Evaluation of blanket diesel dynamics for new caverns VE-5 and VE-6

Prepared by	Well Engineering Partners B.V., Hoogeveen
Author:	Dr. A.J.H.M. Duquesnoy
Version:	3 (final)
Publication date:	18 October 2017
Agreed:	A.J. Smit, Head Nedmag Production Mining

Contents

1 Introduction

Nedmag plans to drill in 2018 two new wells VE-5 and VE-6 from Wellhead Cluster 1 (WHC-1) in westerly direction with 1600 m to 1700 m outstep, as indicated in the map of Attachment 1. According to the detailed design reports of the wells, the respective planned target depths are circa 1790 m TV for VE-5 and 2000 m TV for VE-6. Magnesium salts will be extracted only from the Zechstein III-1b bischofite layer. This approach leaves Zechstein salt roofs with thicknesses between 445 m (VE-5) and 315 m (VE-6) above the new 1b-caverns. The characteristic Zechstein layer structure and the overburden are schematically shown in Attachment 2.

During cavern development by water injection, the rock salt roof must be protected against fast upward leaching by means of a diesel oil blanket, until the brine becomes sufficiently bischofitic (ref.1). Nedmag aims at hydraulically connecting the two caverns. Thereafter, the shallower well VE-5 will be used as water injector and the deeper well VE-6 as brine producer. During cavern development, a cumulative net volume of circa 2500 m³ of diesel blanket per cavern is expected to be needed and to stay behind, based on mining experience from previous Nedmag caverns.

An important question from an environmental point of view is whether the trapped blanket diesel might reach the biosphere sometime after cavern 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 are investigated, focusing on trapping, permeation and dispersion in the overburden rocks above the caverns.

2 Recent insights in cavern abandonment circumstances

The Nedmag caverns are highly irregular-shaped and filled with residue. The caverns are for a large part hydraulically connected, as indicated in Attachment 1. The diesel is trapped in local highs, because of its lower density than brine. The local highs are scattered pockets, in which the diesel is not directly connected to the wells. This is suggested by the fact that diesel, which could not be retrieved from one well, did not appear in an up-dip well after the wells had become hydraulically connected. After final abandonment, brine pressure gradually rises to lithostatic values, caused by ongoing cavern convergence (refs.2,3,4).

The halite roof permeability is a function of effective fluid pressure (brine or diesel), defined as the difference between the minimum principle stress in the roof salt and the cavern fluid pressure. Minimum principle stress in salt is approximately equal to lithostatic pressure.

After definite production stop followed by final closure of the twin-cavern VE-5/6, the effective brine pressure at the cavern roof will rise. A plausible end-geometry of the twin-cavern is as follows. Average vertical 1b layer thickness is circa 85 m and the dip angle of the layer is 16° (29%). If the cavern would have been leached along the axis VE-6 to VE-5 up to the crest of the salt pillow (see Attachment 1), the maximum up-dip roof length of the twin cavern could be around 900 m.

After final abandonment, the cavern brine pressure is controlled by cavern convergence (mainly by bischofite salt creep) and the total stress in the salt at the deepest point of the twin-cavern, in the NW-corner. The leak-off point is the roof top in the opposite SE corner. The maximum effective fluid pressure at leak-off point is calculated next. For sake of simplicity a ‘stand-alone’ calculation is done, instead of applying the analytical balanced permeation model of previous studies (refs.2,4). The height difference between the cavern extremities is circa 345 m TV (= 85 + 0.29x 900). The bischofitic brine column has specific pressure gradient of 0.0137 MPa/m and the Zechstein salt gradient is circa 0.0210 MPa/m. Assuming an impermeable salt roof, the difference of these gradients (0.0073 MPa/m) yields a potential brine overpressure (effective pressure) at leak-off point of maximally 2.5 MPa. The short-term failure strength of salt is controlled by its tensile strength, which is circa 2 MPa (ref.5).

In practice, brine pressure-rise in the abandoned cavern system is not immediate or short-term, because active mining is done under a sub-lithostatic pressure regime. It will take months or more after shut-in for effective brine pressure to reach a value significantly larger than zero. It is generally thought that when fluid pressure gradually raises above the minimum salt stress, the rock salt permeability is increased by diffuse dilatancy only. Under these circumstances, the 2-MPa failure-strength criterion will not be reached, meaning that short-term failure by the formation of a macroscopic fracture is unlikely. In short, the long-term behavior of rock salt under positive effective fluid stresses is mainly ductile with diffuse dilation (secondary porosity by microcracking), not brittle with macro-fracturing.

However, in the very unlikely case that a macro-fracture would develop through the more than 300-m thick salt roof, the accelerated brine outflow will cause a significant drop in brine pressure, followed by healing of the roof fracture by salt creep. Possibly, when the high-pressure fluid pulse enters the overlying porous Lower Bunter, some consequential fracturing of this formation may be expected, but the fluid drive is of short duration and will fade away over short fracture length.

In summary, the regular post-abandonment process will be a slow migration of bischofitic brine through secondary porosity of the Zechstein cavern roofs (refs.2,3).

2.1 Blanket diesel dynamical behaviour after cavern abandonment

When in the twin-cavern a blanket diesel volume of circa 5000 m³ is trapped, a worst-case and a most-likely scenario of diesel dynamical behavior after abandonment can be distinguished, depending on the specific distribution of the trapped diesel volume.

Worst-case diesel leakage scenario
In the very unlikely case that all diesel would have been trapped in the upper regions of the dipping twin-cavern, diesel is located at the ‘leak-off point’ on top of bischofitic brine, in direct contact with the halite roof. Diesel is lighter than brine with diesel density of 0.85 ton/m³ versus bischofitic brine density of 1.37 ton/m³. The dynamic viscosity of diesel is factor 2.5 smaller (1.2 10^{-9} MPa.s) than bischofitic brine viscosity at formation temperature of 65-70 ºC. Therefore, after cavern abandonment diesel tends to preferentially migrate through the Zechstein roof when brine pressure increases to lithostatic values.

The high ratio of the surface area of the cavern walls to their volume means that cavern closure will be irregular, probably leaving behind smaller isolated pockets of both brine and diesel. It is well known from geological studies (ref.6) that small brine, oil and gas pockets (tenths to hundreds of m³) can remain immobile in salt over geologic times.

Pressure-driven diesel permeation can only occur for effective diesel pressures larger than necessary in case of 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.7). 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, compared to the roof permeability for brine (ref.2).

However, it should be noted that there is a risk of macroscopic fracturing of the salt roof because of the largely reduced permeability of salt for diesel flow. This might happen in case of a thick diesel layer floating on the cavern brine at the shallowest leak-off point (crest). For, if excess diesel pressure must highly raise before capillary resistance is significantly overcome, while at the same time the diesel cannot be displaced and passed by brine migration, the effective pressure at leak-off point could, in the absence of sufficient diffuse dilatancy, increase to its maximum value of circa 2.5 MPa and, then, at the crest exceed the tensile strength of salt.

While arriving in the porous water-filled Bunter formation (by permeation of macro-fracturing), diesel fluid-pressure will pass from lithostatic to hydrostatic pressure regime. The diesel will still have a driving force to migrate further upward, because of its specific density being smaller than pore-water specific density (positive buoyancy). Dependent on the local geological structure above the Veendam salt pillow, the gravity-driven migration, trapping and dispersion process is investigated in chapter 3.

Most-likely diesel permeation scenario
If the trapped diesel volume is not entirely located at the uppermost leak-off point of the twin-cavern, but more scattered in (small) pockets over the entire twin-cavern, it is unlikely that the diesel will migrate out of the Zechstein. The scattered case is a realistic scenario, because Nedmag extracts the magnesium salts by means of subsequent strip-mining in the complex internally folded structure of the 1b bischofite layer, with large insoluble blocks of rock salt. Each strip-mining sequence is protected against unwanted upward leaching by a diesel blanket.

As indicated by the partially non-retrievable blanket diesel volume before the next salt strip is to be produced, strip mining leads to diesel trapped in a series of smaller cavities. After definite cavern abandonment and migration of the brine out of the Zechstein, the small diesel pockets will likely remain immobile, because the buoyancy pressure of short diesel columns is low. This effect is enhanced by the capillary resistance (ref.8).

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 0.0210 MPa/m. The difference between these gradients is 0.0127 MPa/m, which implies that the minimum diesel column height needed to overcome the capillary resistance is 79 m. The total height of the 1b bischofite section is typically circa 85 m, so the probability for isolated small diesel pockets to be sufficiently high to overcome capillary resistance in the water-wet salt roof is practically nihil.

3 Local geological structures above Veendam salt pillow

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

3.1 Important overburden characteristics

The pore fluid pressure regime in the overburden is essentially hydrostatic. There are no known natural hydrocarbon accumulations above the Veendam pillow. The geometry of the pillow consists of an elongated domal structure with omnidirectional dip closures and several crestal faults. This means that any migration of the diesel can only take place above the salt pillow, whereas lateral migration away from the Veendam pillow is impossible (ref.9)

In Attachment 3, the geological structure of the salt pillow and its overburden is shown (ref.10). A general pattern of normal faults in the overburden of the Veendam pillow has been mapped, based on high-quality 3-D seismic data. The faults are associated with the rise of the salt pillow in geological times. Neo-tectonic activity is absent in the area under consideration. The faults have offsets (throws) of up to 200 m in the Triassic, decreasing upwards. The faults are well visible at the top Triassic formation and in the Cretaceous. None of the faults seems 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. On the contrary, in the overburden of the cavern field arching takes place, with increasing horizontal stresses and further compression of the faults. The normal faults become more stable and remain inactive (ref.10).

3.2 Faults along new Veendam well trajectories

Nedmag aims to drill the new wells VE-5 and VE-6 into the NW-flank of the Veendam salt pillow. In Attachment 4, seismic cross sections along the planned well trajectories of VE-5 and VE-6 are shown. The wells cross the Cretaceous and Triassic fault zones. The rectangles indicated ‘A’ identify major normal faults with significant offsets of circa 40 m at the top of the Triassic formation. In the fault zone, Triassic rock layers abut Cretaceous sediments. 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 a separate study (ref.11), it has been examined whether one or more faults could create well stability problems. It was found that the faults are inactive and that stress changes or rock movements during salt production will most likely not reactivate the faults.

In Attachment 5, a normal fault in impermeable rock layer (for example shale) is schematically shown, with offset larger than rock layer thickness (ref.12). If the fault is sufficiently filled with clay smear (yellow colored), the fault is likely sealing for non-wetting pore fluids. 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.

3.3 Diesel migration paths in Veendam overburden rock

In Attachment 6, 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.13). Most petroleum system characteristics are equally essential to the diesel migration issue.

In case of the Veendam salt pillow, the Zechstein formation may conceptually be seen as a kind of ‘source rock’. If the diesel would migrate through the Zechstein cavern roofs, it penetrates the Triassic Main claystone that acts as an aquitard. An aquitard is a rock layer with poor permeability for fluids. In ref.1, the meant layer is denoted Lower Bunter mudstone and considered rather tight with permeability $K_{LB} = 10^{-16}$ m² (0.1 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.14). The Volpriehausen members, mentioned in Attachment 6, were not found in the wireline logs of the Nedmag wells. Top of

Triassic formation is formed by the Solling claystone with up to 60 m thickness at the crest. This claystone is a sealing rock for fluids ($K < 10^{-18}$ m²). Apart from possibly non-clay-smeared faults, 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 resistance 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). This also holds for the Lower Bunter with capillary resistance much higher than can be overcome by the buoyancy pressure of a geologically small volume of diesel. The only possible migration of some diesel through the Lower Bunter is via open fractures. In the Veendam area, drilling mud losses have been observed in the oolite beds of the Rogenstein just above the Lower Bunter, but not in the Lower Bunter itself. So, open fractures in the Lower Bunter are not expected.

Above the sealing Solling claystone, the Lower Cretaceous Vlieland sandstone 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 a good capillary seal. The overlying Upper Cretaceous formations Texel and Ommelanden consist of poorly to non-permeable calcareous claystone and limestones.

The cross sections of Attachments 3 and 4 display 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 5, 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. Hence, the migrating diesel is trapped at the top of the Vlieland sandstone.

The Vlieland claystone and Holland member have undergone some faulting, but offsets are smaller than the thicknesses of the members and the faulting has taken place in a sequence of hardly-permeable claystone and limestone layers. It is virtually impossible that diesel will ever reach the overlying Upper Cretaceous formation (Texel and Ommelanden members), which is the ultimate sealing configuration that forms a robust barrier to upwards flowing diesel.

3.4 Worst-case migration process of diesel in the overburden

After leaking off from the Zechstein formation into the overlying porous Bunter formation, the diesel must migrate through much rock volume to arrive in shallower rock layers. The Lower Bunter is a mudstone on average 240 m thick, with porosity of circa 7% (ref.2). Before diesel would reach top of Vlieland sandstone, being the ultimate barrier preventing diesel oil from penetrating in the biosphere, an immense bulk volume of porous rock must be crossed.

The diesel pressure regime switches from lithostatic to hydrostatic after passing the Zechstein leak-off interface. Then, the upward migration of diesel 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.

In practice, a two-phase flow 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.15). Then, after diesel has passed to a new pore volume, there stays 5% of its volume behind and only 95% reaches the nextp reservoir compartment. So, after having migrated through a rock pore volume of more than 20 times the volume, which the diesel occupied at the Bunter interface above the Zechstein, most diesel will have been dispersed and bound in the pores.

For a net diesel volume of 5000 m³ at the bottom of the Lower Bunter, the diesel must pass a pore volume of 100 000 m³ only, before freely movable diesel volume is reduced to practically zero. Even for a (geological speaking) minimum residual saturation of circa 1%, the Lower Bunter pore volume to be passed before complete diesel fixation is still negligible (500 000 m³). For an average rock porosity of 7%, gross Lower Bunter volume involved amounts to circa 7 million m³. This volume corresponds to a cylinder of 240 m tall with radius of 96 m.

Only for the very conservative and geologically unlikely hypothesis that a direct macro-fracture would already exist from the crest of the Zechstein pillow through the Lower Bunter and Rogenstein formation to the Solling claystone, it might happen that a significant amount of diesel would arrive at the bottom of the Solling claystone. Then, it depends on where exactly the diesel collects below the Solling claystone. The underlying Rogenstein oolite beds are permeable and porous and preferentially collect the migrating diesel. In this case, the Rogenstein functions as a reservoir barrier.

If the remaining free diesel assembles right below the major fault in the Solling claystone (see Attachments 3 and 4), the fault must both be permeable and sufficiently in contact with the Vlieland sandstone, to allow continued diesel migration to shallower depth. Clearly, many unlikely conditions must be all together fulfilled before this ultimate migration process can happen.

4 Conclusions

- The deep, subsurface dynamic process of blanket diesel after cavern abandonment will very likely result in an end-situation of diesel predominantly adsorbed in the Zechstein salt, 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.

- Even when part of diesel or all diesel (worst-case scenario) would escape from the twin-cavern VE-5/6, the highest 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 800 m TV. 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 reservoir. 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.

Overall conclusion

Although it may not be possible to accurately predict the precise distribution of the diesel fluid with time after cavern abandonment, the presence of potential hydrocarbon traps and seal *in series*, combined with the geometry and thickness of the Veendam overburden, make it extremely unlikely that groundwater contamination can occur by upward migration of the Veendam diesel blanket. Therefore, the use of diesel for developing the caverns VE-5 and VE-6 does not constitute a risk for the regional biosphere, not in the short term (during active mining), nor in the (very) long term after cavern abandonment.

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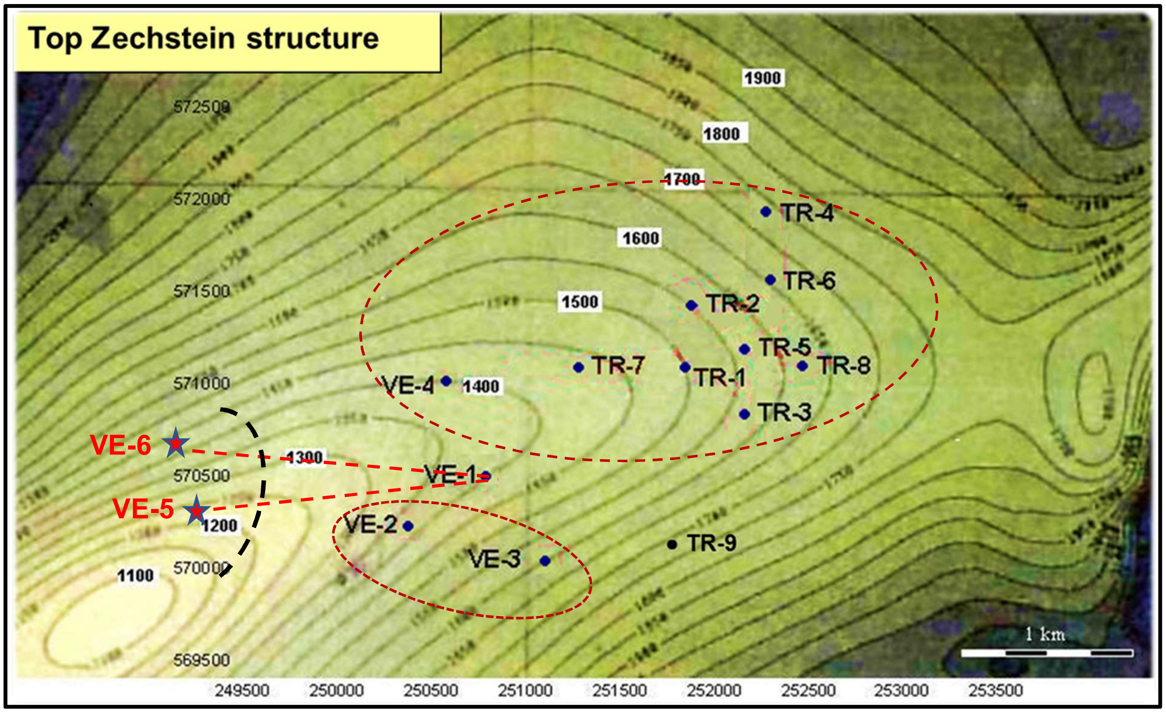
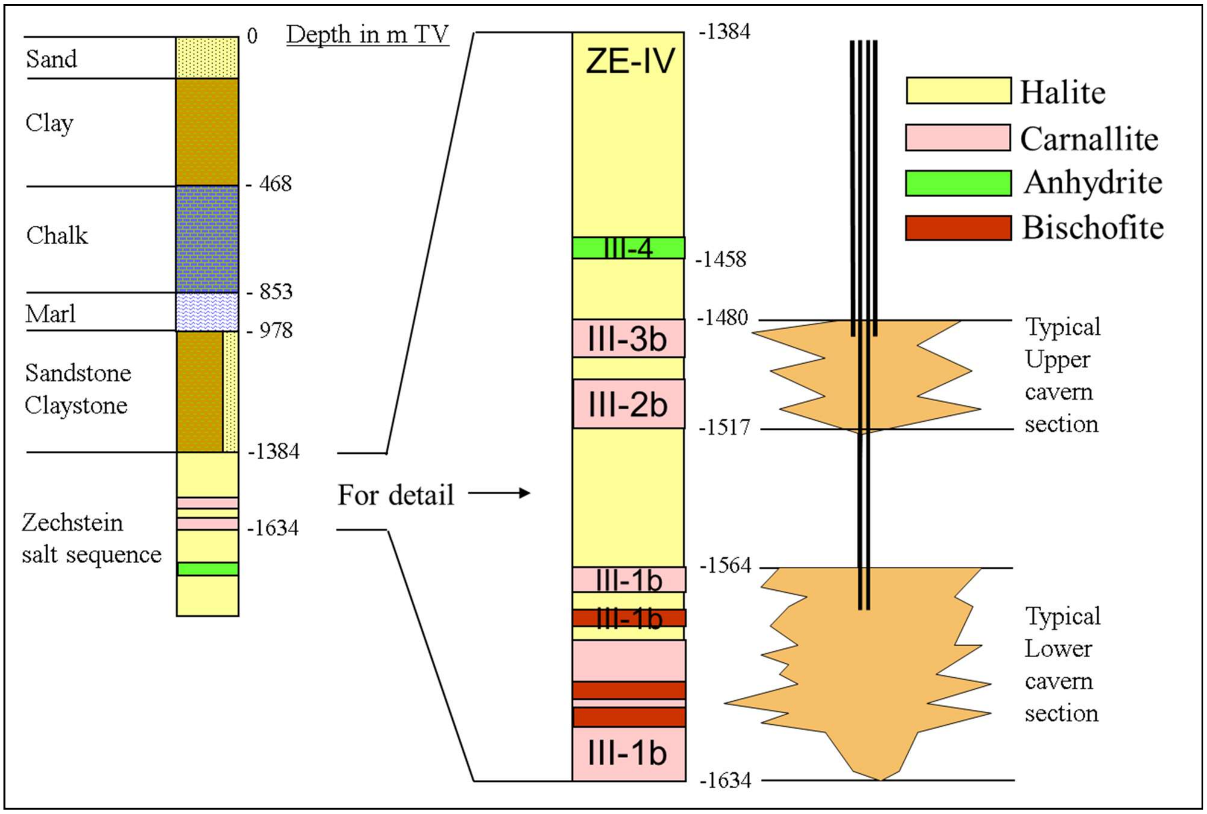
Attachment 1: Map of Nedmag cavern system 2017



Nedmag well positions projected on top of the Zechstein (ZE) pillow structure. Positions of the planned wells VE-5 and VE-6 are indicated by red stars. The VE-wells are drilled from location WHC-1 located above well VE-1 (dotted trajectories). The black dotted curve is the expected leaching boundary in the direction of the other VE-wells.

The positions of the current 4 VE-wells (WHC-1 location) and 9 TR-wells (WHC-2 location, located above well TR-**2**) are also shown. The dotted red ovals indicate mutual cavern connections in 2017 at the ZE-III-1b level. VE-1 and TR-9 are stand-alone caverns.

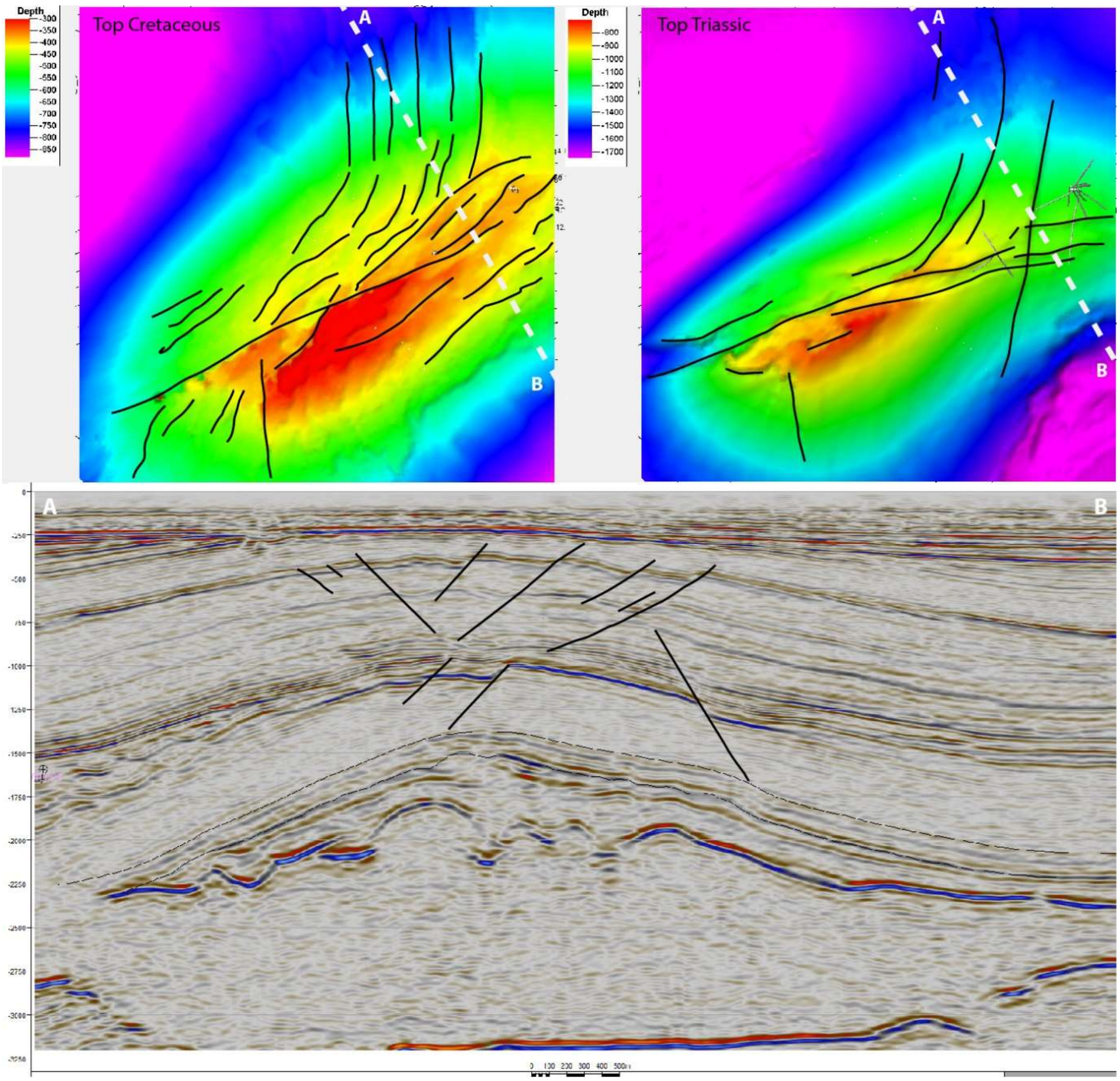
Attachment 2: Typical stratigraphy of the VE and TR cavern field



The magnesium salt extraction from the planned caverns VE-5 and VE-6 will only be performed in the Zechstein III-1b carnallite/bischofite sequence.

The overlying Zechstein III-2b/3b carnallite layers will not be produced.

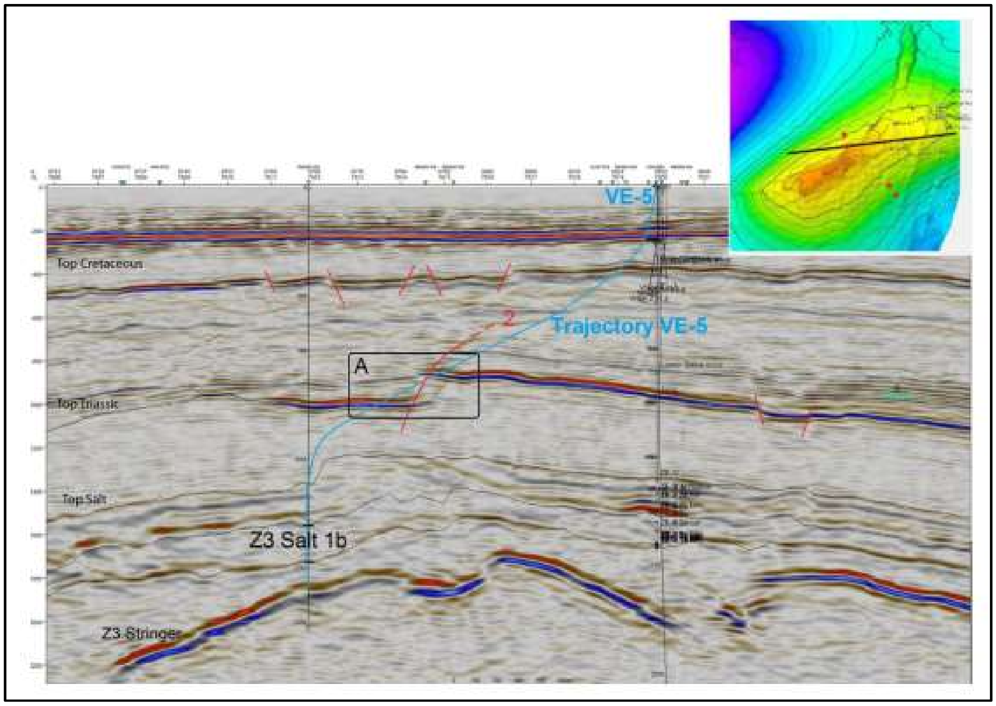
Attachment 3: Triassic and Cretaceous depth maps above Veendam salt pillow



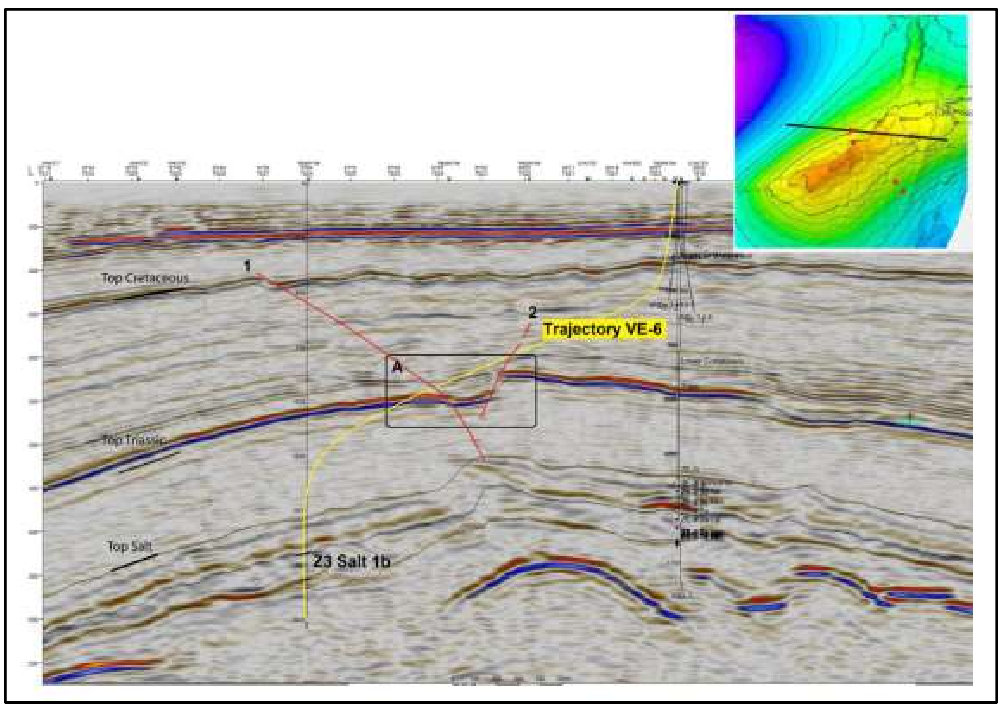
Top left figure: Top Cretaceous depth map with faults indicated by black lines.
Top right figure: Top Triassic depth map and faults. The tiny grey lines in the middle right section of the figure indicate the trajectories of the VE-wells and TR-wells into the Zechstein salt formation below the Triassic 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 4: Cross sections along planned well trajectories VE-5 and VE-6

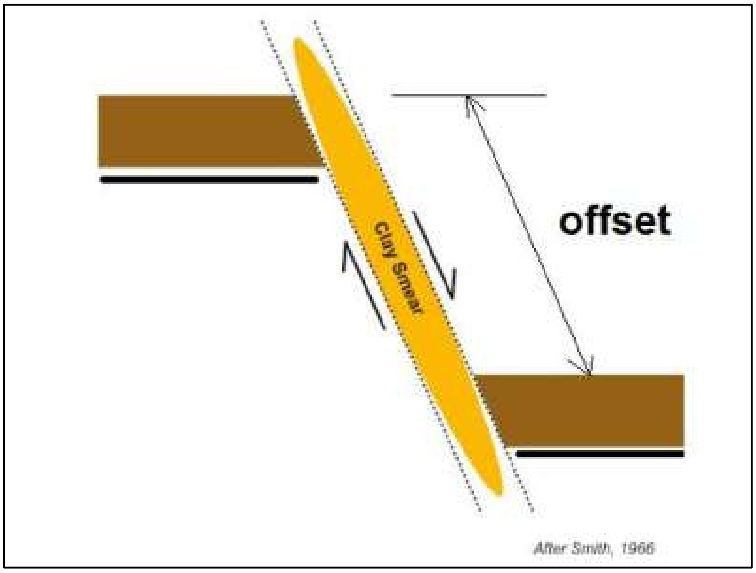


Right upper corner: Veendam salt pillow depth contour map, with cross section projected on map. Cross section shows well trajectory VE-5 (blue line) with major faults in zone A.



Right upper corner: Veendam salt pillow depth contour map, with cross section projected on map. Cross section shows well trajectory VE-6 (yellow line) with major faults in zone A.

Attachment 5: 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.

(Figure adopted from ref.12)

Attachment 6: 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.12).

*) Note: Volpriehausen Clay-siltstone and L.Volpriehausen Sandstone may not be present above the Nedmag cavern field.