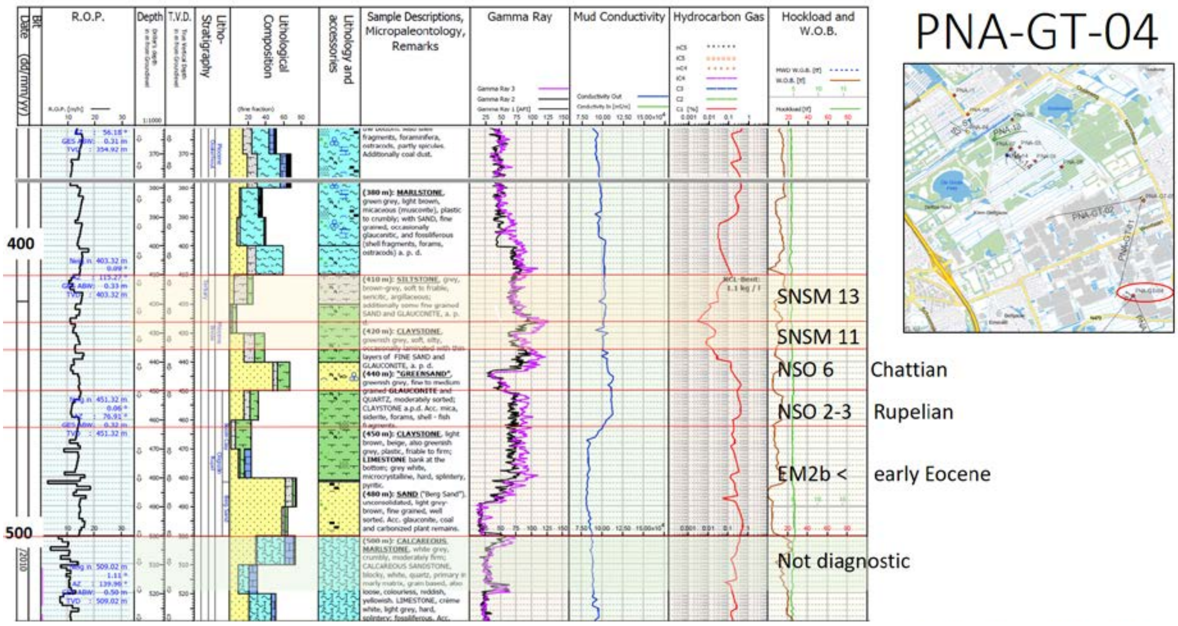

Figure 7. *Well-logs and data from PNA-GT-04 and biostratigraphic results of TNO identifying Eocene, Oligocene and Miocene strata.*

E2b to NSO-2 (Fig. 6), in PNA-GT-01, occurs in an interval of little log response, while below strong caving of the borehole is visible in the Caliper log along with changes in the Gamma Ray. It seems more likely that the start of the Oligocene clays/silts of the Rupel occurs at the top of this caved interval along with increase in GR (see Fig. 9). Although, in PNA-GT-04, the Eocene to Oligocene seems lacking any coarser clastic intercalation, so it can also be that the Eocene includes a more clastic intercalation. The Rupelian to Chattian transition, known from Belgium to be a hiatus, seems more clastic with greensands reported possibly pointing to a condensed interval. That seems absent at PNA-GT-01.

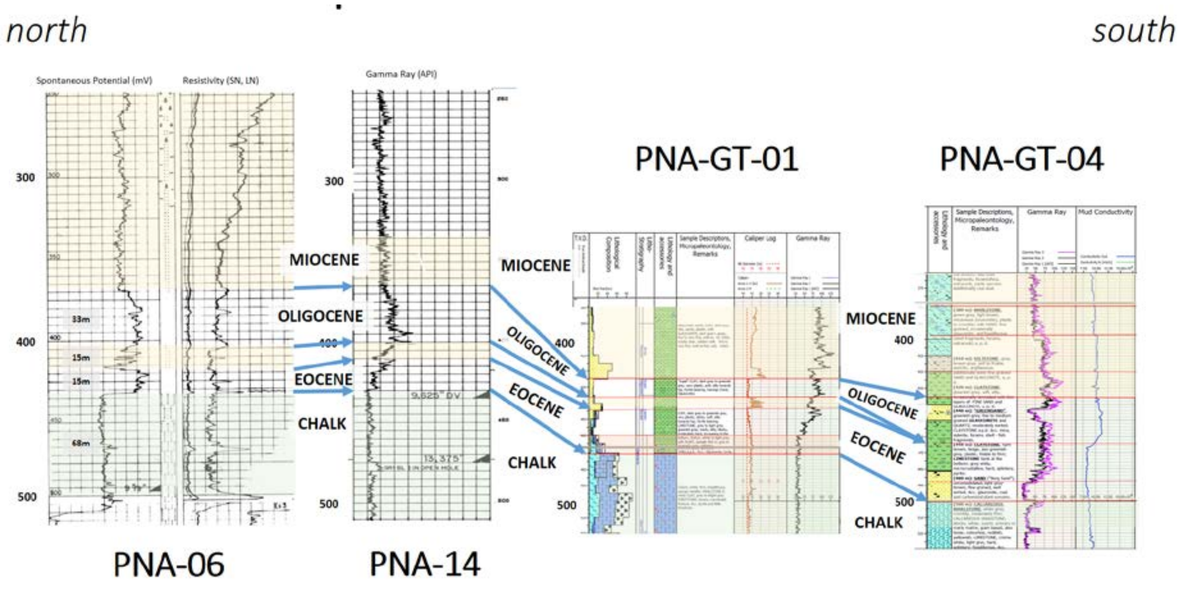

Figure 8. *Proposed correlation between typical older PNA wells with SP and RES logs, the newer PNA-14 well with GR log, and the geothermal PNA-GT wells. Note that we slightly adjusted interpretations of the PNA-GT wells to better fit biostratigraphic findings with log responses fitting a geological model.*

Correlating the Delftse Hout area to the PNA-GT area shows that the early Cenozoic interval occurs lower in the subsurface towards the south (Fig. 8). Also, it seems that the Eocene becomes thicker towards the south and the Oligocene becomes thinner. However, some variability occurs between PNA-GT-01 and PNA-GT-04 with the glauconitic greensand interval and Chattian sediments lacking in PNA-GT-01, and the lowermost Eocene and possibly the topmost Paleocene lacking in PNA-GT-04. Alternatively, the sandy lowermost Eocene of PNA-GT-04 could also relate to this interval.

In Fig. 8, we simplified the stratigraphy to four differentations: Chalk, Eocene, Oligocene and Miocene. This is to not provide too many details that remain relatively uncertain at the moment. For many of the targets of coring these fines in the monitoring well, the specific stratigraphy is not crucial. Note that we slightly adjusted the detailed stratigraphy of PNA-GT wells in Fig. 8, to better fit the log stratigraphy and a possible geologic explanation to the stratigraphy and related environmental evolution through time, while these details do not change the main outcomes of the study.

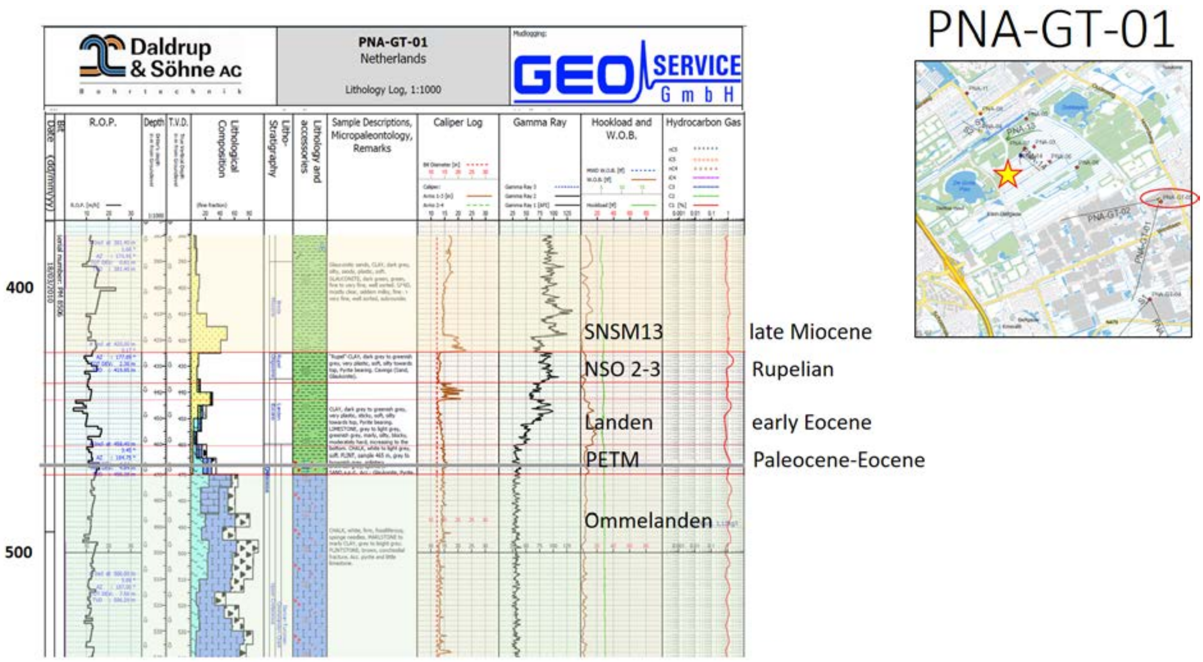

Figure 9. *Discussion figure in which the stratigraphy as recognized by the biostratigraphic data is adjusted to better fit the well logs in combination with a geological explanation, discussed in the text. Only way to resolve is to perform biostratigraphy on core material, currently not available.*

Discussion

The chalk (Ommelanden) is followed stratigraphically rapidly by Eocene or latest Paleocene sediments in the Delftse Hout area. The rapidity of this change may be because (1) we do not recognise sufficiently the exact boundary and the Ommelanden may end lower in the strata, (2) this boundary is an unconformity, or (3) the boundary really was a geologically rapid change.

The Eocene interval may be continuous from the Paleocene-Eocene boundary upwards and halted or eroded at some point to only return to sedimentation conditions by early Oligocene times. This change from Eocene to Oligocene is abrupt in some wells or seems to occur along with a coarser clastic phase, possibly glauconitic, in some other wells. Glauconite is formed in times of sediment starvation at the sea floor.

The Eocene is thicker in the southern Vrijenban syncline. The Oligocene shows a phase of fine clastics and in one well of two phases with a Rupelian and a Chattian phase. With NSO-2 to NSO-3 (Rupelian) sediments, there should be sediments present that relate to what is seen as the deepest and finest clastic sediments in Belgium (Vandenberghe et al. 2014). These are labelled the Terhage and Putte members in Belgium and may be centered around the so-called Double Band. Gamma Ray values (75 API) are similar to what is seen in the subsurface of the Campine area. The deepest relative sea levels may have produced most and finest sedimentation in the Vrijenban syncline due to increased connection of the area with the open ocean. Sediment starvation may have occurred at times of relative low sea level when the Vrijenban syncline may have been a sluggish, poorly connected side arm of the North Sea Basin where little sediment could enter.

The thickness of the Oligocene interval seems to increase northward from the PNA-GT wells. The Gamma Ray is slightly lower (60 API) in PNA-14 for the finest phase of Rupelian stratigraphy, so these sediments could be slightly coarser. The reason for the thickness trends of the Eocene and Oligocene intervals has probably to be found in variable tectonic subsidence trends within the shallow marine Vrijenban syncline at those times causing thicker sediment packages or more sediment eroded or winnowed in one area as opposed to the other.

Caving of the boreholes is visible in the Caliper log of PNA-GT-01 in two phases of Eocene or Eocene or Oligocene age, depending on the stratigraphic interpretation (see discussion above), and upper Rupelian or lowermost package of the Miocene. This is important for retrieval of cores from these interval, with the middle calved interval clearly being part of the targeted stratigraphy and the upper calved interval either being part of it or directly following it. Borehole instability may occur and (intact) core retrieval may be difficult for these more clastic intervals as GR logs shows coinciding lower values.

Details of the stratigraphy will remain enigmatic until cores have been retrieved also because the different wells in the area indicate non-continuous deposition in phases that also have different character and thickness through the area likely related to different tectonic settings at different times. Either erosion of previously deposited materials or non-deposition possibly including subaerial exposure is the cause behind the sedimentary gaps in the Vrijenban area. The intervals between the Eocene and Rupelian and between the Rupelian and Chattian are known to show lower relative sea levels in the North Sea Basin (Vandenberghe et al. 2014). From the middle of the Boom Formation upwards, a shallowing trend occurs in Belgium towards the top of the Rupelian succession. Likely, the shallow character of the Vrijenban syncline area cause that this shallowing resulted in non-deposition earlier than in Belgium. Whether that was related to lack of subsidence and so a lack of accommodation space creation or to a paleohigh to high for sediment arrival remains enigmatic at this stage.

Conclusions

The conclusions of this study are:

- PNA wells in the near proximity of circa 1 km of the proposed monitoring well at Delftse Hout show very similar stratigraphic log patterns at similar depths
- Uncertainty will remain about the detailed stratigraphy and lithology of this package until biostratigraphic analysis on core samples can be done
- A thickness of between 60 and 65 meters of Eocene and Oligocene clastic sediments is expected with reasonable certainty at Delftse Hout
- Two clay packages are found totalling between 45 and 55 meters that are expected to be the clay-rich equivalents of both the Ieper and Rupel clay members.
- Earliest Eocene sediments are less expected in the Delftse Hout area than in PNA-GT area due to thinning of Eocene stratigraphy northward and more rapid transition above the Ommelanden formation
- Oligocene successions seem thickening northward of the PNA-GT wells towards Delftse Hout
- A 10-15m interval of coarser clastic sediments, possibly glauconitic greensands, is expected in the Delftse Hout area between the Eocene and Oligocene sediments, but detailed stratigraphy may resolve to be different
- The Rupelian shows similar or slightly lower Gamma Ray excursions as in Belgium and are expected to be equivalents of the deepest facies in the so-called Terhagen and Putte Members
- Borehole caving is observed in the Eocene to Oligocene package, likely in the coarser-grained glauconitic intermediate interval between Eocene and Oligocene, and in either the top of the Rupelian or lowermost interval of the Miocene
- Borehole caving in these coarser grained intervals likely indicates the unconsolidated nature of these sediments, while the clayey intervals show borehole diameters to remain intact.

Acknowledgements

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References

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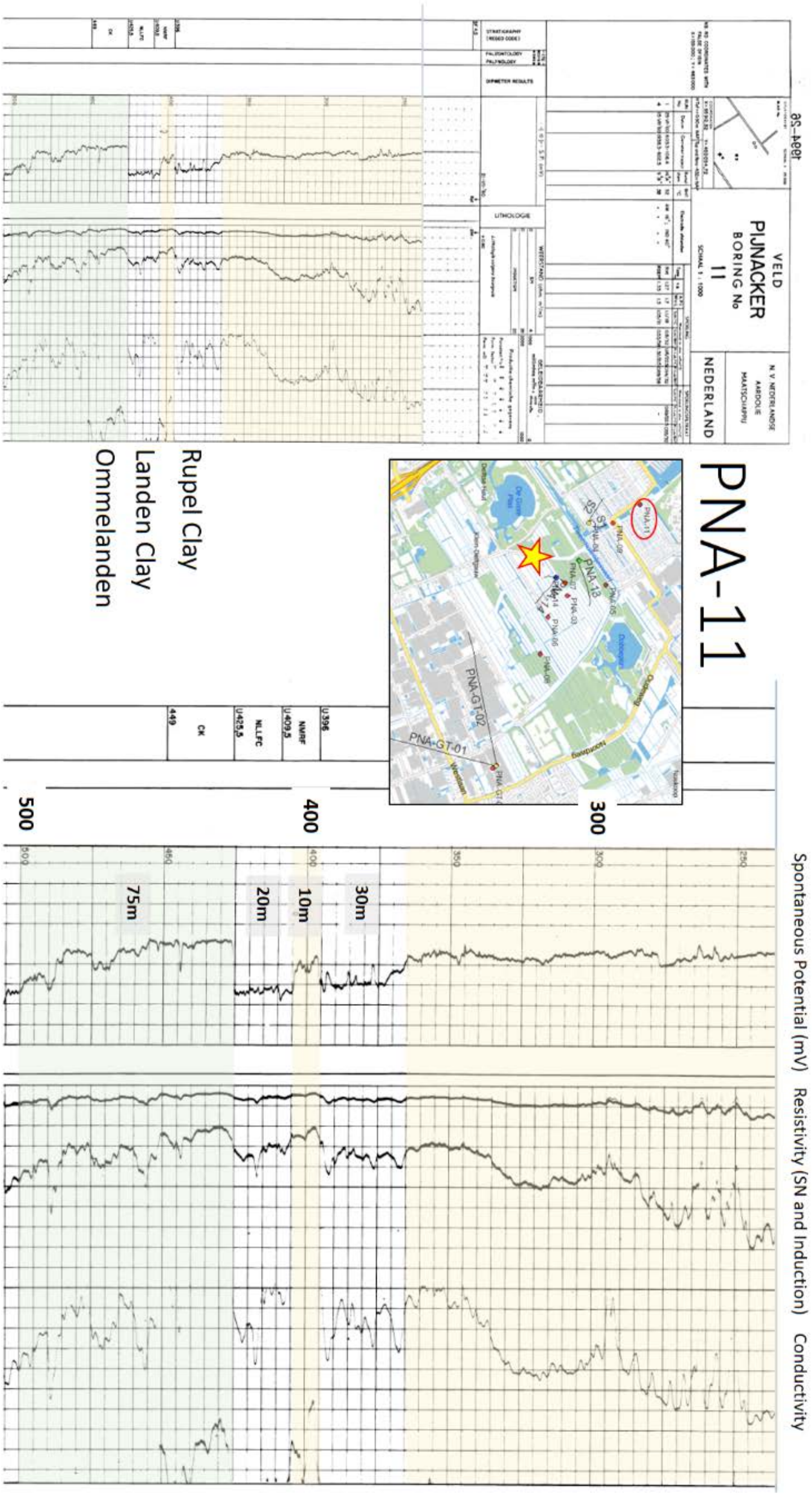
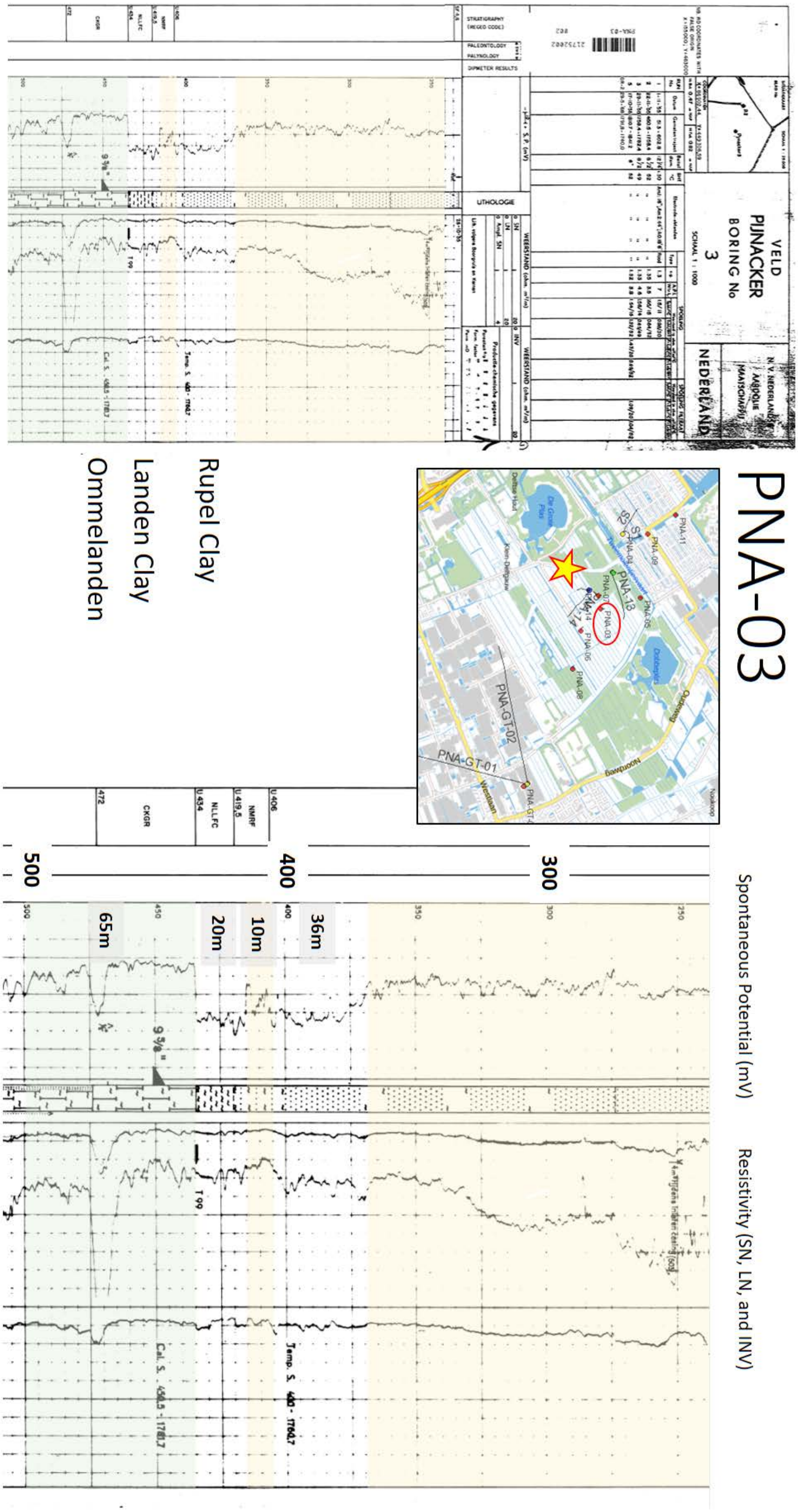
TNO (2011) Tectono-stratigraphic charts of the Netherlands continental shelf. TNO, https://www.nlog.nl/sites/default/files/tectonostratigraphic%20charts%20-%20offshore%20the%20netherlands.pdf

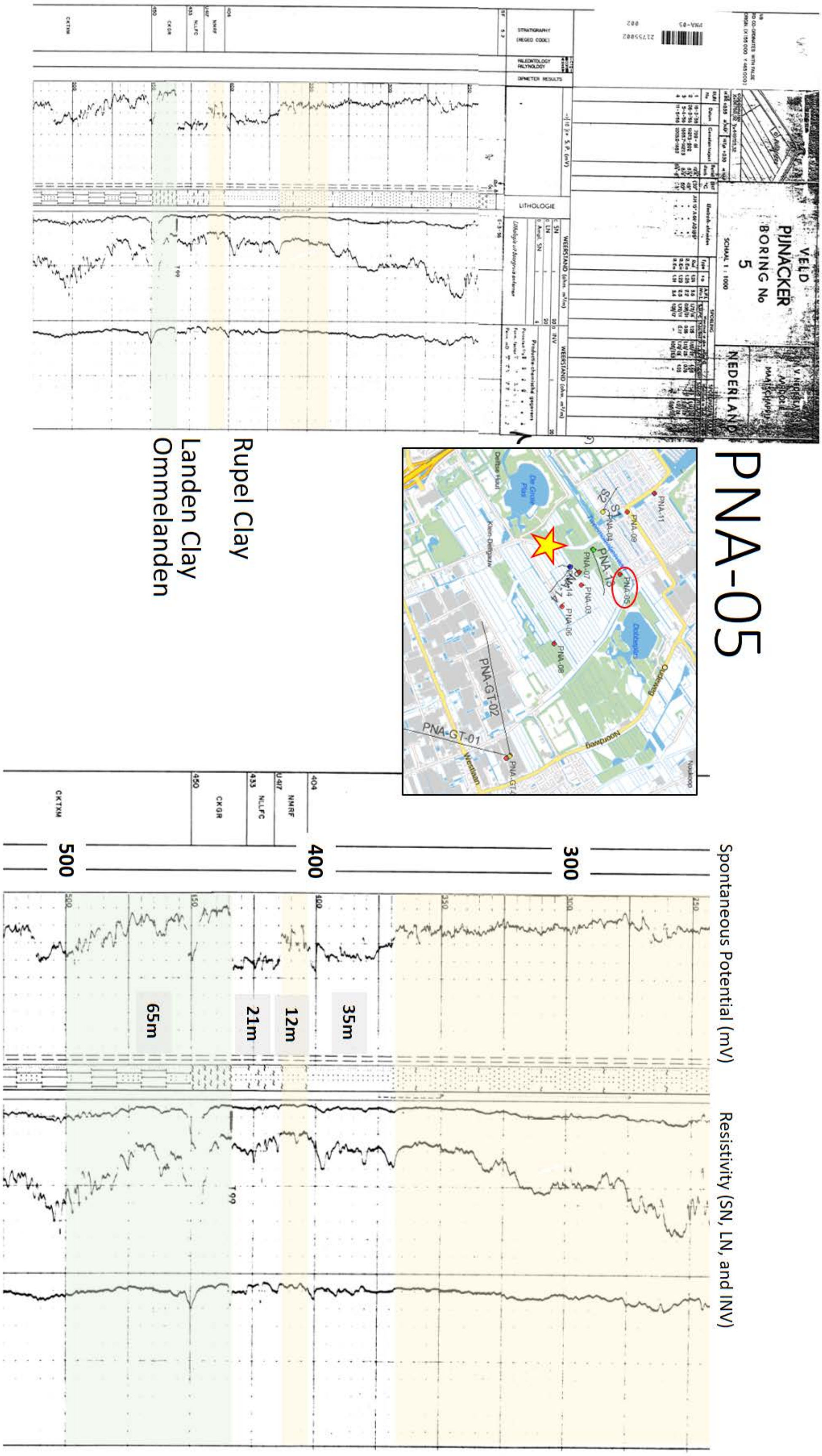
Vandenberghe, N, M. De Craen, and L. Wouters, 2014. The Boom Clay Geology – From sedimentation to present-day occurrence – A review. Memoirs of the Geological Survey of Belgium 60, 76p.

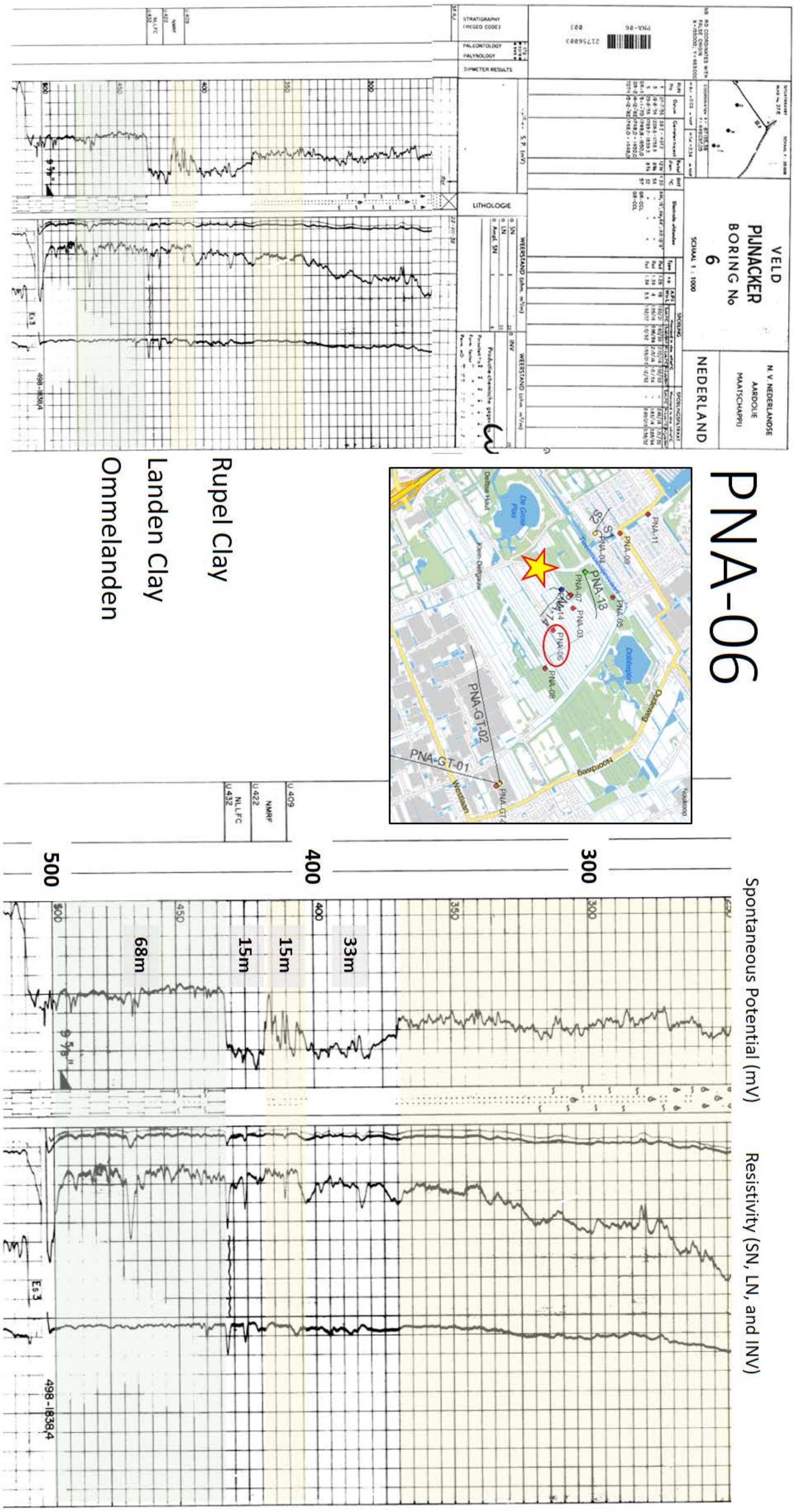
Appendix A

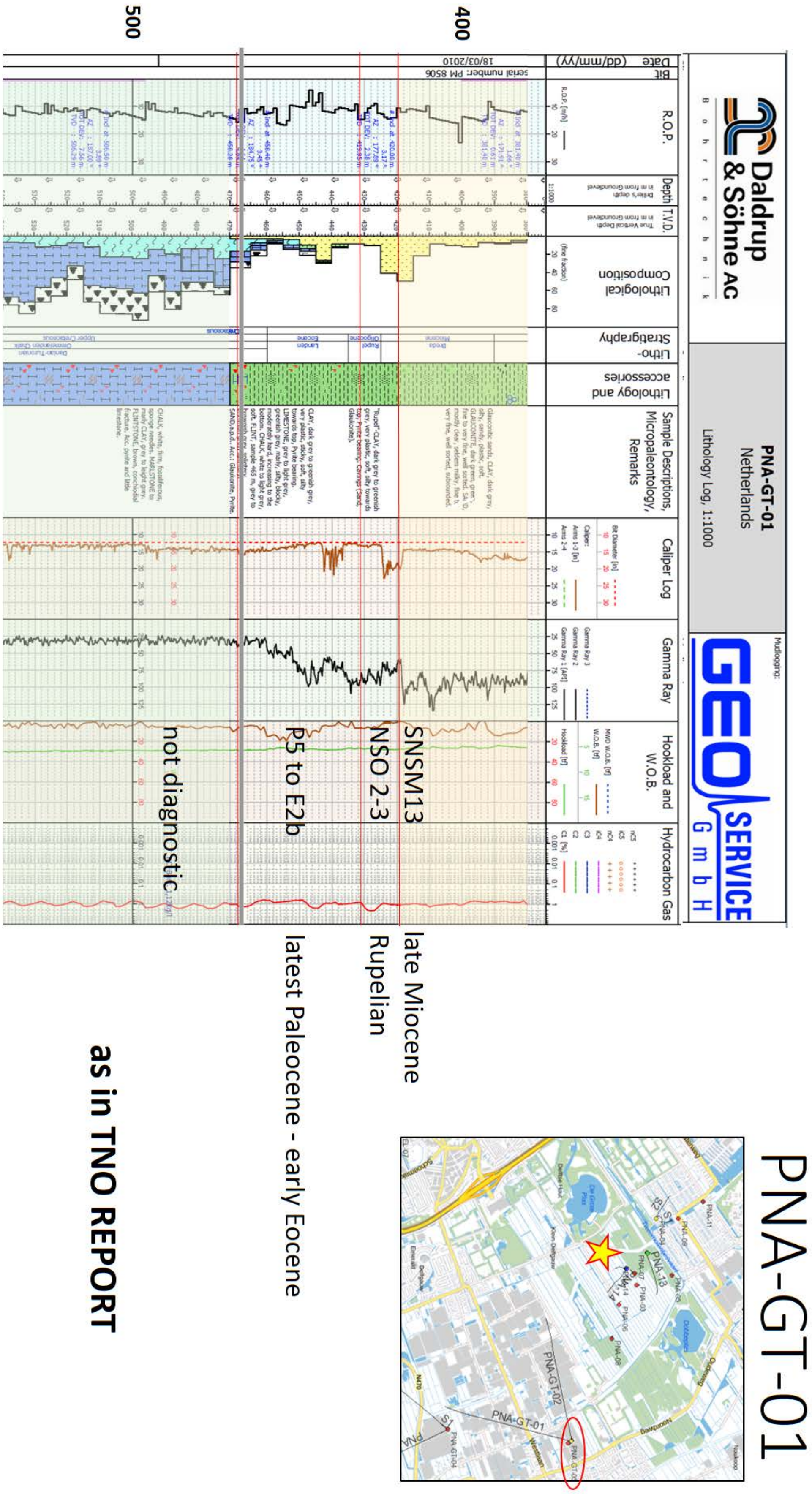
Detailed log information from nlog.nl for different PNA-wells and modified with stratigraphic interpretations as performed in this study.

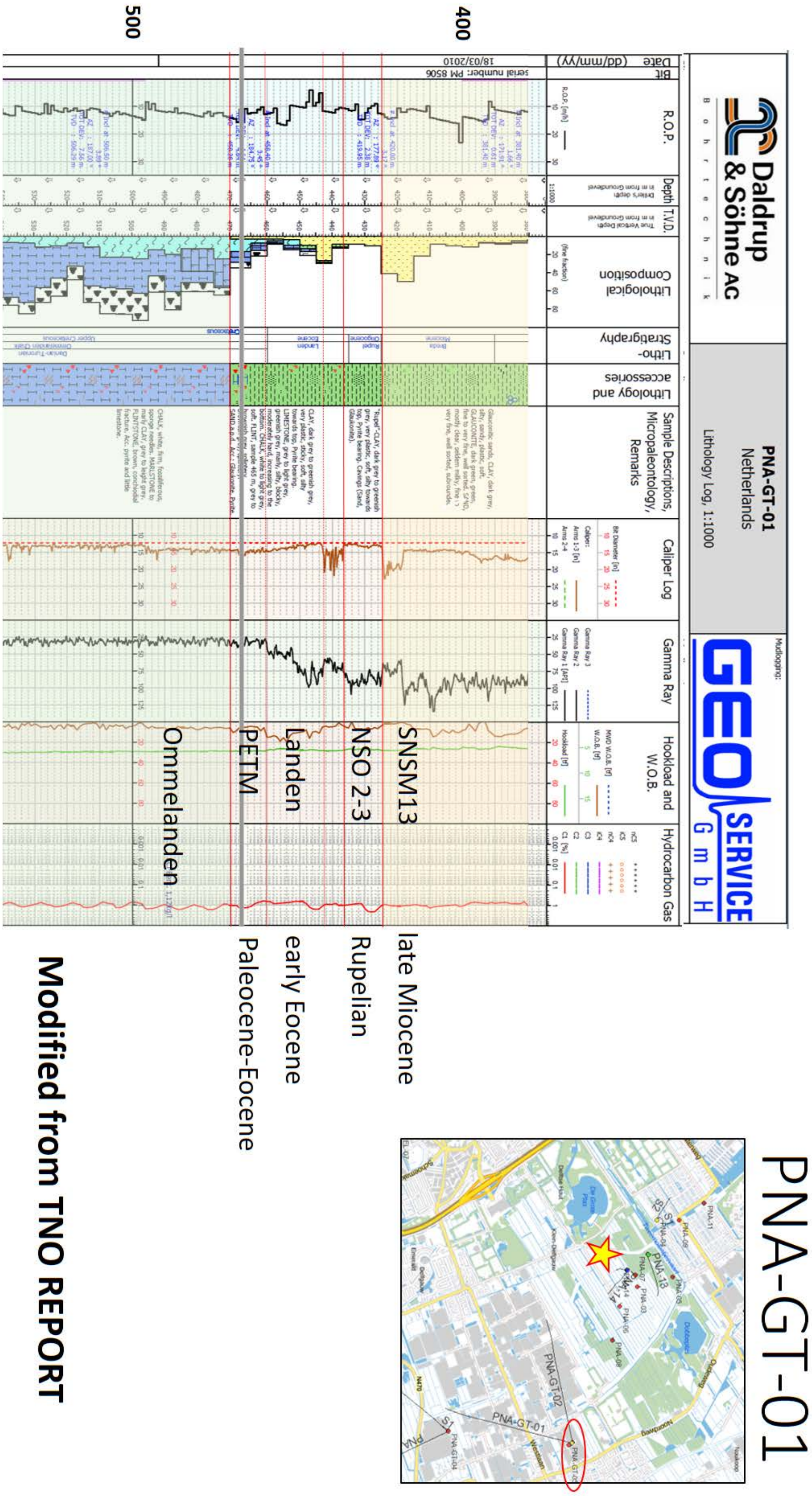

PNA-11
Rupel Clay
Landen Clay
Ommelanden
75m
20m
10m
30m
500
400
300
Spontaneous Potential (mV)
Resistivity (SN and Induction)
Conductivity
VELD
PIJNACKER
BORING No
11
NEDERLAND
449
U425,5
U409,5
U396
CK
NLLFC
NMRF

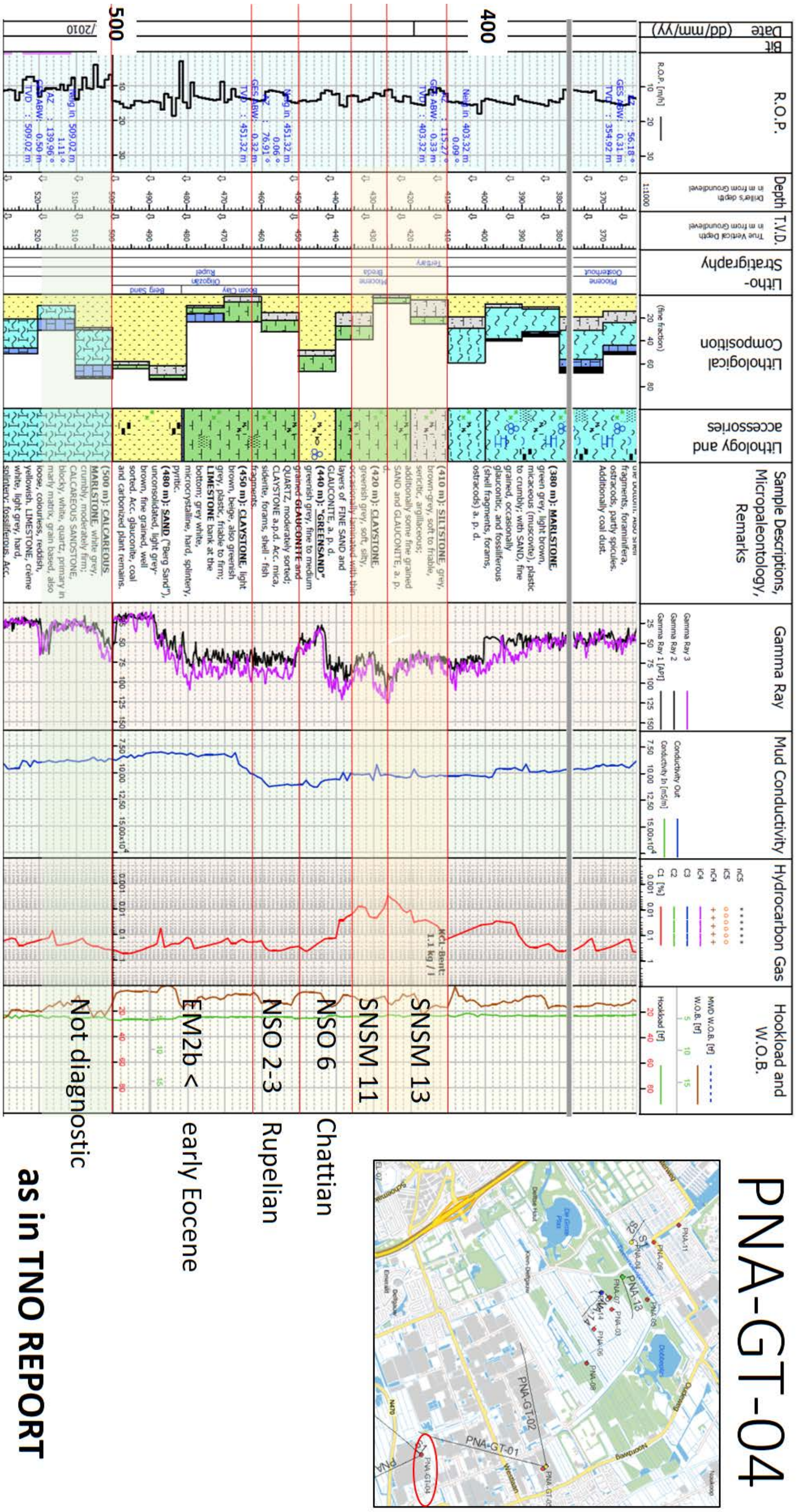

PNA-03
VELD
PIJNACKER
BORING No
3
NEDERLAND
Rupel Clay
Landen Clay
Ommelanden
Spontaneous Potential (mV)
Resistivity (SN, LN, and INV)
500
400
300
65m
20m
10m
36m
U406
NMRF
U419,5
NLLFC
U434
CKGR
472
PNA-GT-01
PNA-GT-02

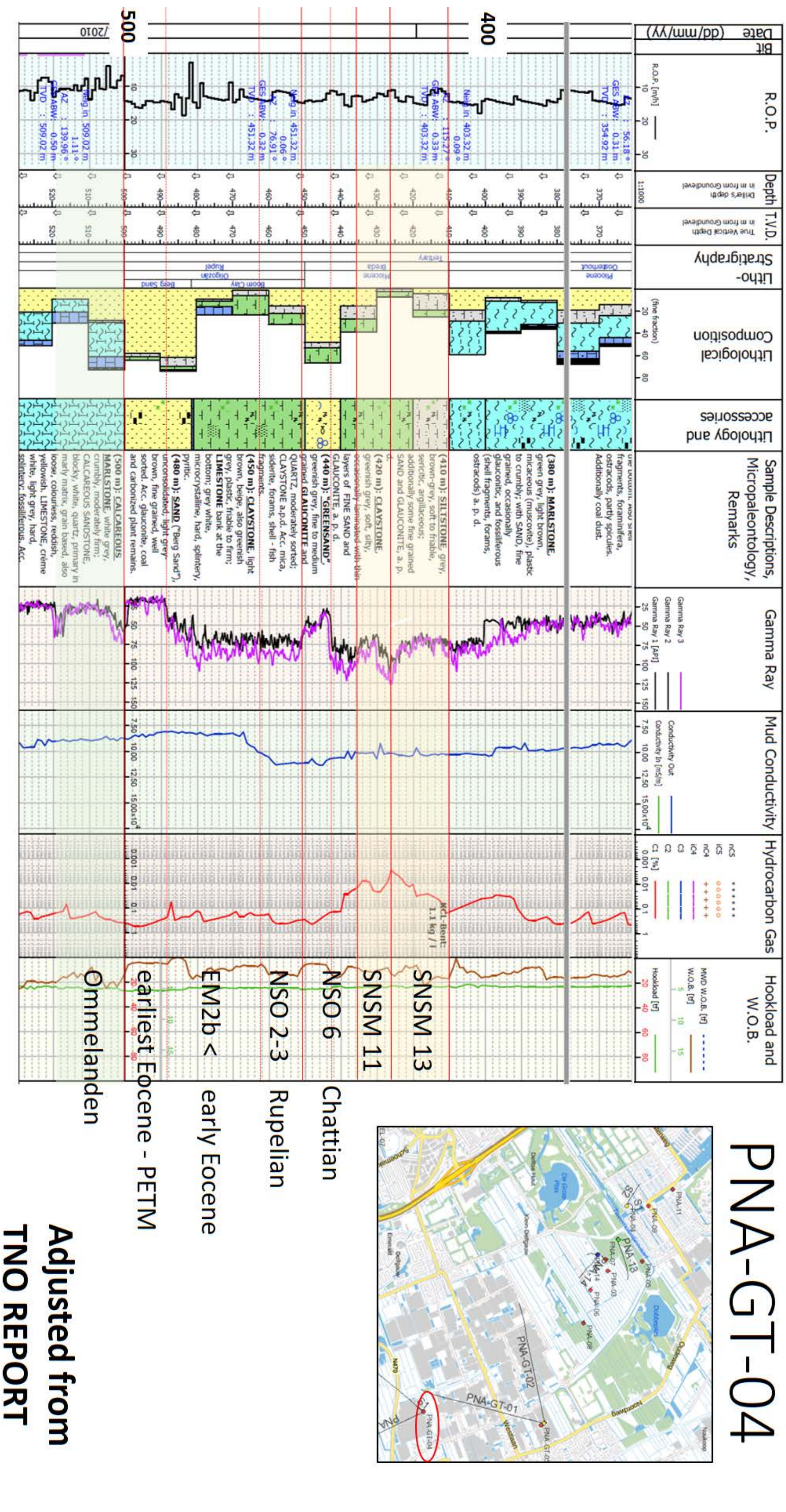

PNA-05
Rupel Clay
Landen Clay
Ommelanden
Spontaneous Potential (mV)
Resistivity (SN, LN, and INV)
500
400
300
65m
21m
12m
35m
CKTXM
CKGR
NLLFC
NMRF
PNA-GT-01
PNA-GT-02
PNA-10


PNA-06
Rupel Clay
Landen Clay
Ommelanden
VELD
PIJNACKER
BORING No
6
NEDERLAND
N. V. NEDERLANDSE AARDOLIE MAATSCHAPPIJ
LITHOLOGIE
68m
15m
15m
33m
500
400
300
Spontaneous Potential (mV)
Resistivity (SN, LN, and INV)
PNA-GT-01
PNA-GT-02


400
500
PNA-GT-01
Netherlands
Lithology Log, 1:1000
SNSM13
NSO 2-3
P5 to E2b
not diagnostic
late Miocene
Rupelian
latest Paleocene - early Eocene
as in TNO REPORT
PNA-GT-01


400
500
PNA-GT-01
Netherlands
Lithology Log, 1:1000
SNSM13
NSO 2-3
Landen
PETM
Ommelanden
late Miocene
Rupelian
early Eocene
Paleocene-Eocene
Modified from TNO REPORT
PNA-GT-01


PNA-GT-04
SNSM 13
SNSM 11
NSO 6
Chattian
NSO 2-3
Rupelian
EM2b <
early Eocene
Not diagnostic
as in TNO REPORT
400
500
R.O.P.
Gamma Ray
Mud Conductivity
Hydrocarbon Gas
Hookload and W.O.B.
Lithological Composition
Lithology and accessories
Litho-Stratigraphy
Sample Descriptions, Micropaleontology, Remarks


PNA-GT-04
SNSM 13
SNSM 11
NSO 6
Chattian
NSO 2-3
Rupelian
EM2b <
early Eocene
earliest Eocene - PETM
Ommelanden
Adjusted from
TNO REPORT