Blanket diesel dynamics after abandonment of cavern field TR, including the caverns VE-1 to 4

Scenario 1: Diffusive migration

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Executive summary

Between 1982 and 1995, about 41000 m^3 of diesel oil has been trapped cumulatively in the Nedmag cavern field VE&TR, mainly during salt leaching operations, applying a diesel blanket for performing subsequent strip mining of magnesium salts. During the following period 1995-2018, leaching has mainly taken place without actively using diesel blankets. Meanwhile, only little amount of the earlier injected diesel volume could be recovered via the casing annuli. Likely, most diesel is dispersed in smaller cavern pockets, where it is trapped between brine and overlying halite, although some diesel can be trapped in the pores of dissolution residues and precipitates.

In case of sufficiently low pressure of the brine and blanket oil during mining operations relative to the stresses in the adjacent salt formation, brine and diesel oil will be trapped by the impermeable halite cavern roof. After complete abandonment of the cavern field (i.e. all wells sealed and abandoned), salt creep will pressurize the brine towards lithostatic pressure. Some years after final abandonment, it is expected that at the shallowest position in the cavern field, which is the roof of cavern VE-2, brine pressure will rise slightly above lithostatic. A condition for this to occur is that cavern VE-2 is hydraulically connected to the other TR-cluster caverns, which is currently not yet the case. Assuming that the halite roof of the VE-2 cavern stays intact (not damaged by a macro fracture), the salt will allow the migration of cavern fluids, due to micro-fracturing of the salt. Over geological times, most of the brine will leak away towards the Lower Bunter aquifer on top of the Zechstein formation. In the first decades, the likely leak rate is about 5200 m^3/year. This rate is governed by the creep rate of the deepest caverns, where the brine has a pressure deficit relative to the lithostatic pressure in the surrounding salts. The magnesium brines are heavier than the aquifer fluid and will most likely be kept by density differences in the first overlying aquifer. The lighter blanket diesel that co-migrates with the heavy brines into the overburden aquifer will continue to go up by buoyancy.

In the worst-case situation, almost all diesel oil will migrate towards the cavern roofs of the shallowest caverns. The oil will preferentially leak off after cavern sealing and abandonment, since it floats on top of the brine, with highest over-pressure relative to local pressure in the salt roof, and it is less viscous than brine. If capillary entry pressure for diesel in salt is conservatively ignored, most diesel could leak away by smooth permeation in some decades.

If a *macro* fracture in the salt roof would develop, the blanket diesel might leak faster out of the Zechstein formation. Such scenario will be shortly evaluated in a separate investigation.

This study anticipates that the diesel oil will be largely, or even totally, dispersed during its migration into the Triassic mudstone/sandstone aquifers above the Zechstein formation. A residual oil value of circa 5% is expected. Even if some diesel oil would reach and accumulate below the Vlieland shales, it will be finally trapped because of high capillary entry pressures for oil. It is not expected that the diesel oil can create (buoyancy) overpressures, given the very small volumes to be accommodated in the huge aquifer pore volume. The probability of diesel reaching shallow sweet water layers and hence the biosphere is practically nihil, even in geological times.

Given the virtually absent risk that diesel oil migration might cause post-abandonment pollution of the (living) environment, extensive efforts to further investigate and detail diesel migration into the overburden is not adding to any more predictive capacity, nor will it help in designing monitoring systems. Monitoring of diesel migration and accumulation will be virtually impossible, given the long time-frames, expected large dispersion and the small total diesel volumes (with respect to the other subsurface fluid volumes).

1 Introduction

Until 1996 and in 2012, Nedmag has used diesel blankets in the VE-caverns of Well Head Center 1 (WHC-1) and TR-caverns of Well Head Center 2 (WHC-2) to prevent undesired upward leaching of magnesium salts during progressive strip mining in the caverns. In the map of Attachment 1, the positions of the 4 VE-wells and 9 TR-wells are projected on top of the Zechstein (ZE) structure.

Between 1972 and 1996 and in 2012, diesel was lost from the injected blanket volume. In Attachment 2, the cumulative net (non-retrieved) volume of diesel pumped into each of the wells is summarized. Circa 3/4 of the diesel loss occurred during mining of the deeper, mixed magnesium salts (carnallite and bischofite) layers from the Zechstein III-1b. The other 1/4 of diesel was lost in the overlying Zechstein III-2b/3b salt layers that contain carnallite salt, but no bischofite salt. Although some diesel oil will be trapped in the pores of insoluble dissolution residues and precipitates, the most likely cause of diesel loss is the highly irregular shape of the caverns. For example, selective dissolution of magnesium salts around a large halite inclusion can form a (temporary) diesel trap. Thus, the lost diesel is presumably contained in numerous smaller traps, dispersed over the whole cavern field. During progressive dissolution of the magnesium salts, these isolated diesel pockets can move and because of the interconnection of caverns diesel may flow up-dip towards a shallower well.

From 1996, use of diesel blankets was not needed anymore in the full-grown cavern field (ref.1), apart from one new cavern (TR-9), the well of which was drilled in 2011. Meanwhile, many caverns have made hydraulic contact in the period 1982-2009 as specified in Attachment 1. This happened during ongoing water injection and magnesium salt dissolution. Only a little amount of diesel has been retrieved from up-dip wells after 1995. At present, total diesel volume of circa 41000 m³ is deemed irretrievable from the cavern field. At definite abandonment of the cavern field this volume of diesel will still be in place.

An important question from an environmental point of view is whether the trapped blanket diesel might reach the regional biosphere sometime after cavern field abandonment. Soil or drinking water contamination and surface water pollution caused by blanket diesel must be prevented, also in the very long run. In this report, the fluid dynamics of diesel in terms of permeation and dispersion probability in the overburden rocks are investigated, as well as the absorption and sealing capacities of the geological structures above the caverns. The dynamics of diesel flowing through macro fractures will be investigated in a separate study.

2 Cavern fluids migration after field abandonment

After final abandonment of the complete cavern field, hydraulic integrity of the cavern roofs is a relevant item, when brine pressure gradually rises to lithostatic values, caused by ongoing cavern convergence (salt creep).

The cavern field consists of a highly irregular, hydraulically connected network of squeeze-mined caverns, in which blanket diesel is trapped in unknown local highs (crestal pockets) because of its lower density than brine. The local highs are scattered cavern pockets not directly connected to the wells. It is very unlikely that all irretrievable diesel has collected into larger volumes on top of cavern brine, because in that case more diesel should have been seen in the up-dip wells and caverns at times of hydraulic connection between caverns.

2.1 Magnesium brine migration

Primarily, analyses of post-abandonment processes have been focused exclusively on carnallitic brine permeation through intact Zechstein salt roofs of the sealed caverns (refs.2,3,4).

Salt permeability as function of effective brine pressure
For brine pressures not exceeding local minimum principle stress, which normally is assumed to be close to the overburden stress, the halite cavern roofs are practically impermeable for brine (or diesel). For above-lithostatic brine pressures, halite permeability increases drastically, in a strongly nonlinear manner. The halite permeability is a function of effective brine pressure σ_e, which is defined as the difference between the minimum principle stress and the brine pressure. This value is the highest at the position of the shallowest cavern roof in the hydraulically connected cavern field.

In a recent WEP abandonment study (ref.4), a linearized version of the TUC (Technical University Clausthal) permeability relation (ref.3) was used, given by:

$\mathbf{K_h = 5.10^{-21}.10^{1.5\sigma e}}$ [m²], for conditions where $\sigma_e \geq 0$ [MPa]

In Attachment 3, relevant K_h relations as a function of σ_e are shown, basically indicating three orders of magnitude (1000 times) increase in salt permeability per 2 MPa of fluid pressure above ambient salt stress. Cavern salt roofs subjected to larger-than-lithostatic brine pressures ($\sigma_e > 0$) will become permeable and allow brine flow into the roofs. This so-called permeation process in the abandoned cavern field develops towards a balance between cavern convergence and brine flow through the roofs.

Presumably, at final cavern field abandonment the 3b cavern-roof of VE-2 at an average depth of 1414 m TV NAP will play this role, although to date the cavern is not yet connected to the caverns of the TR-cluster. Until final abandonment, no new 3b caverns will be developed. In Attachment 4, a true-scale final cross-section of the shallower part of the cavern field is depicted.

Salt permeability enhancement reduced with cavern depth
Assuming a known specific value for σ_e at the 3b-cavern roof of VE-2, the (reduced) effective brine pressures at deeper cavern roofs can be determined. The stand-alone cavern VE-1 is isolated from the system brine pressure trends and has been omitted. Three other cavern roofs are subjected to above-lithostatic brine pressures, namely TR-7, VE-4 and TR-1. Because of reduced brine overpressures at the deeper 3b cavern roofs, the enhanced roof salt permeabilities are reduced by factor $10^{-1.5\Delta\sigma}$ compared to K_{VE-2}. The pressure reductions $\Delta\sigma_e$ are, respectively, 0.575 MPa (TR-7), 0.58 MPa (VE-4) and 1.10 MPa (TR-1) (ref.4).

Effective brine pressure σ_e at VE-2 roof and yearly brine permeation flows
The hydraulic equilibrium between cavern convergence, migration of brine through the Zechstein cavern roofs and the containment capacity of the overlying permeable Lower Bunter mudstone is controlled by a coupled balanced model. The analytical model is based on laminar Darcy flow through a permeable medium and consists of five equations (ref.4).

If a 40% operational squeeze scenario until production stop and field abandonment in 2035 is assumed, the volume of squeezable free brine in the sealed VE&TR cavern field amounts to 7.7 million m³ (ref.4). Circa 15% of the free volume consists of carnallitic brine, collected in the upper 3b-caverns at an average depth of 1582.5 mTV NAP. The other 85% of free brine volume is bischofitic brine, contained in the deeper 1b-caverns at an average depth of 1695 mTV NAP. The bottom of the cavern system is formed by a thin carnallitic layer below the bischofitic 1b-section at a medium depth of 1726 mTV NAP. The bottom section contains negligible free brine (data from Table 1, ref.2). Ground level of the area is at +2 m NAP.

Solving the five equations for the situation after one year of brine migration, leads to an effective brine pressure of σ_e = 2.30 MPa at the 3b-cavern roof of VE-2. At the deeper roofs of the other caverns, reduced effective pressures apply as follows: 1.725 MPa at TR-7 roof, 1.72 MPa at VE-4 roof and 1.2 MPa at TR-1 roof. Total (carnallitic) brine permeation flow dV_{ZE}/dt from the sealed caverns, based on σ_e = 2.30 MPa, amounts to 5235 m³ (0.68‰ of free brine). The relative cavern flow contributions dV_p/dt are as follows: VE-2: 5%, TR-7: 48.5%, VE-4: 27% and TR-1: 19.5% (ref.4). In Table 1, the yearly leakage volumes through the respective cavern roofs are specified.

Diffuse dilatancy of roof salt
In this report, it is assumed that the effective pressure of the brine in the Nedmag caverns does not lead to macro fracturing of the roof. Instead, a process of diffuse dilatancy, as described in ref.15, is assumed, which leads to an increase of rock salt permeability without salt fracturing.

In that case, the Nedmag post-abandonment hydraulic process will presumably consist of slow migration of magnesium brine through secondary porosity of the Zechstein cavern roofs (refs.2,3,4,16). The cylindrical permeation patterns are depicted in Attachment 4 (taken from ref.4). In the first post-abandonment years the cumulative permeation flow is maximal and amounts to circa 5200 m³ per year. In subsequent years, permeation flow rate will gradually decrease, caused by the slowly shrinking free brine volumes and by the fading of effective brine pressure, resulting from decreasing brine column height due to proceeding convergence of the deepest caverns. In ref.4, it was calculated that after 100 years the migration flow has decreased to 2413 m³. The leakage process will last for thousands of years before the free brine volume has mostly migrated out of the Zechstein formation.

In Table 1, the net pore volumes V_{pore} of the permeating roofs above leaking caverns are given, as well as the breakthrough time t_{bt} in years after final field abandonment. Conservatively, the secondary roof-salt porosity is taken as 0.1% only. Brine breakthrough time varies between 2.2 and 3.3 years.

Cavern	Δl_{ZE} (m)	R_{roof} (m)	A_{roof} (m²)	V_{pore} (m³)	dV_p/dt (m³/yr)	t_{bt} 40% (years)
VE-2	92	54.5	9331	859	262	3.3
TR-7	79	159.5	79923	6314	2539	2.5
VE-4	96	130.0	53093	5097	1413	3.6
TR-1	75	98.5	30480	2286	1021	2.2

Table 1: Brine breakthrough times t_{bt} (40% squeeze scenario) in years per leaking cylindrical cavern roof after field abandonment, with Δl_{ZE} cavern roof thickness, V_{pore} pore volume of permeating salt roof and dV_p/dt yearly brine leakage through cavern roofs.

Nevertheless, some authors state that the development of macroscopic fractures under conditions pertinent to the Nedmag cavern field is easily possible (refs.16,17). This scenario will be addressed later in a separate study.

2.2 Blanket diesel migration

The previous studies were focused on permeation and migration of carnallitic brine. However, a blanket diesel volume of circa 41000 m³ is also left behind in the cavern field. Depending on the specific distribution of this trapped diesel volume, worst-case and most-likely scenarios of diesel dynamic behavior after field abandonment can be distinguished.

2.2.1 Worst-case diesel leakage scenario

In the very unlikely (conservative) case that all diesel would have been trapped in the upper regions of the 3b caverns, diesel is located at the 'leak point' on top of carnallitic brine, in direct contact with the halite roof. In that case, pressure-driven diesel permeation will presumably take precedence over brine permeation. Diesel is lighter than brine (diesel density 0.85 ton/m³) and the dynamic viscosity is smaller (1.2 10^{-9} MPa.s) than carnallitic brine viscosity (3.1 10^{-9} MPa.s, ref.4) at the formation temperature of 65 ºC. Therefore, diesel tends to preferentially escape from the Zechstein formation with increasing brine pressures after cavern field abandonment.

As mentioned in section 2.1, calculated permeation flow for carnallitic brine is circa 5235 m³/year. Taking the increased diesel fluidity compared to brine fluidity into account, diesel permeation rate will roughly be twice as large as the brine permeation rate. In the worst-case, the entire diesel volume of 41 000 m³ will be pressed out of the Zechstein formation into the Bunter formation. Although exact timing of the diesel migration process is impossible, the process is estimated to be completed within circa 10 years after field abandonment (diesel migration >5235 m³/year).

It should be noted that capillary entry pressure for diesel in water wet salt is neglected in the above analysis. Normally, pressure-driven diesel permeation can only occur for effective diesel pressures larger than needed for brine permeation, because diesel permeation through a halite cavern roof is considerably limited by capillary resistance. Diesel is immiscible with brine and non-wetting. Capillary resistance is an additional counter force to the migration and diffusion process of diesel, because the diesel-water interface must be forced through the salt pore throats.

The capillary pressure P_{cp} is the pressure difference across the oil-brine interface and is calculated with the expression $P_{cp} = 2(\gamma/r)\cos\theta$, where the wetting angle for diesel is $\theta = 0º$ (for completely water-wet salt micropores), interfacial surface tension $\gamma = 0.025$ N/m and average pore-throat radius in salt $r = 0.05$ µm (ref.6). Inserting the given parameter values yields $P_{cp} = 1$ MPa. The 1-MPa reduction of effective diesel oil pressure relative to effective brine pressure may significantly reduce the apparent salt roof permeability for diesel flow through the diffusely dilated salt roof by circa factor 10^3 (3 orders of magnitude), compared to the roof permeability for brine (ref.2).

At arriving in the porous brine-filled Bunter formation, diesel fluid-pressure will pass from a lithostatic to a hydrostatic pressure regime. However, diesel will still have a driving force to migrate further upwards, because of its low density being smaller than brine or sweet water (buoyancy). Dependent on the local geological structure above the Veendam salt pillow, gravity-driven migration, trapping and dispersion are investigated in detail in chapter 3.

2.2.2 Likely diesel permeation scenario

The high ratio of the surface area of the cavern walls to their volume means that cavern field closure will be irregular, probably leaving behind smaller isolated pockets of both brine and diesel. If the diesel volume is not fully trapped at the top of the 3b caverns, but more scattered in pockets over the entire cavern field, it is much less likely that it will migrate out of the Zechstein. It is well known from geological studies (ref.7) that small brine, oil and gas pockets (tenths to hundreds of m³) can remain immobile in salt over geologic times.

The scattered pocket case is a realistic scenario, because Nedmag used to extract the magnesium salts by means of a strip mining method. Each strip was protected against unwanted upward leaching by a dedicated diesel blanket. For example, cavern TR-4 has been mined through 31 slices over a total height of 144 m. After mining of a slice, diesel volume was partially not retrievable and stayed behind somewhere in the leached salt slice. Strip mining easily leads to diesel trapped in a series of smaller cavities. In Attachment 2, cumulative net volumes of irretrievable diesel are specified per well.

Since 1996, the mining method has been modified, such that wells are intermittently used as injector or producer without using oil blankets. Meanwhile, many caverns have been hydraulically interconnected, presumably via the Zechstein 1b bischofite layer. Currently, the brine field forms a labyrinth of interconnected caverns, the wells of which are shown in Attachment 1.

After definite cavern abandonment, the small diesel pockets will likely remain immobile, because the buoyancy pressure of short diesel columns is low (ref.8). The immobility is intensified by the capillary resistance. In the previous worst-case scenario, it was calculated that at least 1 MPa capillary entry pressure is needed for enabling diesel migration through the water-wet, dilated salt roof. The pressure gradient of diesel is 0.0083 MPa/m, compared to a salt pressure gradient of 0.0215 MPa/m. The difference between these gradients is 0.0132 MPa/m, which implies that the minimum diesel column height needed to overcome the capillary resistance is circa 75 m. The probability for isolated small diesel pockets to be sufficiently large in column height to overcome capillary resistance in the water-wet salt roof is practically nihil.

In the scattered diesel pockets case, net pore volume V_{pore} of the overlying Zechstein salt available to adsorb migrating diesel is far larger than the cylindrical volumes given in Table 1. Therefore, it might well be possible that the diesel, isolated and diffused in pockets of limited height, will get predominantly stuck in the micropores of the overlying Zechstein salt layers, causing immobile residual diesel saturation in salt before reaching base of the Bunter formation.

3 Local geological structures above Veendam salt pillow

Nedmag extracts the magnesium salts from the Veendam salt pillow. In view of the worst-case diesel leakage scenario, presented in section 2.2.1, knowledge of the local overburden above the Veendam salt pillow is essential for determining possible diesel migration paths towards the shallower subsurface.

3.1 Essential overburden characteristics

The pore fluid pressure regime in the overburden is essentially hydrostatic. Natural hydrocarbon accumulations are not found above the Veendam pillow. The geometry of the pillow consists of an elongated domal structure with omnidirectional dip closures and several crestal faults (ref.9). So, any migration of leaked diesel will take place above the salt pillow, whereas lateral migration away from the Veendam pillow is impossible because of the dip closures.

In attachment 5, the geological structure of the Veendam salt pillow and its overburden is shown (ref.10). A general pattern of normal faults in the overburden of the pillow could be mapped. The faults are associated with the rising salt pillow in geological times. Neo-tectonic activity is absent in the region. The faults have offsets of up to 200 m in the Triassic group, decreasing upwards. The faults are well visible at the top of the Triassic and in the Cretaceous. None of the faults seem to continue into the Tertiary and Quaternary sediments up to the surface.

Model calculations of stress development have shown that cavern field convergence does not change the in-situ stress to values required for fault reactivation in the overburden (ref.10). On the contrary, in the overburden of the cavern field arching takes place, with increasing horizontal stresses and further compression of the faults in the stress arch. The normal faults become more stable and remain inactive.

Clay smear in faults
The faults are probably clay-smeared, which occurs when a shear zone contains clay originating from a faulted and offset clay bed. Clay beds are largely impermeable for pore fluids. In Attachment 6, a normal fault in impermeable rock layer (for example shale) is schematically shown, with offset larger than rock layer thickness. If the fault is sufficiently filled with clay smear (yellow colored), the fault is likely sealing for pore fluids lighter than pore water. The buoyancy pressure of (for example) diesel is not sufficient to enter the seal. Thus, if diesel is trapped under the impermeable rock layer at the left side of the fault, it cannot flow into porous permeable rock at the right side of the fault and continue migrating into the overburden.

3.2 Diesel migration paths in Veendam overburden rock

In Attachment 7, the lithostratigraphic column of the Veendam area is shown, including essential elements of a petroleum system: source rock, reservoir, aquitard, seal rock and traps (ref.11). Most petroleum system characteristics are equally essential to the diesel migration issue.

Rock permeability and migration
In case of the Veendam salt pillow, the Zechstein formation may be interpreted as a kind of ‘source rock’. The diesel migrates through the Zechstein cavern roofs and penetrates the Triassic Main claystone that acts as an aquitard. An aquitard is a rock layer with poor permeability for fluids. The meant layer is here denoted Lower Bunter mudstone and considered rather tight with permeability K_{LB} varying between 10^{-16} to 10^{-15} m² (0.1 to 1.0 mD). The Rogenstein member is distinguished from the Lower Bunter mudstone by the regular intercalation of up to 1 m thick oolite beds in small-scale cycles. The oolite beds are far more permeable than mudstone and may be naturally fractured. In offset gas wells in the Veendam area, differential sticking problems and drilling mud losses related to the oolite layers have commonly been observed (ref.12). The Volpriehausen members, mentioned in Attachment 7, were not found in the wireline logs of the Nedmag wells. Top of Triassic formation is formed by the Solling claystone that is a sealing rock for fluids ($K_{SL} < 10^{-18}$ m²), apart from possibly non-clay-smeared faults. Very likely, the claystone also forms an obstacle for upward migrating diesel.

Not only permeability is variable and differs from layer to layer, but also the capillary entrance pressure is highly variable through the sedimentary column. Migration of diesel, being a light hydrocarbon, is hindered by capillary resistance. For example, sealing layers in the Triassic, such as the Solling claystone, have a sealing capacity that can hold several hundred meters of diesel column (ref.8).

Above the sealing Solling claystone, the Lower Cretaceous Vlieland sandstone is deposited, which is a permeable rock acting as reservoir. This layer can also contain and trap diesel because it is overlain by the Vlieland claystone, which is hardly permeable for fluids. The overlying Upper Cretaceous formations Texel and Ommelanden consist of poorly to non-permeable calcareous claystone and limestones. So, the sealing configuration of the Lower and Upper Cretaceous formation forms a robust and ultimate barrier to upwards flowing diesel.

The cross section of Attachment 5 displays major faults at the top of Trias. The fault offsets are probably large enough to locally breach the fluid sealing function of the Solling claystone. Then, the Lower Bunter mudstone is partially juxtaposed by permeable Vlieland sandstone. If the faults are clay-smeared, as depicted in Attachment 6, the fault is impermeable for hydrocarbons and the broken Solling claystone still acts as fluid seal.

If, however, the faults are non-sealing, migrating diesel can be assembled just below the crest of the Solling claystone and finally escape into the Vlieland sandstone via the faults. Then, diesel will gradually collect at the top of the sandstone. The sandstone is overlain by hardly-permeable Vlieland claystone. The migrating diesel is trapped at the top of the Vlieland sandstone.

It is virtually excluded that diesel will ever reach the overlying Upper Cretaceous formation (Texel and Ommelanden members). The Vlieland claystone and Holland member have undergone some faulting, but offsets are small, and the faulting has taken place in a sequence of hardly-permeable claystone and limestone layers.

3.3 Dispersion process of diesel in the Zechstein overburden

After leaking off from the Zechstein formation and migration into the overlying porous Bunter formation, the diesel must migrate through much rock volume, before it would reach top of Vlieland sandstone. The diesel pressure regime switches from lithostatic to hydrostatic after passing the leak-off interface. For diesel, the upward migration occurs via a complex two-phase flow in a porous medium.

Two-phase flow of diesel in the pores of a water-wet rock is controlled by buoyancy pressure, diesel saturation and relative permeability. This process invariably leads to the formation of residual saturation and dispersion of the diesel fluid (ref.8). A rough estimate of residual diesel saturation is 5% (ref.13). Then, after diesel has passed a pore volume equal to the diesel volume at pore volume entry, the remaining freely-movable diesel volume amounts to 95% of its entry volume. So, after having migrated through 20 times the porous rock volume that the diesel initially occupied in the Bunter interface rock section above the Zechstein, all diesel will have been dispersed and bound in pores.

A circumstance not leading to predominant diesel-adsorption in the overlying Lower Bunter rock pores would be the presence of open fractures or re-opening of mineralized veins in the Lower Bunter (ref.14) by high-pressure magnesium brine or blanket diesel flowing out of the Zechstein.

Another circumstance for concentrated, non-diffusive diesel-migration could be that the capillary entry pressure of the Lower Bunter is so high that an upward flow of diesel can only take place if open or re-opened (micro)-fractures or veins are present.

The leakage of diesel through fractures will be addressed in a separate report. In this study, it is presumed that all diesel volume leaked off from the Zechstein formation is dispersed and stuck to the walls of the passed rock pores of the Lower Bunter before diesel could even collect at the top of the Vlieland sandstone. This hypothesis is investigated next, using a simple geometric model.

Semi-quantitative dispersion estimation
Although accurately predicting the distribution of the diesel fluid after cavern field abandonment requires elaborate and detailed reservoir modeling studies, an orientating estimation is performed, using the characteristic geological data presented in this report

The cavern field cross-section shown in Attachment 4 is adopted as simplified ‘reservoir’ model. It is conservatively assumed that 41000 m³ diesel is assembled at the interface between the halite roofs and bottom of Lower Bunter formation for the caverns VE-2, VE-4, TR-7 and TR-1. The diesel volume distribution over the permeating roofs is taken proportional to the surface area of the cylindrical cavern roofs. The dimensions of the roofs and the attributed diesel volumes are given in Table 2.

It is assumed that the intruding diesel floats upwards through the pores of the Lower Bunter according to a roughly cylindrical geometry until it reaches the impermeable Solling claystone. The Lower Bunter is on average 240 m thick, with 7% porosity. The diesel will spread in the top section of the Lower Bunter in a corridor-like pattern (‘roof strip’) below the crestal interface of Lower Bunter and Solling claystone. On its way to the crestal interface diesel leaves a residual saturation of circa 5% in the Lower Bunter pores that it has passed.

Cavern	R_{roof} (m)	A_{roof} (m²)	A_{roof} (%)	V_{diesel} (m³)
VE-2	54.5	9331	5.5	2255
TR-7	159.5	79923	46.2	18942
VE-4	130.0	53093	30.7	12587
TR-1	98.5	30480	17.6	7216

Table 2: Dimensions of permeating cylindrical cavern roofs. Total diesel volume of 41000 m³ is distributed over the roofs proportional to the leaking-interface area between Zechstein and Lower Bunter.

According to Table 2, the total area where diesel leaks off through the Zechstein - Lower Bunter interface is circa 173 000 m². The pore volume in the Lower Bunter up to the bottom of the Solling claystone is circa 2.9 million m³ (173 000x 240x 0.07). If the roof strip below the crestal interface is roughly modeled as 500 m wide, 5 m high, and with 2.5 km length, as suggested by the pillow structure in Attachment 1, this strip represents a net pore volume of circa 0.44 million m³.

For an assumed residual diesel saturation of 5%, the total diesel volume of 41000 m³ must pass at least circa 0.82 million m³ of pore volume, before freely movable diesel volume is reduced to practically zero. Modeled pore volume for diesel migration from Zechstein up to and including the Lower Bunter roof strip amounts to circa 3.34 million m³ in total. Thus, residual diesel saturation in the Lower Bunter must be as low as circa 1.2%, before free diesel would touch the Solling claystone. In view of above conservatively estimated pore volumes to be passed in vertical and horizontal directions before reaching the Solling claystone, a volume of 41 000 m³ diesel left behind in the cavern field is very little with respect to the amount of absorbing porous rock volume right above the Zechstein formation.

4 Conclusions

The realistic scenario is that most diesel is trapped in small pockets up-dip from the wells. Hydraulic connection between the caverns did not (or almost not) lead to an upward migration of the oil, at least not leading to an accumulation at a casing shoe in one of the up-dip wells.

The deep, subsurface process of blanket diesel migration after cavern field abandonment will likely result in an end-situation of diesel predominantly adsorbed in the Zechstein salt formation itself, instead of leaking off into the overburden rock formations. The diesel will be contained in smaller, lithostatically pressured, pockets outside the brine leak-off point after abandonment and, thus, become geologically immobile.

In the unlikely (conservative) case that all diesel would have been trapped in the upper regions of the 3b caverns, diesel is located at the ‘leak point’ on top of carnallitic brine, in direct contact with the halite roof. In that case, assuming a diffusive migration scenario, pressure-driven diesel permeation will presumably take precedence over brine permeation.

Even if all 41 000 m³ of diesel volume would completely escape from the Zechstein formation (worst case scenario), the shallowest migration depth level of permeating diesel into the overburden is very likely the bottom of the overlying Solling claystone.

The shallowest possible migration level of permeating diesel is the bottom of the Vlieland claystone, which seals off the Vlieland sandstone. The shallowest bottom of the Vlieland claystone is below 750 mTV. During its way upwards, the diesel is likely trapped in the hydrostatically pressured overburden by a series of capillary barriers and permeable layers, perhaps in combination with natural fracture systems.

The Vlieland sandstone will act as ultimate diesel trap. For a Vlieland migration process to be justified, a permeable fault *must* exist in the Solling claystone, with sufficiently large offset to be juxtaposed to the permeable Vlieland sandstone. Then, the remaining small amount of diesel finally arriving in the Vlieland sandstone will form a small low saturation accumulation, which is geologically stable under the overlying clay-rich seal. Consequently, it is not effective to further investigate blanket diesel migration to the Cretaceous formations, overlying the Vlieland formation. The Vlieland group constitutes the ultimate barrier to blanket diesel migration.

5 References

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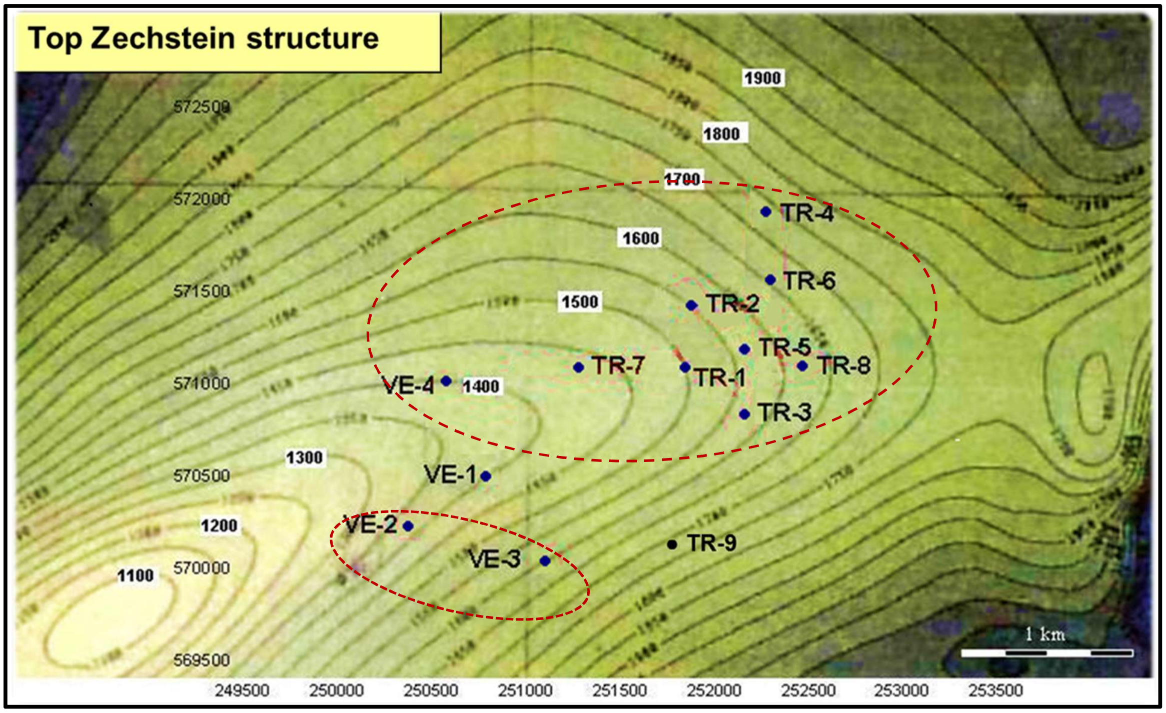
Attachment 1: Map of Nedmag cavern field January 2018



Positions of the 4 VE-wells (WHC-1) and 9 TR-wells (WHC-2), projected on top of the Zechstein (ZE) structure.

Well VE-1 has a cavern in carnallite salt layer ZE-III-2b/3b only. Wells TR-8 and TR-9 have a cavern in the deeper ZE-III-1b bischofite layer only. The other wells are connected to caverns in both the 1b and 2b/3b magnesium salt layers.

The dotted red ovals indicate mutual cavern connections beginning 1982 at the ZE-III-1b level. VE-1 and TR-9 are stand-alone caverns.

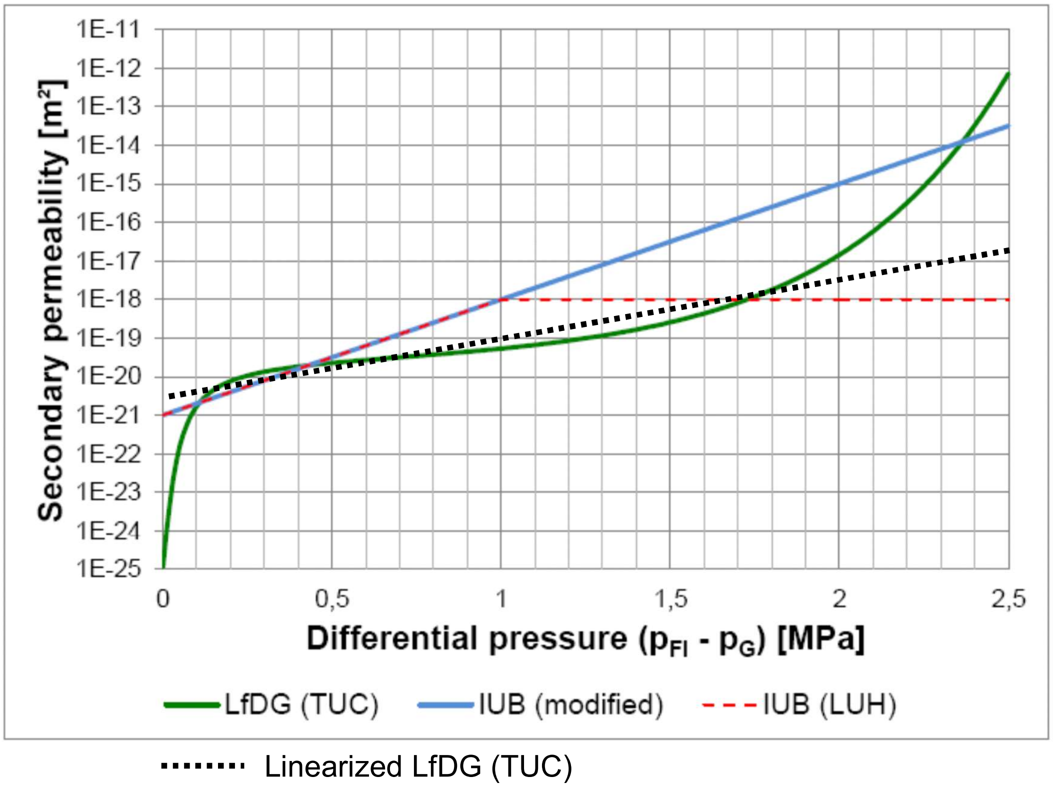
Attachment 2: Net diesel volumes left behind in the cavern field

Well	Status 1-10-1995	From 1-10-1995 to 1-1-2017	Dissolved oil in brine produced until 1-1-2017 *	Present in caverns on 1-1-2017
	m3	m3	m3	m3
TR-1	3.988	-9		
TR-2	3.525	0		
TR-3	3.853	0		
TR-4	4.919	0		
TR-5	5.057	325		
TR-6	6.799	0		
TR-7	2.462	0		
TR-8	2.802	-151		
TR-9	0	1.105		
VE-1	3.020	0		
VE-2	3.283	-495		
VE-3	2.145	-800		
VE-4	2.419	-2.130		
Total	44.272	-2.155	1.057	41.060

*) Based on an assumed solubility of 50 mg/l and 18.0 million m³ of brine produced.

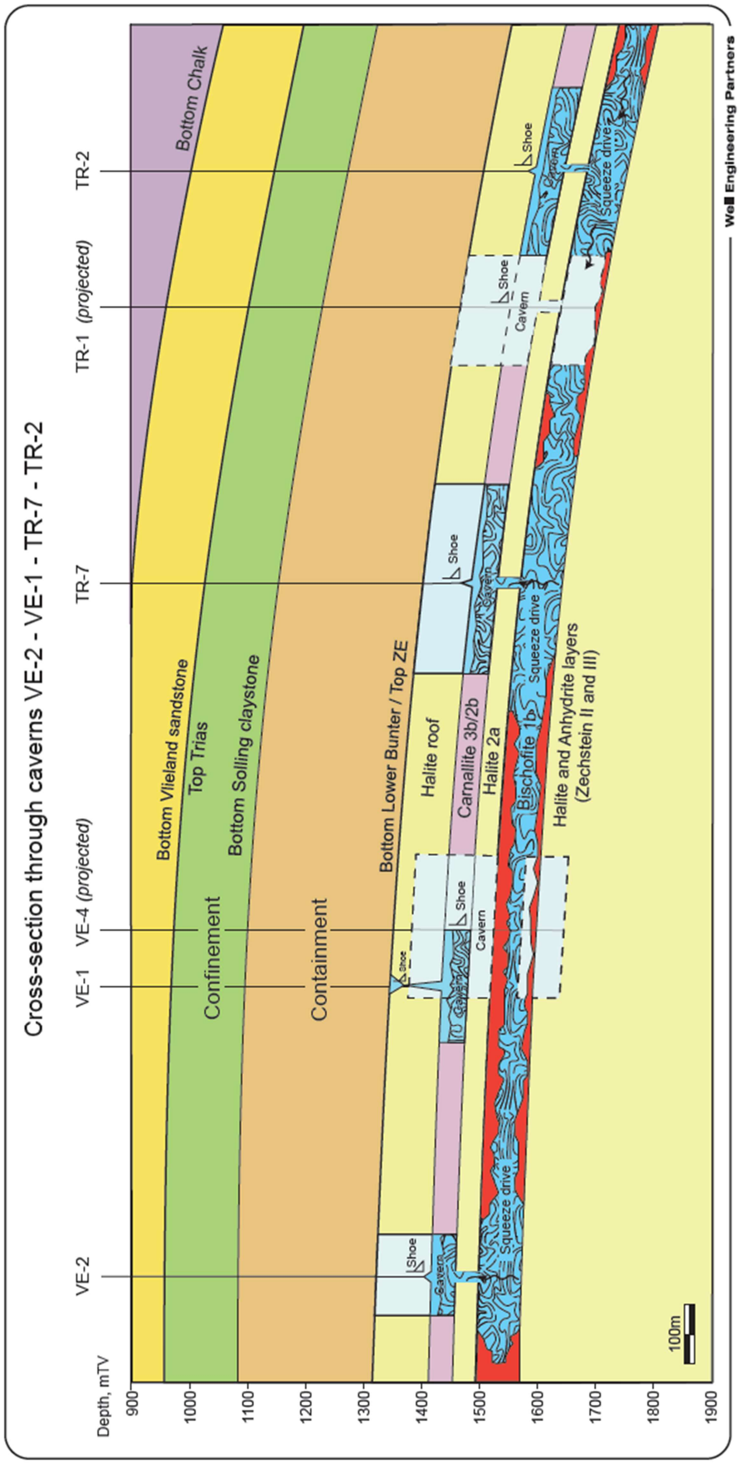
In fact, diesel is not dissolved in brine, but it is entrained in dispersed phase with brine production flow. During strip mining in the past, diesel traces of up to 50 mg/l have been measured in brine.

Attachment 3: Functional relations between σ_e and K



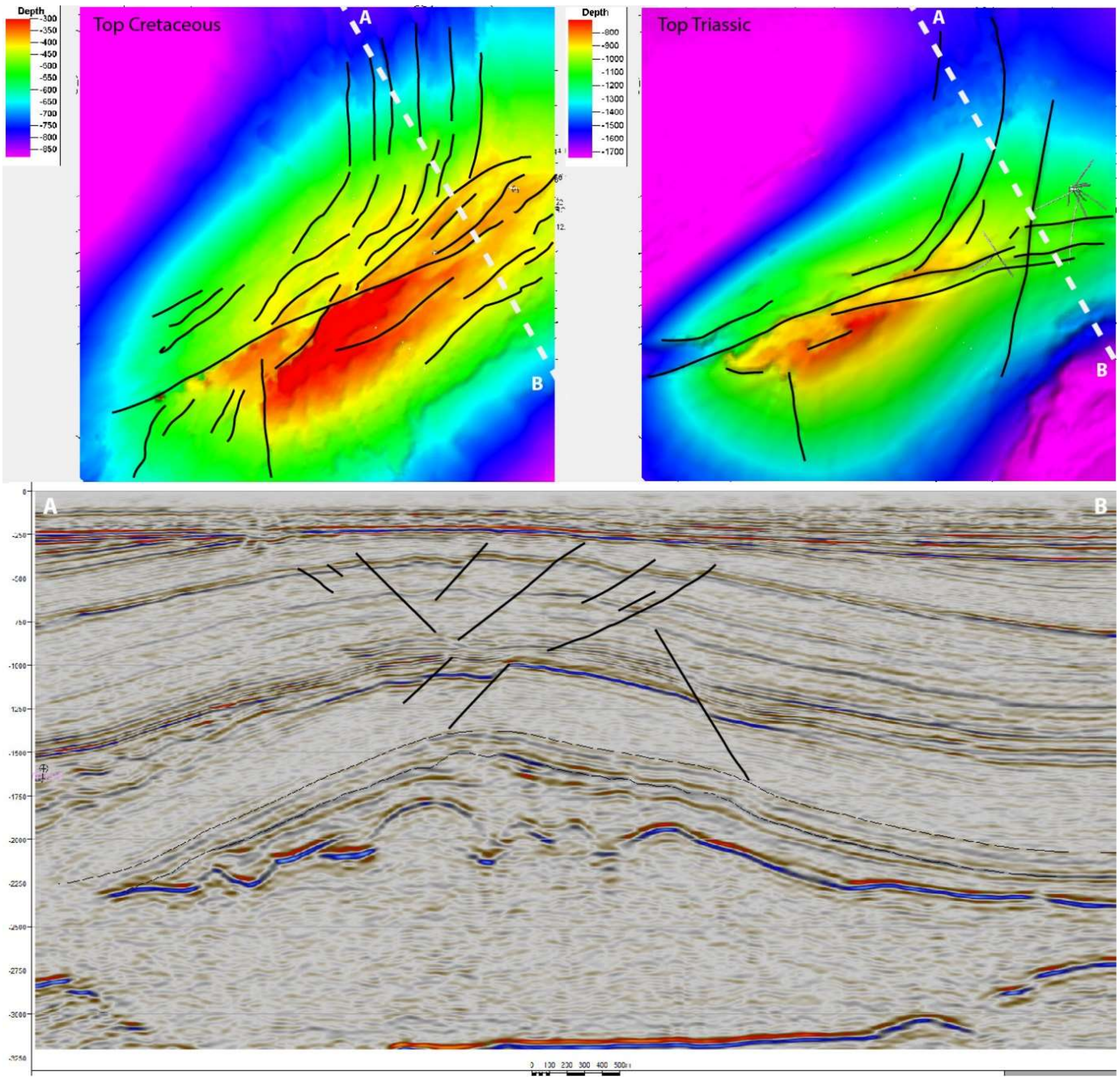
Different functional relations between effective brine pressure σ_e (= Differential pressure) and increase of salt permeability K (= Secondary permeability). The IUB modified curve has been applied in a Nedmag abandonment study (ref.2). In a new abandonment study (ref.4), a linearized version (dashed black curve) of the LfDG (TUC) curve is used.

Attachment 4: Cross section of WHC-1&2 cavern field



Cross section of WHC-1&2 cavern field with brine permeation patterns (light blue cylinders) per 3b cavern roof after final abandonment (adopted from ref.4).

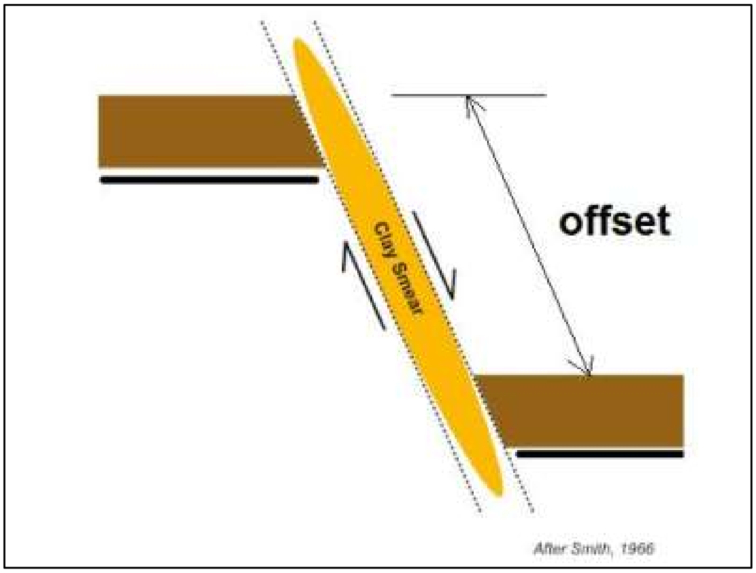
Attachment 5: Triassic and Cretaceous depth maps above Veendam salt pillow



Top left figure: Top Cretaceous depth map with faults indicated by black lines.
Top right figure: Top Triassic depth map and faults. The tiny grey lines in the middle right section of the figure indicate the trajectories of the VE-wells and TR-wells into the Zechstein salt formation below the Triassic formation.
Lower central figure: Cross section showing profile A-B, shown as white dotted line in the upper two maps. The profile is crossing between the clusters of VE-wells and TR-wells. The black lines are normal faults in the Triassic and Cretaceous formations above the cavern field. The vertical axis ranges from surface to 3 km depth. At the horizontal axis, 500 m distance-indication is shown.

(Figures adopted from ref.9)

Attachment 6: Clay smear in normal fault



Schematic normal fault in impermeable rock (brown-colored), with offset larger than rock layer thickness. If the fault is sufficiently filled with clay smear (yellow colored), the fault is likely impermeable for hydrocarbons due to high capillary resistance. Then, if fluid lighter than pore water is trapped under the impermeable rock layer at the left side of the fault, the fluid cannot flow into porous permeable rock at the right side of the fault.

Attachment 7: Lithostratigraphic column of Veendam area

Lithostratigraphic Column Veendam

Era	Group	Period	Formation	Epoch (Age)	Member	Lithology	Source rocks	Reservoir	Aquitard	Seal rock	Traps
Cenozoicum	Upper North Sea NU	Quaternary	"Diverse"	Holocene-Pleistocene		Diverse continental deposits, mostly fluvial sands and silts intercalated by some thin layers of grey or greenish-grey, silty clays. Plant remains.					
		Tertiary	Oosterhout NUOT	Pliocene		Succession of sands, sandy clays, and grey and greenish clays. The lower part consists of sands that are extremely rich in shells and bryozoans.					
			Breda NUBA	Miocene		Sequence of marine, glauconitic sands, sandy clays and clays. In many places a glauconite-rich layer occurs at the base.					
	Lower North Sea NL		Dongen NLFF	Eocene Lutetian to Bartonian	Asse NLFFB	Dark greenish-grey and blue-grey, plastic clays. The unit may be glauconitic and somewhat micaceous.					
				Eocene Ypresian to Lutetian	Brussel Sand NLFFS	Green-grey, glauconitic, very fine-grained sand with, mainly in the upper part, a number of hard, calcareous sandstone layers.					
				Eocene Lutetian to Bartonian	Ieper NLFFY	Soft, tough and sticky to hardened and friable clay. Lower part: brown-grey clay, tending to beige or red-brown locally (pyrite, non-calcareous, coalified plant remains). Upper 2/3: green-grey colour, a sandy upper part and it is somewhat calcareous and glauconitic.					
					Basal Dongen Tuffite NLFFT	Tuffaceous clays, blue to violet-grey in colour, alternating with dark-grey and red-brown clays.					
			Landen NLLF		Landen Clay NLLFC	Grey to greenish grey clays with local marl intercalations (especially in the basal part). The member contains glauconite, pyrite and mica.					
Mesozoicum	Chalk CK	Cretaceous	Ommelanden CKGR	Upper Cretaceous Turonian to Maastrichtian		Succession of white and light-grey marls, chalks and fine grained limestones, in places very argillaceous. Traces of chert, pyrite and scattered glauconite.					
			Texel CKTX	Cenomanian	Plenus Marl CKTXP	Dark-grey, partly black, calcareous, laminated claystone.					
					Texel Marlstone CKTXM	White to light-grey, locally pinkish, limestones and marly chalks or marls. Tr. of chert, pyrite & glauconite.					
	Rijnland KN		Holland KNGL	Lower Cretaceous Middle to Late Albian	Upper Holland Marl KNGLU	Grey and/or red-brown calcareous shaly claystone with a distinctly lower lime content than the under- and overlying members.					
				Late Aptian to Early Albian	Middle Holland Claystone KNGLM	Grey and/or red-brown calcareous shaly claystone with a distinctly lower lime content than the under- and overlying members.					
				Early Aptian	Lower Holland Marl KNGLL	Generally consists of grey and red-brown marl or calcareous, fissile claystone, frequently with intercalated bituminous claystone beds.					
			Vlieland Claystone KNNC	Valanginian to Barremian/Early Aptian	Vlieland Claystone KNNCM	Dark brownish-grey to grey claystone. Mica and very fine lignitic matter are common. Slightly calcareous.					
			Vlieland Sandstone KNNS		Friesland KNNSF	Mainly consists of fine- to medium-grained argillaceous, glauconitic sandstones. Bioturbation, mica, shell fragments and lignite particles are often present.					
	Upper Germanic Trias	Triassic	Solling RNSO	Upper Triassic Latest Scythian	Solling Claystone RNSOC	Red, green and locally grey claystones, which often show high gamma-ray readings in the basal part.					
	Lower Germanic Trias RB		Lower Buntsandstein RBSH	Latest Permian to Early Scythian	Volpriehausen Clay-Siltstone* RBMVC	Fining-upwards cycles of fine-grained sandstone, siltstone, and claystone. Oolite beds may be intercalated. It displays reddish to greenish colours.					
					L.Volpriehausen Sandstone* RBMVL	Pink to grey, (sub-)arkosic sandstone unit.					
					Rogenstein RBSHR	This member is distinguished from the Main Claystone Member by the regular intercalation of up to 1 m thick oolite beds in the small-scale cycles.					
					Main Claystone RBSHM	The member consists of a succession of red-brown to green silty, sometimes anhydritic claystones. Some thin sandstone beds and oolitic beds also occur.					
Paleozoicum	Zechstein ZE	Permian	Zechstein Upper Claystone ZEUC	Late Permian Thuringian		Red-brown to pale brown, occasionally grey-green claystones with some anhydrite and/or carbonate stringers. These claystones often show remarkably low velocities on the acoustic log.					
			Zechstein 4 (Aller) ZEZ4		Z4 Salt ZEZ4H	Member consists of relatively pure halite in its lower part, capped by a potassium-magnesium-rich salt layer.					
					Z4 Pegmatite Anhydrite ZEZ4A	The Pegmatite Anhydrite Member is a distinct white anhydrite unit, commonly with coarse halite crystals.					
					Red Salt Clay ZEZ4R	This unit is a red, generally anhydritic claystone. It may include some calcareous or dolomitic intercalations.					
			Zechstein 3 (Leine) ZEZ3		Z3 Salt ZEZ3H	This is a pure salt sequence. In the middle and upper part two potassium-magnesium-rich salt beds are present.					
					Z3 Salt, 4b	The fourth cycle contains mostly halite and anhydrite.					
					Z3 Salt, 4a						
					Z3 Salt, 3b	The third cycle contains the salts: halite, carnallite and some kieserite.					
					Z3 Salt, 3a						
					Z3 Salt, 2b	The second cycle contains the salts: halite with minor amounts of carnallite.					
					Z3 Salt, 2a						
					Z3 Salt, 1b TARGET	The first cycle contains the majority of magnesium salts and about all of the bischofite. The magnesium salts are interbedded with thin layers of halite.					
					Z3 Salt, 1a	The lowermost section contains pure halite.					
					Z3 Main Anhydrite ZEZ3A	A relatively pure anhydrite body, but it can contain a large number of dolomitic or claystone intercalations.					
					Z3 Carbonate ZEZ3C	A brownish, slightly argillaceous, dolomitic limestone or coarse-crystalline dolomite					

Five most right columns specify essential elements of a petroleum system (from ref.11).

*) Note: Volpriehausen Clay-siltstone and L.Volpriehausen Sandstone are probably not present in Veendam area.