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Characterisation of a shallow geothermal resource in The Netherlands: the Brussels Sand Mb.

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ABSTRACT

The Brussels Sand Member (BSM) is a relatively shallow aquifer at a depth range of around 200 to 1200 m and is present over a large part of the Dutch onshore territory. It is considered a potential target for low-temperature (< 35°C) geothermal projects and could be a heat source for urban heating networks. Like many shallow aquifers that were never targets for petroleum production, characterization is poor despite the roughly 700 wells that penetrate the aquifer and the wide availability of seismic data. Current maps are based on inconsistent interpretations in wells only. As a step towards the estimation of the geothermal potential of this aquifer, the BSM has been characterized as part of the WarmingUP project: presence, depth and reservoir properties have been estimated at the national level by interpreting and analysing existing data.

1. INTRODUCTION

In the Climate Agreement in The Netherlands it has been agreed that 1.5M houses need to be heated sustainably in 2030. Heating of these houses is currently done using natural gas. Part of these houses will be heated using collective heat networks and geothermal energy is an important source of heat for such networks. Within the WarmingUp project Theme 4, the goal is to accelerate the development and use of geothermal sources for use in urban heat networks. One of the main goals in the project is improved characterisation of the relatively poorly studied shallow subsurface between 500 and 1000 m depth to facilitate geothermal development of these formations. Of the shallow formations, the Brussels Sand Member (BSM) is expected to be one of the most prolific reservoirs and is present across a large part of The Netherlands and therefore a prime focus in the project. Estimates of the geothermal potential of the BSM are already made available via ThermoGIS.nl (Vrijlandt et al., 2019, 2020). However, these estimates carry considerable uncertainty.

The Brussels Sand Member is present at a depth range of around 200 to 1200 m. It consists of a 150-200 m thick cleaning-up/coarsening up sequence which is interpreted as a marine shelf sand that gradually becomes shallower and cleaner toward the top (Van Adrichem Boogaert and Kouwe, 1997). The Brussels Sand is for the most part unconsolidated, but usually contains a number of thin calcite-cemented or sometimes silica-cemented streaks, especially near the top. To the south of The Netherlands, in Belgium, outcrops of the Brussels Sand Mb are found and could in principle serve as an analogue for the Dutch subsurface. However, these time-equivalent deposits were deposited in a different sedimentary environment than in the Dutch subsurface (mostly estuarine and tidal marine embayment (Houthuys, 2011)) and permeability in these outcrops is considerably higher, up to tens of Darcies (Possemiers et al., 2012), than what is expected in the Dutch subsurface. For example, at the only geothermal doublet producing from the Brussels Sand Mb at Zevenbergen a horizontal permeability of 750 mD was estimated (Buik and Bakema, 2019).

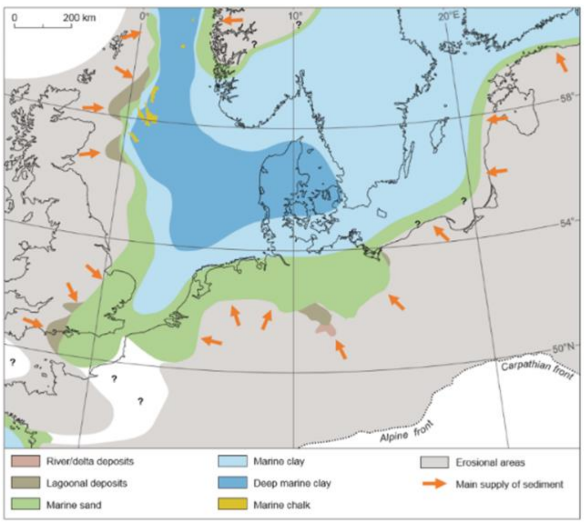

Figure 1. Paleogeographic reconstructions and distribution of predominant sediment types in northwestern Europe for the Middle Eocene (early Lutetian, deposition of the BSM in green) situation. Adapted from Gibbard and Lewin (2016).

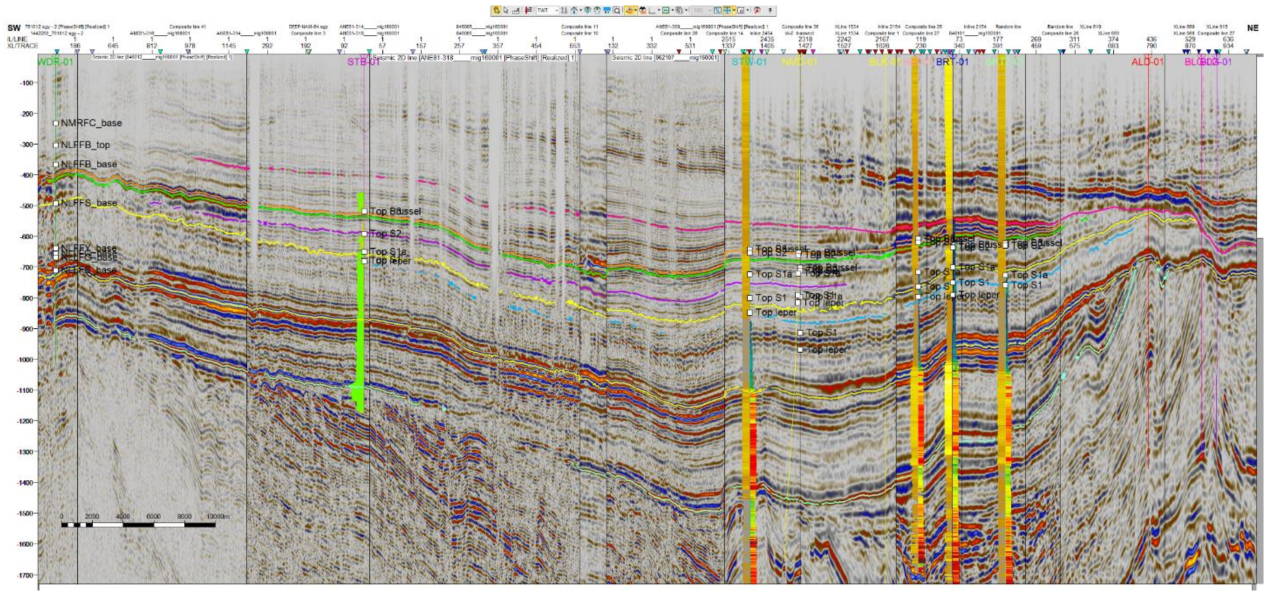

Figure 2. Example of a seismic line south of the city of Rotterdam that is composed of several 2D and 3D surveys of various vintages. Despite the differences in phase, amplitude, and frequency most seismic markers of the Brussels Sand Member could be picked and tied to the wells. Note the truncated top of the BSM toward the North East (near well ALD-01).

In terms of paleogeography, these sandstones are thought to predominantly originate from a south-easterly source, an assumption supported by the development of more proximal facies in Belgium and the southeast of the UK (Figure 1).

Like many shallow aquifers that were never targets for petroleum production, reservoir characterization is poor despite the roughly 700 wells that penetrate the aquifer and the wide availability of seismic data. Current depth and thickness maps are based on inconsistent interpretations in wells only. Reservoir property estimation is based on only a few data points. As a step towards the improved estimation of the geothermal potential of this aquifer, the BSM has been characterized: presence, depth and reservoir properties have been estimated at the national level by interpreting and analysing existing data. First the improvement of the presence, depth and thickness using seismic interpretation is discussed. Next the improved reservoir characterization using petrophysical analysis is presented.

2. SEISMIC INTERPRETATION

The wide availability of seismic data made it possible to map the BSM across the entire Netherlands (de Haan et al., 2020). The BSM is present in a large part of The Netherlands, but is absent in a 60-100 km wide, WNW-ESE trending strip in the middle part of the country (the inverted West- and Central Netherlands Basins). In this area the BSM was eroded during the Pyrenean phase of the Alpine orogeny (De Jager, 2007).

The consistency of the current top and base of the BSM in wells was checked and the top and base of this interval were interpreted ("picked") and correlated on seismic data (Figure 2). Well log correlation shows that the BSM in the Netherlands consists of three sequences which will be referred to as S1, S2 and S3 from bottom to top (Figure 3). Only the top of the upper sequence S3 was picked on well logs in a consistent way in the past. The base of the BSM was inconsistently picked: locally the base of the lowermost sequence S1 was picked and in other regions the base of the middle cycle S2. For this study, the BSM is now consistently interpreted, at least for wells with well logs of sufficient quality. For the southern study area, the base of the lowermost sequence was taken as the base of the BSM. For the northern study area, the base of the middle sequence was taken as the base of the BSM, because the base of the lowermost sequence is not sufficiently visible on seismic data in this area. A net thickness for the lowermost sequence has been calculated in order to be able to compare thicknesses in the two study areas. The use of seismic data made it possible to better pinpoint the boundary of the area in which the BSM is present (see Figure 2).

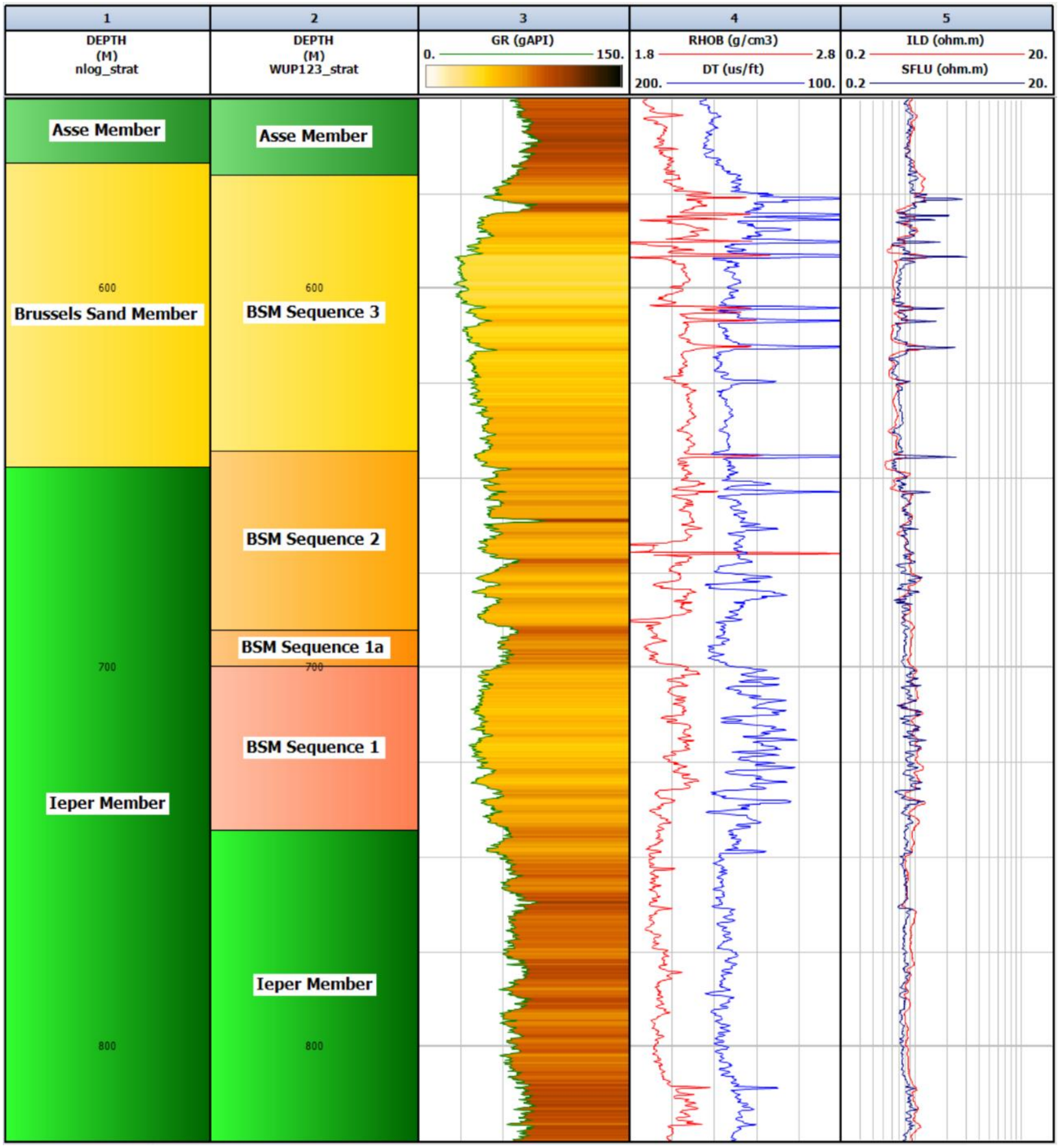

Figure 3. Typical well-log section through the BSM in well BRT-01, near Rotterdam. The leftmost track shows the BSM according to the lithostratigraphic interpretation provided by the Dinoloket.nl website, while the adjacent track shows the new interpretation with a subdivision into Sequence 1, 1a, 2, and 3.

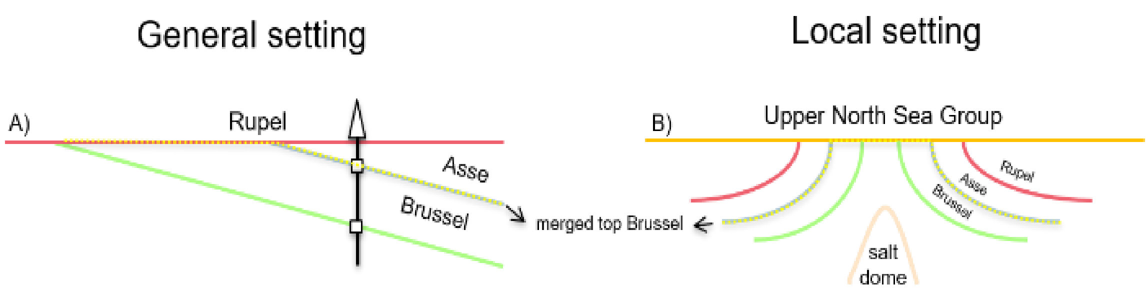

Figure 4: Two geological situations for generation of a merged top Brussel surface (yellow dashed line).

On the edges of the West- and Central Netherlands Basins the BSM is partly eroded. In these areas the BSM is not covered by the Asse Mb, but by the Rupel Fm (Figure 4 left). Locally in the northern study area, especially above salt domes, the BSM may be directly covered by the deposits if the Upper North Sea group (Figure 4 right). In these areas, the overlying units were interpreted to arrive at a complete top BSM surface. The results are presented in Figure 5 (top depth) and Figure 6 (thickness). In the southern area, the depth decreases from south to north, except in the northern edge near the West Netherlands Basin. In the northern part, the depth decreases from west to east. On the southern edge of the northern part, the thickness is very limited due to erosion.

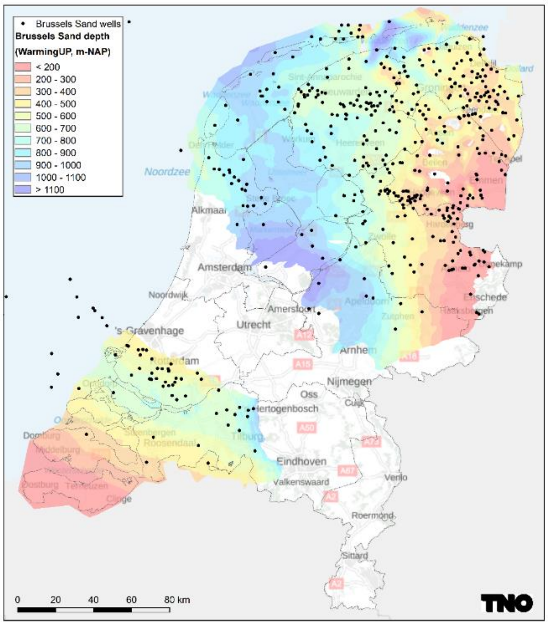

Figure 5: Depth of top of the Brussels Sand Mb.

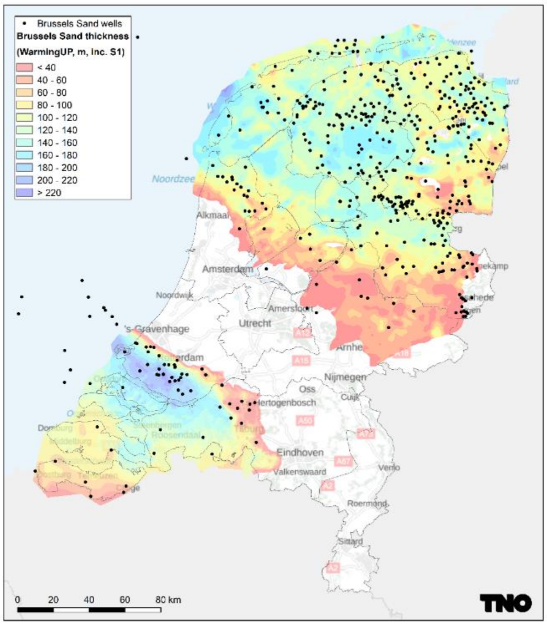

Figure 6: Total thickness of the Brussels Sand Mb.

3. PETROPHYSICAL CHARACTERISATION

Although roughly 700 wells have been drilled through the BSM, many wells have few or poor quality logs and only a few cores are available, because the BSM was rarely the target formation. Therefore, little is known about the reservoir properties of the Brussels Sand. Found at depths between 200 and 1200 m, it is too shallow to be of interest to the oil and gas companies, and too deep for hydrological studies. As a consequence, hard data on porosity, permeability and net reservoir thickness are hardly available. A handful of core measurements and a few pumping tests from which gross permeability can be derived is basically all there is in terms of hard data. This means that the evaluation of the reservoir properties of the Brussels Sand must be derived mainly from well logs. Fortunately, most wells do have well logs that cover the Brussels Sand.

Well logs have been acquired in The Netherlands from the 1940's onward. Drilling equipment, drilling techniques, and logging tools have evolved over time. That means there is a wide variety in the number of logs acquired in a well, the type of logs, as well as the drilling mud used. Three different log evaluation techniques have been used, depending on well log suite: 1) standard shaly sand evaluation with gamma-ray, neutron and density, and resistivity logs; 2) shaly sand evaluation with gamma-ray, sonic, and resistivity logs, with sonic compaction factor estimate as much as possible verified with resistivity-derived effective porosity; 3) resistivity-based porosity, which is actually a reversed Archie equation with shale correction.

For 32 wells distributed over the country, a petrophysical analysis was done to determine clay volume, effective porosity, net thickness and permeability (Geel and Foeken, 2021). In addition, the average thickness and distance between the calcite cemented streaks was determined. These streaks are known from Belgian sand quarries, where they are collected as a by-product and sold as natural building stone ("Ledesteen" and "Gobertanger steen" Gullentops and Broothaers, 1996)). Fobe (1988) described the calcite-cemented streaks in West Flanders in detail. He came to the conclusion that the calcite in these streaks originates from the dissolution of aragonite and magnesian calcite in fresh water. The dissolved carbonate precipitates then again around nummulites, tube worms and shells, which act as large crystallisation nuclei, thus forming cemented layers. The high concentration of fossils in these beds can be explained by the sorting activity of storms, washing away the finer fraction and thereby concentrating the fossils (Fobe, 1988). Although volumetrically not very important (they are usually between 0.2 and 2 m thick, and the vertical spacing is some 5 m) they may be of importance for flow into and out of wells, especially if the wells are highly deviated or horizontal.

Most challenging was the estimation of the permeability. The main sources of information are cores with poro-perm measurements for three wells

(WYK-12, DON-01 and WAP-01), well tests from one geothermal well (ZVB-GT-01) and three shallow wells and NMR (nuclear magnetic resonance) measurements in KKP-GT-01. Unfortunately, the NMR measurements proved inconclusive for the unconsolidated sands of the Brussels Sand Mb. Therefore, the poro-perm relation was based on the core measurements which were converted to effective porosity and corrected for Klinkenberg effect, dry clay swelling and overburden stress (Juhasz, 1986) (Figure 7).

To determine the net sand values, the following cut-off limits were used: clay volume (VCL) < 50%, effective porosity > 20%, permeability > 1 mD, and no calcite-cemented streaks .

Maps have been produced that show the regional distribution of the reservoir properties of the Brussels Sand in The Netherlands. Properties mapped include net thickness (Figure 9), net gross ratio, effective porosity (Figure 10), permeability (Figure 8), transmissibility (Figure 11), and average interval thickness between thin tight calcite-cemented streaks. The maps have been created by using a similar method as described for ThermoGIS (Pluymaekers et al., 2012, Vrijlandt et al 2019, 2020). In this case, the porosity-depth trend was used as a basis, after which the residual between the porosity estimated from the porosity-depth trend and the petrophysical evaluation were Kriged (Geel and Foeken, 2021). This porosity trend map is then converted to a permeability trend map using the porosity-permeability relationship. The residuals between the permeability values obtained from the petrophysical evaluation and trend permeability are then Kriged and added to the trend to better reproduce the petrophysical evaluation results. Note that, because a variogram with a non-zero nugget was used, the exact permeability values are not necessarily reproduced. A non-zero nugget is often used in geostatistical practice when uncertainty exists regarding the measured. Net sand thickness and net-to-gross ratio were Kriged directly.

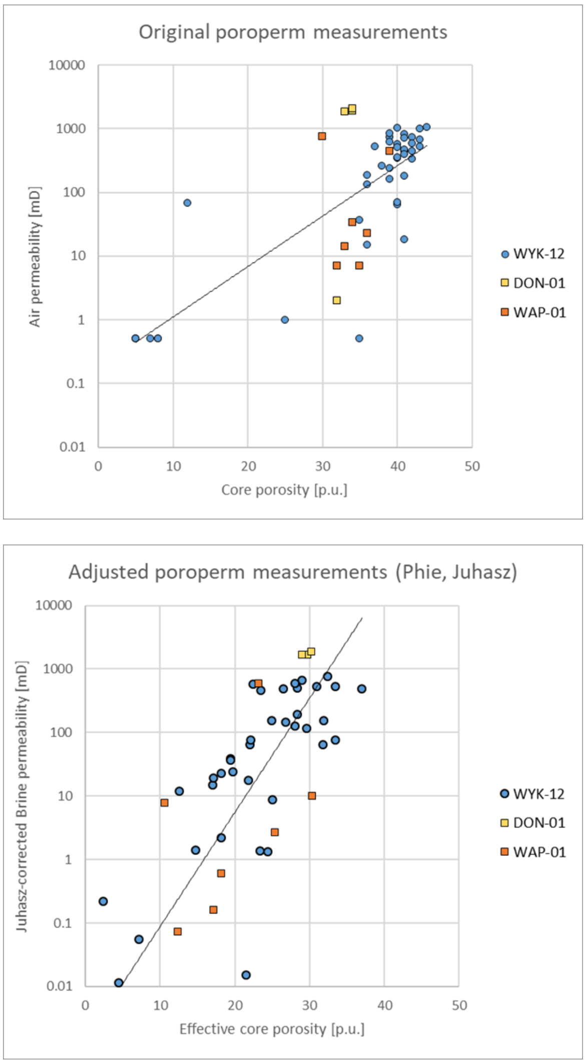

Figure 7: Core plug data from WYK-12, WAP-01, and DON-01. Top: original core plug data. Bottom: corrected core plug data; core porosities were converted to clay-free (effective) porosity, and core permeability corrected to brine permeability following Juhasz' (1986) corrections.

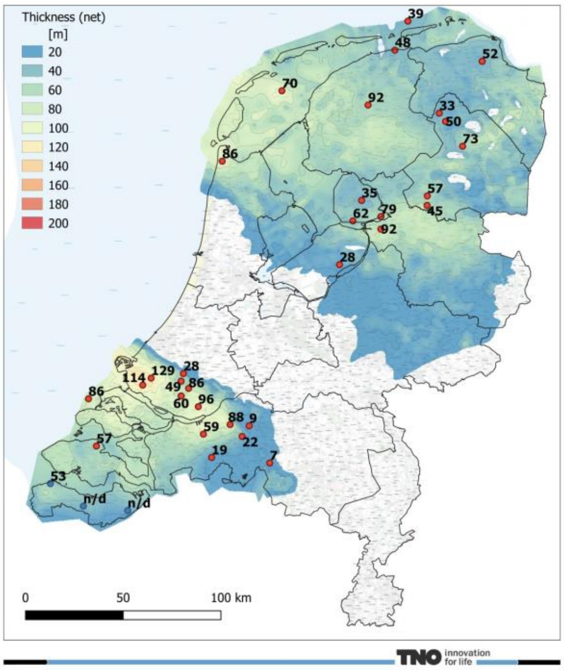

Figure 11: Net thickness of the Brussels Sand Mb.

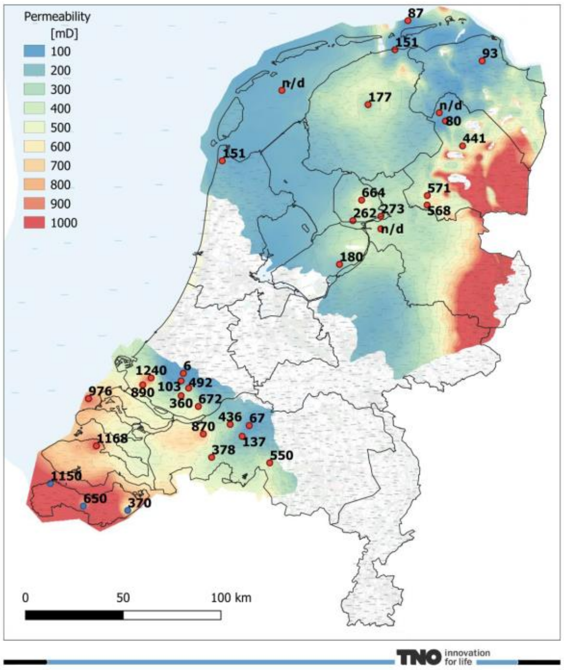

Figure 10: Permeability of the Brussels Sand Mb.

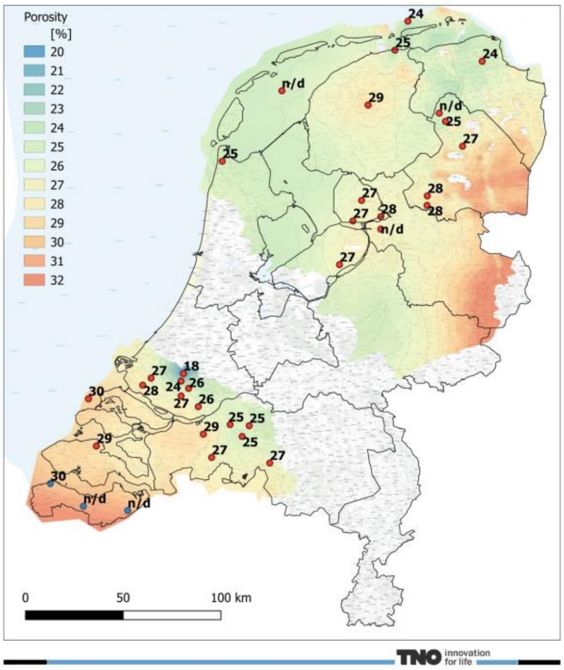

Figure 9: Effective porosity of the Brussels Sand Mb.

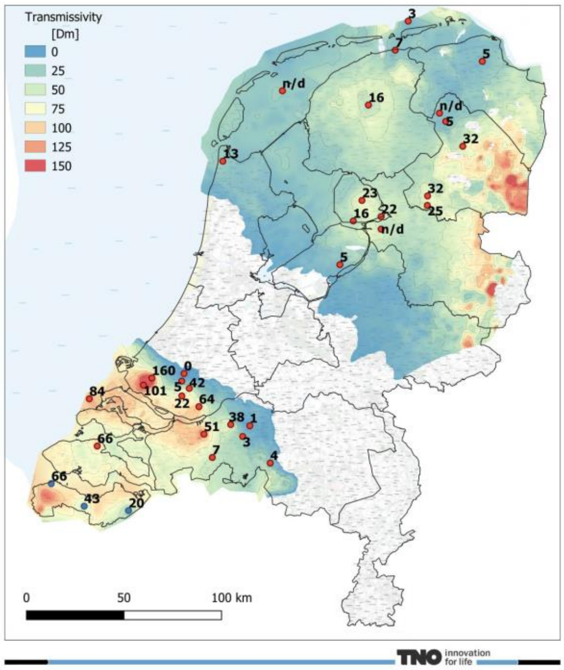

Figure 8: Transmissivity (net height x permeability) of the Brussels Sand Mb.

The best properties can be found in an area south of the city of Rotterdam to Zeeuws-Vlaanderen. Average permeabilities are between 500 and 1200 mD. North of the zone where the Brussels Sand is not present (the inverted West- and Central Netherlands Basins) permeabilities are in the 100-200 mD range, with some areas in the 500 mD range. The uppermost unit of the BSM (S3) is the only unit which has good reservoir properties. The lower units S2 and S1 have little or no reservoir potential, with S1 generally a bit better than S2. However, S3 does have the highest number of calcite-cemented streaks that divide the reservoir unit into compartments of a few meters thick. They occur at relatively regular vertical distances of about 5 m and are most abundant at the southern edge of the country (Geel and Foeken, 2021).

In the far north, the Brussels Sand Mb transitions into the Brussels Marl. This can most clearly be seen in the transmissivity map.

4. CONCLUSIONS

A comparison with the previous (well-based) maps of the BSM learns that improvements are mainly seen in the thickness map and the depth map of the base of the BSM. Both show on the one hand a smoother thickness distribution than the earlier maps that suffered from inconsistencies in well picks that lead to bull's-eyes, and on the other hand an increased spatial resolution caused by the abundant use of seismic data. The previous inconsistent interpretation of the base of the BSM, either at base S1 or base S2, was the main cause of the bull's eyes. Another important improvement is the improved definition of the boundary polygon enclosing the distribution of the BSM. There is no noticeable change in the average depth of the Brussel Sand. An overall increase of the average thickness is attributed to the consistent incorporation of the S1 sequence sands. This especially holds for the northern area where the base of the BSM used to be placed at the base of the S2 sands.

For the determination of reservoir properties of the Brussels Sand a total of 32 wells, spread all over The Netherlands, have been evaluated. These properties include clay volume, effective porosity, permeability, presence of calcite-cemented streaks, net sand, and net to gross ratio. The cut-off limits for the definition of net sand were chosen as follows: clay volume less than 50%, effective porosity more than 20%, permeability more than 1 mD, and no low-perm streaks.

The upper part of the Brussels Sand, S3, is the only unit which has good reservoir properties. The lower units S2 and S1 have little or no reservoir potential. The Brussels sand, especially the upper unit S3, contains thin, tight, calcite-cemented streaks (20-200 cm) that divide the reservoir unit into compartments of a few meters thick. This may have consequences for how the Brussels Sand is drilled and completed, particularly when horizontal wells are used.

In general, reservoir properties of the Brussels Sand Member deteriorate from South to North through The Netherlands. However, there are a few exceptions to this trend. The best properties can be found in the area between Rotterdam and Zeeuws-Vlaanderen, with average permeabilities between 500 and 1200 mD. Toward the Belgian border however, the BSM has undergone more diagenesis, resulting in many tight streaks and an overall lower permeability. Northwest of the line Alkmaar-Arnhem permeabilities are in the 100-200 mD range, with some areas in the 500 mD range. Within the Northern area, the southmost part has the best permeabilities. Also around salt diapirs permeabilities may locally be higher. In the far North, towards the present-day coastline, the BSM becomes too fine-grained to be permeable.

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