

Isolation Strategy: Twenthe-Rijn brine field

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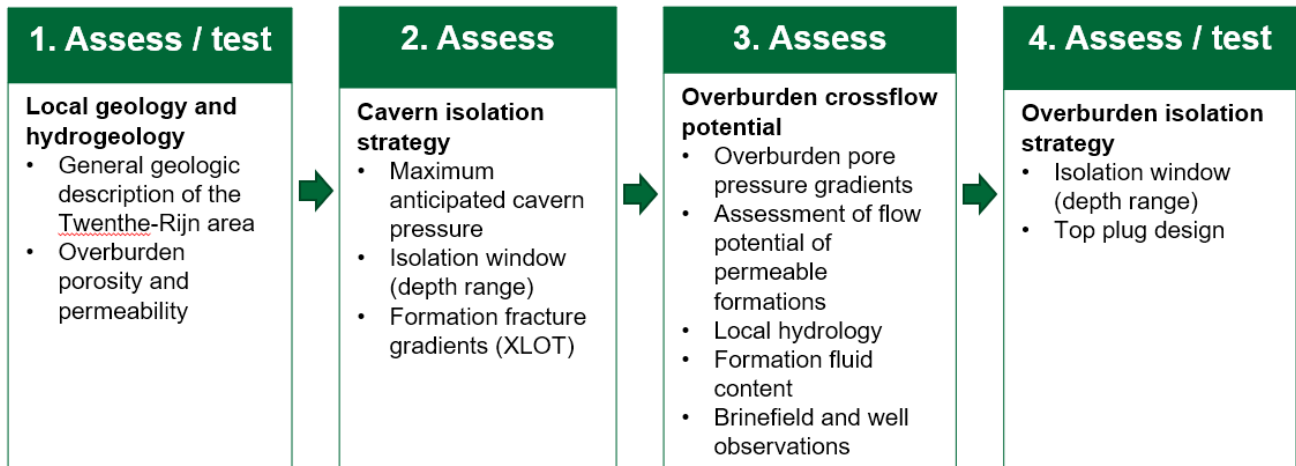
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1. Introduction

This isolation strategy describes the geological and geomechanical information related to well- and cavern abandonments of the Twenthe-Rijn area. The document was prepared by Nobian's Well Lifecycle Engineering and Brine field Technology departments. The general workflow for the isolation strategy is shown below.



Abandonment design of wells connected to salt caverns can be challenging. Throughout the process of assessing cavern abandonment it is important to keep in mind that regulatory requirements and industry “*best practices*” are based mostly on the oil- and gas industry (NOGEPA). The most notable difference compared to the solution mining industry is that most oil- and gas reservoirs are being abandoned with low remaining pressures within depleted reservoirs. While a worst-case scenario is often assumed for such reservoirs, where reservoir pressure returns to the virgin reservoir pressure (pore pressure), this is not the case for cavern abandonment within the solution mining industry. After cavern abandonment, cavern pressure will start to increase (mainly) through thermal expansion of cavern brine and cavern convergence by salt creep processes. These processes may result in cavern pressure values (much) higher than pore pressure. It is, therefore, important to design cavern abandonment barriers considering maximum anticipated cavern pressure during the entire abandonment lifetime.

The objective of this document is to present the assessments and design considerations related to salt cavern- and well abandonment within the Twenthe-Rijn brine field (see **Figure 1** on the next page). Throughout this report, the Usseler Es and Ganzebos area are considered part of the Twenthe-Rijn brine field and are included in this evaluation (see **Figure 2** in the next chapter). The Haaksbergen area is not yet included as geology within that region varies from the Twenthe-Rijn brine field.

Throughout this document, reference is made to regulatory requirements and industry standards:

1. Mining Regulation (Mijnbouwregeling) applicable from 1st of January 2022 to date (ref.1)
2. NOGEPA standard 45, 26th of July 2019 (ref.2)

When any of these reference documents is updated or progressive insights develop within the company or solution mining industry, this document will be re-evaluated and updated as required.

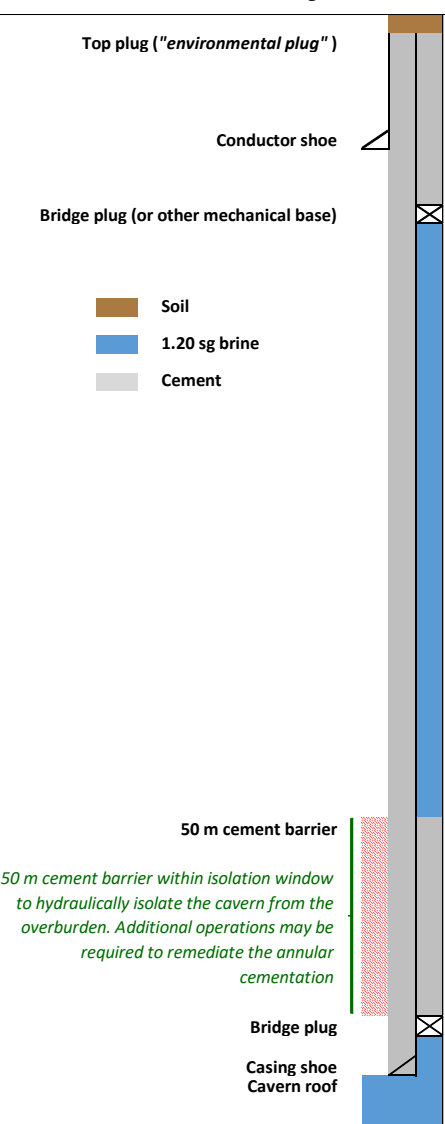
Draft P&A Design	Geology Group & Formation	Main concerns and topics evaluated	Report sections
 <p>Top plug ("environmental plug")</p> <p>Conductor shoe</p> <p>Bridge plug (or other mechanical base)</p> <p>50 m cement barrier</p> <p>50 m cement barrier within isolation window to hydraulically isolate the cavern from the overburden. Additional operations may be required to remediate the annular cementation</p> <p>Bridge plug</p> <p>Casing shoe</p> <p>Cavern roof</p> <p>Cavern bottom</p> <p>Soil</p> <p>1.20 sg brine</p> <p>Cement</p>	<p>3.0 m</p> <p>Quaternary</p> <p>North Sea Supergroup (NL)</p> <p>N2</p> <p>N1b</p> <p>N1a</p>	<p>Shallow groundwater contamination</p> <ul style="list-style-type: none"> - Hydraulic properties of the North Sea Supergroup (permeability) - Formation strength - Water production sites in the Twente-Rijn area - Flow of freshwater in the shallow subsurface 	<p>3.1</p> <p>5.1 - 5.5</p>
	<p>Upper Germanic Trias Group (RN)</p> <p>Muschelkalk (RNMU)</p> <p>Upper Röt Claystone (RNROU)</p> <p>Upper Röt Evaporite</p> <p>Intermediate Rot Claystone (RNROM)</p>	<p>Determining the P&A isolation window (formation barrier qualities)</p> <ul style="list-style-type: none"> - Formation tightness (permeability) - Formation strength: risk of fracturing by trapped cavern pressure from below, resulting in hydraulic communication with overburden 	<p>3.1 and 4.4</p>
	<p>Röt Evaporite (RNRO1E)</p> <p>Röt Salt (RNRO1)</p>	<p>Cavern pressure containment</p> <ul style="list-style-type: none"> - Formation tightness (permeability) - Formation strength: risk of fracturing by trapped cavern pressure from below, resulting in hydraulic communication with overburden 	<p>3.1 and 4.4</p>
		<p>Trapped brine pressure increase</p> <ul style="list-style-type: none"> - salt squeeze - thermal expansion of cavern brine 	<p>4.1 - 4.5</p>

Figure 1: Example P&A schematic for the Hengelo brine field. The well- and annular cement integrity shall be evaluated as per Nobian standards to evaluate potential remedial operations (ref.3). The main concerns and risks are presented as well as the sections of the Isolation Strategy covering these topics in more detail.

2. Twenthe-Rijn history and well architecture

Brine solution mining within the Twenthe-Rijn concession area has a history of over 80 years. During this period, different technologies evolved such as the drilling-, solution mining and monitoring technologies. Similar to these practical technological advancements, theoretical understanding of geomechanics related to cavern design and solution mining processes progressed. These changes in solution mining methods can be differentiated into five phases, each with its own specific characteristics and parameters. The different mining phases are graphically presented below in **Figure 2**. For this isolation strategy, the specifics of the different phases are irrelevant as they did not affect well architecture or any of the parameters important for the evaluation presented in this report. However, it is important to note that this isolation strategy only covers wells drilled during phase 1 through 4. Phase 5 are wells drilled in the “Ganzebos” area, on the South-West side the Boekelo fault zone. These wells are not ready for abandonment and are not covered by the evaluation presented in this isolation strategy as the geological setting is different.

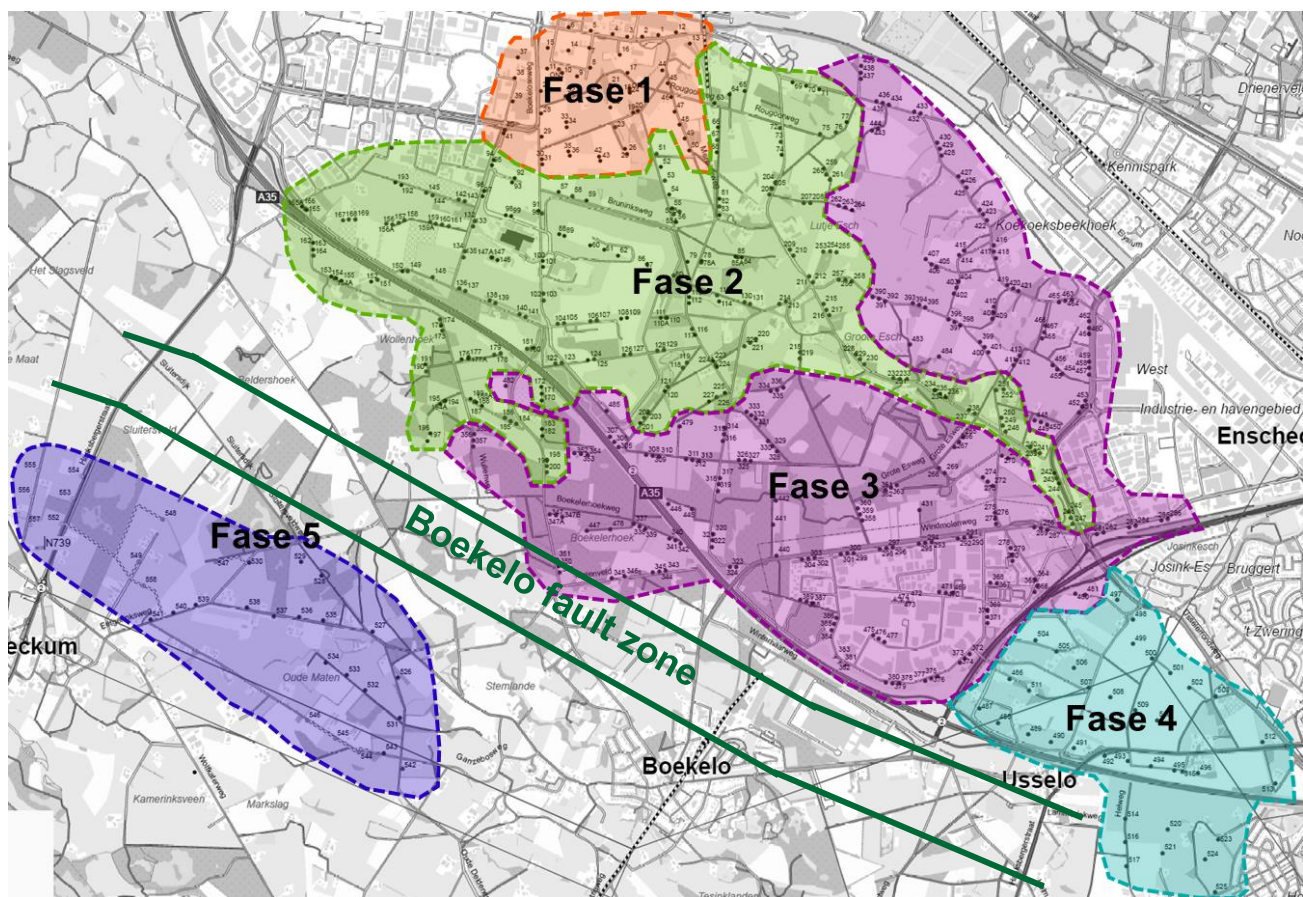


Figure 2: Graphical presentation of different mining phases differentiated based on technological and theoretical advancements.

2.1. Well design

The wells drilled within the area of the Twenthe-Rijn brine field all have very similar design: the wells (generally) consist of a conductor casing piled to a depth of approximately 20 m to 40 m below ground level, based on resistance during the conductor installation operations; a steep increase in resistance during piling indicated a competent silt- or clay layer and piling operations were then stopped. The conductor casings consist of either 16", 13-3/8" or 10-3/4" casing. At some well locations, the conductor has been removed after drilling operations finished.

Subsequently, the wellbore was drilled to, and a last-cemented casing set in, the Main Röt Evaporite salt layer (only well HEN-01 was drilled to the underlying Zechstein formation and is therefore excluded from this Isolation Strategy). All last-cemented casings have been cemented to surface: standard procedure was to set cement applying a plug-type cementation. Cement was pumped until cement returns were observed at the drill rig shakers ensuring cement returns from the annulus to surface. Subsequently, the cement pumps were stopped

and the well shut-in to prevent u-tubing of the cement, even if the plugs had not bumped yet. After hardening of the cement, the plugs and (excess) cement within the last-cemented casing and rathole were drilled. Drilling operations then continued until clay- or sandstone cuttings from the Solling formation were observed over the shakers indicating the full Röt salt layer had been fully penetrated.

Some wells in the Twenthe-Rijn brine field showed cement sag in the annulus while the cement was hardening, likely due to losses into permeable and unconsolidated formations (see section 3.1 and chapter 5.1 for more details). Remedial cementing operations were performed on wells where cement sag resulted in an open annulus near surface.

When production from a well is suspended, production tubings are removed and a cement quality assessment of the last-cemented casing is currently being done using wireline tools (CBL-VDL and ultrasonic). The wireline results are used to evaluate if cement quality is sufficient for hydraulic isolation within the defined isolation windows, or whether remedial actions are required as described in Nobian procedure "*Cement Barrier Design and Verification Procedure*", version 1.0, dated 25th of November 2021 (ref.3).

3. Geological assessment of the Twenthe-Rijn area

The first step in the process of well- and cavern abandonment design is a geological evaluation of the area. The geological evaluation of the Twenthe-Rijn brinefield was conducted in cooperation with the Nobian Brine field Technology department and third parties. The geological evaluation is related to the first step of the isolation strategy workflow presented in the introduction of this report and Mining Regulation article **8.5.1.2**:

Before abandoning a well, the operator identifies all zones with flow potential and evaluates which measures are required to prevent flow of gasses or fluids to- or from layers out of the zone with flow potential, or to surface.

The purpose of the geological evaluation is to identify which layers, or combination of stacked layers (zones), are permeable and which formations may act as a seal. When considering abandonment design, the ultimate objective is to prevent crossflow between any formations with flow potential and prevent contamination of the (shallow) hydrology. NOGEPA standard 45 defines flow potential as:

Flow potential is generally related to layers which show permeability and a pressure differential to other formations or surface. [...] Several layers may be grouped in a zone with comparable fluids and/or pressure regimes if isolation between layers is not required to prevent damage. Such layers may be isolated from other zones and the surface by a common barrier.

P&A barrier design should be done in the context of mitigating risks to people, the environment, and potential natural resources (freshwater) in the area. Barrier placement is based on the geological evaluation in compliance with:

Mining Regulation article **8.5.2.1**:

- The operator abandons a well by:
- Placing a barrier across each sealing formation.
 - Placing a top plug; and
 - Removal of well material near ground level

Mining Regulation article **8.5.2.2**:

- The operator designs a barrier across a sealing formation such that the barrier is at the same depth as the sealing formation, which is:
- Impermeable and of sufficient strength to hold the expected maximum pressure of gasses and fluids at that depth.
 - Shows no faulting and
 - Is above a zone with flow potential

This chapter presents the geological assessment of the Twenthe-Rijn area.

3.1. Twenthe-Rijn Geology

Several geological evaluations were performed for the Twenthe-Rijn brine field by Geowulf. Specifically, a permeability and porosity evaluation is presented in report "*Final Report Aquifer Properties of the MRE overburden (detailed Geology)*" (ref.4). No hydrocarbon bearing zones have been encountered while drilling the wells of the Twenthe-Rijn brine field. A summary description of the formation lithologies found in the Twenthe-Rijn area, based on the various reports prepared by GeoWulf (ref.5), is discussed in the section and graphically presented in **Figure 3**. The reports prepared by Geowulf consider the entire Twenthe-Rijn brine field and should be used as reference document for P&A design of individual wells. A well-specific lithostratigraphic column identifying formation tops, aquifers, flow potential, sealing formations and barriers shall be part of the well-specific P&A work programs. An example is shown in **Figure 1**.

Hengelo License Area; Summary Aquifer Properties

Refer to report GL21.1102 for more information

No indications for the presence of hydrocarbons are reported, pores are assumed water filled

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chrono-strat.	litho-strat.	Lithology	Lithological summary & facies	thickness (m)	reg code	porosity /meas.	permeab /meas.	aquifer properties
Quatern.			periglacial coarse clastics	included in N2				good aquifer
Tertiary	North Sea Supergroup	N2	marine very fine argillaceous sands and silty to sandy clays	TWR: 54 - 135 UES: 43 - 68 Gbos: 107 - 142	N2			good aquifer
		N1b	marine silty to very fine sandy clays with locally very fine sands	TWR: 9 - 19 UES: 9 - 13 Gbos: 10 - 14	N1b			aquifer
		N1a	marine very fine to fine (medium) glauconitic sands	TWR: 0.5 - 6 UES: 2 - 5 Gbos: 0.7 - 3	N1a			good aquifer
Cretaceous Lower Cretaceous	Rijnland Gp. Vlieland Fm.		marine silty claystones	Molenveld only (wells 348//351) 37 - 79	KNNC	regionally no porosity		non-aquifer
			coastal marine medium - coarse sandstones	Molenveld only (wells 348//351) 30 - 77	KNNS	regionally 30%		good aquifer
	Niedersachsen Group		marginal marine to lagoonal claystones with plantfragments, bioclastic limestones and micritic limestones	TWR: 0 - 127 UES: 29 - 58 Gbos: 0 - 123 unit E only in wells, 343//346, 348 555, BKM02	SK	no por loc 5-10%	unit E: no perm unit D: loc 100 - 500mD	E: non-aquifer D: loc aquifer A-C: possible v. poor aquifer
Malm			lagoonal to marine organic rich claystones	TWR: 0 - 20 UES: 0 - 11 Gbos: 9 - 65	AT	no porosity	no permeability	non-aquifer
Jurassic Liassic	Altena Group		lagoonal to marine organic rich claystones	TWR: 0 - 20 UES: 0 - 11 Gbos: 9 - 65	AT	no porosity	no permeability	non-aquifer
Triassic	Muschelkalk	B	coastal dolomites, calcareous dolomites and argillaceous dolomites	TWR: 0 - 63 UES: 16.5 - 54.2 Gbos: 23 - 57	RNMU-B	poor por loc 6-12%	very poor perm. < 1mD	non-aquifer
		A	coastal calcareous dolomites and claystones	TWR: 0 - 68 UES: 61 - 66 Gbos: 44 - 61	RNMU-A	no porosity	no permeability	non-aquifer
	Upper Germanic Trias Group	Claystone Mb.	coastal plain dolomitic and anhydritic silty claystones	TWR: 69 - 149 UES: 137 - 146 Gbos: 103 - 124	RNROU	no porosity	no permeability	non-aquifer
		Evaporite Mb.	coastal sebkha thin anhydrite bed	TWR: 0.2 - 2 UES: 0.3 - 1.5 Gbos: 0.3 - 1.7	RNRO-2	no porosity	no permeability	non-aquifer
		Int.R.Clst.Mb.	coastal plain dolomitic and anhydritic silty claystones	TWR: 15.5 - 33 UES: 24 - 27 Gbos: 20.5 - 24	RNROM	no porosity	no permeability	non-aquifer
		MRE.Mb.-E	coastal sebkha anhydrite and claystone beds	TWR: 5 - 14 UES: 10 - 13 Gbos: 10 - 13	RNRO1-E	no porosity	no permeability	non-aquifer
		MRE	coastal sebkha halite with subordinate anhydrite and claystone beds					

Figure 3: Lithostratigraphic column and permeability evaluation summary prepared by GeoWulf and presented in report GL21.1102 (ref.4).

The description below is a summary from Geowulf report GL21.1102 (refs.4,5). An extensive data collection was obtained over the decades of drilling in the Twenthe-Rijn area. Below information is based on extensive cutting analyses, wireline measurements and core material retrieved from various wells (e.g. from TWR-480, TWR-534 and TWR-558, refs.6,7,8,9).

North Sea Supergroup

The North Sea Supergroup in the Twenthe-Rijn area was previously not subdivided formally into the Lower-, Middle- and Upper North Sea Groups. Instead, an unofficial subdivision of the N1a, N1b and N2 (from bottom to top) was applied to describe the Tertiary formation. Depth of the base of the North Sea Supergroup ranges from approximately 70 m below ground level in the southeast to 156 m below ground level in the west of the area, as shown in Appendix 1. More recently, a study into the Tertiary formations was performed by GeoWulf to further detail the respective members of the North Sea Supergroup in the Twenthe-Rijn area (ref.11). A graphic representation of the members is presented below in **Figure 4**.

Chronostratigraphy	Lithostratigraphy				Unconformities
	regional code	stratigraphic name	<i>changed code</i>	<i>changed name</i>	
Quaternary	NU	Upper North Sea Group			Pleistocene erosion
Pliocene					
Miocene					Savian phase
Oligocene	NM	Middle North Sea Group			
	NMRF	Rupel Formation	<i>NMRU</i>		
	NMRFB	Boom Clay Member	<i>NMRUBO</i>		
	NMRFS	Berg Sand Member	<i>NMRUBE</i>		Pyrenean phase
Eocene	NL	Lower North Sea Group			
	NLFF	Dongen Formation	<i>NLDO</i>		
	NLFFB	Asse Clay Member	<i>NLDOAS</i>		
	NLFFS	Brussels Sand Member	<i>NLDOBR</i>		
	NLFFY	Ieper Member	<i>NLDOIE</i>		
	NLFFT	Basal Dongen Tuff. Mb	<i>NLDOWY</i>	<i>de Wijk Mb</i>	
	NLFFD	Basal Dongen Sd Mb	<i>NLDOOO</i>	<i>Oosteind Mb</i>	
Paleocene	NLLF	Landen Formation	<i>NLLA</i>		
	NLLFC	Landen Clay Member	<i>NLLALI</i>	<i>Liessel Mb</i>	
	NLLFS	Heers Sand Member	<i>NLLAOR?</i>	<i>van Orp Mb</i>	Laramide phase

Figure 4: Stratigraphic summary of the North Sea Supergroup in the Hengelo area.

The study is based on the integration of lithological, biostratigraphical and wireline data from wells in the Twenthe-Rijn area as summarized in the next paragraphs. An example cross-section through the Hengelo brine field is presented in **Figure 5**. The cross section shows the North Sea Supergroup dips towards the North-West and the members of the North Sea Supergroup subcrop towards the Southeast.

A1: Correlation Panel Reference wells TWR, line-up NAP

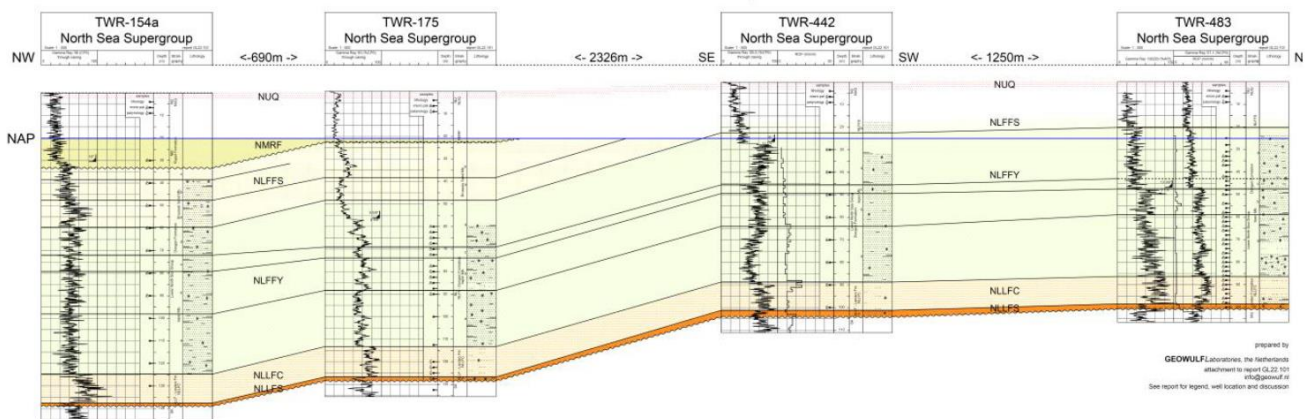


Figure 5: Cross section of the North Sea Supergroup from West to East in the Twente-Rijn brine field (ref.11).

The basal unit of the Tertiary formations in Hengelo consist of unconsolidated very fine clastics, and very fine to medium clastics in the basal unit formerly designated as member N1a, now identified as the Heers Sands. Estimated porosities are high, probably up to 30%. While drilling the wells in the Twente-Rijn brine field, considerable mud losses and water gains have been observed which are related mainly to unit N1a. Based on lithological, biostratigraphical and wireline evaluations on the Twente-Rijn wells and offset exploration well DED-2 by GeoWulf, permeabilities of >500mD are estimated (ref.11). A list of wells that were studied is presented in Appendix 2.

The overlying Landen Clay Member, previously designated N1b, consists of unconsolidated clays of a silty and sandy nature. This section is the most impermeable in the Tertiary succession in the area. Due to its unconsolidated nature, it is unlikely to resist any pressures, but it cannot be excluded to act as a (poor) barrier for hydrostatic pressures.

The Landen formation in the area consists of a relatively thin section of greyish to brownish grey silty and very fine sandy claystones with intercalated sand / sandstone beds. At the base of the formation a thin but very porous sand bed is found lithologically representing the lateral diachronal equivalent of the regionally recognized Heers Sand Member. These sands have a thickness of only a few meters and they are found in the entire area. During the drilling of many of the wells these sands have caused considerable mud losses or gains. Lithologically, the sands are very uniform, grain sizes are fine with only traces of medium sized grains; grain shapes are angular in general, glauconite is abundant.

The Dongen formation in the area comprises a package of very fine glauconitic sands and sandy clays which lithologically do not compare well with occurrences regionally. The formation is subdivided in a thin Basal Dongen Sand member, Basal Dongen Tuffite member, a thick section of Ieper (clay) member, Brussels Sand member and Asse Clay Member. It is noted that in a more distal setting, where the Ieper Member is developed as a thick section of slightly silty to silty claystones, the member acts as a seal. However, in the Hengelo area no substantial burial has occurred. Furthermore, the Ieper Member is extremely sandy and can be classified as an argillaceous sand rather than a sandy clay. The Brussels Sand member is considered an aquifer.

The Oligocene Rupel Formation belongs to the Middle North Sea Group and it unconformably overlies the Lower North Sea Group. The unconformity is related to the Pyrenean tectonic phase. The formation is recognized on a regional scale where it is subdivided in a lower Berg Sand Member and an upper Boom Clay Member. Lithologically, Rupel Formation in the Hengelo area consists of very fine glauconitic sands; essentially not very different from the underlying Dongen Formation but, the glauconite has fine to medium grain sizes whereas the Dongen glauconite is very fine to fine. Rupel Formation lithologies are also non to very slightly calcareous only, compared to the more calcareous section underlying the unconformity. The Berg Sand Member is found mainly as fine to medium and locally coarse loose quartz grains with fine to medium glauconite. The Boom Clay Member comprises a section of light greenish grey to light brownish grey slightly silty clays with minor calcareous concretions.

Quaternary sediments are behind the conductor and could not be studied. Regionally, lithologies consist of mainly coarse clastics with high estimated porosities up to 30% accompanied by high permeabilities.

The varying clay- and sand content of the North Sea Supergroup results in varying permeabilities, including some high permeabilities in the sandy intervals (in the order of Darcies). Additionally, the mechanical competence of the Tertiary and Quaternary formations is classified as: non to very weak (ref.11). Therefore, the North Sea Supergroup is not considered tight or a barrier formation.

Vlieland formation (Rijnland group, KN)

In the Twente-Rijn area, the Vlieland Claystone (KNNC) is conformably overlying the Vlieland Sandstone (KNNS). The formations are only present in the Molenveld area, which were drilled in the vicinity of the Boekelo fault zone (wells TWR-348-349-350-351, see Appendix 3).

The Vlieland Sandstone formation is overlain by the sealing Vlieland Claystone formation, which is again overlain by the aquifers of the North Sea Supergroup aquifer. According to the geological interpretation by GeoWulf based on available gamma-ray logs and cuttings analysis, the Vlieland Sandstone is present in well TWR-348 but the Vlieland Claystone is absent (pinch-out). Instead, the Vlieland Sandstone is overlain by the North Sea Supergroup.

No sample material is available for study, but porosities and permeabilities of the Vlieland Sandstone are assumed very high. Bentheim sandstone in the wider area has porosities over 30% with permeabilities of many Darcies. However, no overpressures have been observed and the formation is considered to have no flow potential.

The Vlieland Claystone is considered a tight formation, with no meaningful vertical permeability.

Niedersachsen Group

The Niedersachsen Group is informally subdivided into SK-A to SK-E. The regional subdivision in Weiteveen and Coevorden formations is not followed for practical reasons.

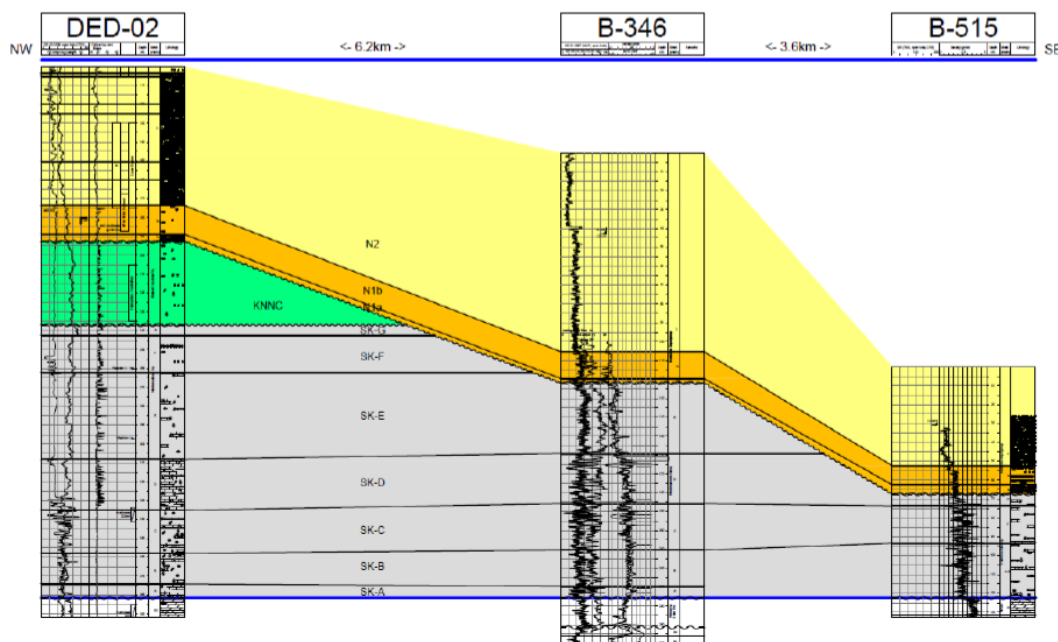
Unit SK-A represents the transgressive part overlying the unconformity and, therefore, lithologies show more lateral variation. The unit is (very) argillaceous in general with some thin layers of silt/sandstone with locally fair porosities. No information on permeability is available, but the section predominantly consists of claystones with subordinate thin limestone beds and permeabilities are considered very poor to absent in the units A to C. Local presence of poor reservoir sections cannot be excluded and the section is classified as 'possible very poor aquifer'.

Unit B is more argillaceous and claystones are calcareous in general; micritic limestones present are rich in plant fragments; in the lower half of this unit much gypsum nodules occur.

Unit C consists of interbedded claystones with common ostracods and micritic limestones with plant fragments

Unit SK-D consists of bioclastic limestones with claystone intercalations and fair porosities can be expected in the shell beds. Mud losses have been reported in this interval and the unit SK-D has to be considered an aquifer at least locally. However, SK-D is unconformably overlain by the North Sea Supergroup in nearly all instances and forms part of this aquifer package **Figure 6**.

SK-E consists of claystones only and is considered tight.



DED-02 - TWR - Ganzebos area, line-up base SK unconformity correlation stratigraphical units for petrophysical properties

Figure 6: A cross section through wells DED-02 (North-West) and TWR-515 (South-East). The member with potentially fair porosities (SK-D) is unconformably overlain by the porous and permeable North Sea Supergroup and is, therefore, considered part of the same aquifer zone.

Altena Group

Altena Group sediments of the Aalburg and Sleen formations both consist of consolidated organic rich claystones and they are tight.

The sections can be subdivided into a lower part (A) and an upper part (B). Unit B consists of very light to light grey non silty and non-calcareous claystones which are locally pyritic. Traces of clear and pale reddish gypsum nodules occur. In some wells, the basal one meter of unit B has pale reddish-brown shades. The lower unit A consists of grey to brownish grey and locally slightly purple to reddish grey, non-silty and non-calcareous claystones which are slightly bituminous. A siltstone is present at the base of unit A.

In a larger area, thick sections of Altena Group sediments are preserved. Just South of the Twente-Rijn area, up to 200 m is present. North-West of the Gronau fault zone (some 10 km North-West of the brinefield), up to 500 m section occurs. Thick occurrences of Altena group sediments are nearly exclusively Aalburg formation; only in well Oldenzaal-01 was Posidonia formation and Werkendam formation documented. In the Twente-Rijn area, where Sleen formation is overlain by the Niedersachsen group deposits, truncation can therefore be dated as Mid- to Late Kimmerian.

Muschelkalk Formation (RNMU)

Muschelkalk in the Hengelo area represents the regional Lower Muschelkalk Formation; in the Hengelo area it is subdivided into the informal units A and B. Because flow potential was suspected from the Muschelkalk formation (see Chapter 5 for more details), the Muschelkalk has been extensively studied for this report. The following data was evaluated (detailed in ref.4):

- Cutting evaluations from wells, e.g. TWR-480 and TWR-558 (refs.6,8)
- Density logs of well TWR-515 (ref.10)
- Microscopic evaluations on cores from TWR-558 (ref.6)
- Poro/perm measurements performed on cores from TWR-558 by Panterra (ref.12).

- Poro/perm data from offset well TUB-12 (ref.13)
- DST data from offset well TUB-12 (ref.14)

The lower unit A consists of argillaceous calcareous dolomites and limestones and claystones. Samples have been studied of several wells and no to negligible porosities have been observed, consequently permeabilities are absent. A density log of TWR-515 indicates no porosities present, including the cleaner carbonites. The unit is considered tight.

The upper unit MU-B is subdivided in B1 to B5. Each unit consists of a repetition of beds with argillaceous dolomites in the lower parts which become gradually cleaner upward. The saccharoidal dolomites show porosity and occur as patches or thin laminae. Porosity distribution is not uniform, which probably limits the development of good permeabilities. Unit B is characterized by increasing amounts of clean saccharoidal dolomites towards the top. The unit is considered tight.

Röt Formation

The Röt formation has been the topic of extensive research as caverns are being leached in the respective salt section. The Röt formation lithological description is based on cutting evaluations and cores obtained from wells TWR-478, TWR-480, TWR-483, TWR-495 and TWR-515 (refs. 5,7,8,9,15,17). The Röt formation conformably overlies the Solling formation and is conformably overlain by the Muschelkalk formation. The Röt formation is subdivided into four members, all of which are present throughout the Twenthe-Rijn area, and all are considered tight:

1. Upper Röt Claystone member (RNROU)
2. Upper Röt Evaporite member (RNRO2)
3. Intermediate Röt Claystone member (RNROM)
4. Röt Evaporite (salt) member (RNRO1)

The Upper Röt Claystone member (RNROU) consists of claystones. Gypsum or anhydrite also occurs. Siltstones with dolomite cement and/or gypsum/anhydrite cement and mica are found most frequently in the upper and lower parts of the Upper Röt Claystone section. No porosity is found present and consequently permeabilities are absent. Locally and regionally no indication for any flow in these units can be found.

The Upper Röt Evaporite member (RNRO2) is a thin section of anhydrite which is locally silty and dolomitic. The Upper Röt Evaporite member is generally very thin with an average thickness of ± 0.7 m (maximum thickness of 2.0 m).

The Intermediate Röt Claystone member (RNROM) consists of claystones with siltstone beds and laminated claystones. The Intermediate Röt Claystone Member does not show significant lithological variation in the Hengelo area. The member has a uniform thickness of approximately 23m. Thinner sections are the result of faulting.

The Röt Evaporite (salt) member (RNRO1) consists of halite sections, with interbedded anhydrites and claystones at the top (RNRO1E). Cavern development and salt leaching within the Twenthe-Rijn area is performed within the halite section of the Röt Evaporite member which is subdivided into the informal units A to D. Generally, part of unit C and unit D form the roof of the caverns to be abandoned.

The Röt formation is considered as a single impermeable zone apart from the caverns developed in the halite section of the Röt Evaporite, which are considered to have flow potential.

Solling Formation

The Solling Fm. in the area consists of a package of claystones which are generally silty and dolomitic. Claystones have reddish brown shades, locally millimeter to centimeter light greenish grey reduction spots are found.

Thin beds of siltstones and very fine to fine sandstones begin to occur some 2.5m below the top of the Solling Formation. Clean, non-argillaceous siltstones and sandstones generally have light greenish grey shades. At other levels silt/sandstones are argillaceous and gradational with silty claystones and they have a reddish-brown color.

Commonly, grainsizes are up to 100 microns and they do not exceed 200 microns. Non argillaceous siltstones and sandstones are tightly cemented with halite. Only in BKM-02 locally minor amounts of admixed dolomite cement are found. In many cases, halite is the only cement type.

Especially in the older cores of wells TWR-120 and TWR-480, sandstones with estimated porosities of some 25% are found, and the halite cement was interpreted leached.

3.2. Faulting in the Twenthe-Rijn area

Tectonic regime

The faulting regime in the Hengelo area has been extensively studied as described (ref.15), as summarized in this section. During the Triassic period, the Early Kimmerian movements continued with movements along the Mid-Netherlands Fault Zone. Uplift and erosion occurred in the southern Netherlands where a system of NE-dipping fault blocks was formed, separated by WNW-trending faults. Local intrusion of Zechstein salt occurred along these faults. In the eastern part of the Netherlands a system of WNW-ESE trending faults was active, including the major Gronau fault zone. This fault-zone consists of three separate branches of which the so-called South Gronau Fault is located just north-east of the city of Hengelo. During the Early Kimmerian phase, this fault was reactivated under influence of an extensional regime, during which many new individual faults were formed. Salt accumulation occurred, especially along this South Gronau Fault.

During the Late Kimmerian tectonic phases the main tectonic elements in the Dutch subsurface, mainly former NW-SE faults, were reactivated. Also the Gronau Fault Zone, located at the transition from the Central Netherlands Basin in the West and the Lower Saxony Basin in the East was reactivated. This fault zone mainly showed normal faulting, but also dextral strike-slip faulting and growthfaulting took place (syndimentary faulting).

During the Late Cretaceous and Early Tertiary compression took place as Europe and Africa collided and many fault systems inverted. Four tectonic phases can be recognized: (1) the Subhercynian phase (Late Cretaceous), (2) the Laramide phase (Paleocene), (3) the Pyrenean pulse (end of the Eocene) and (4) the Savian pulse (end of the Oligocene). Large parts of the topography that was created during the Subhercynian compressional phase were eroded at the end of the Cretaceous and the beginning of the Tertiary after uplift and major sea level drops, causing the major Laramide unconformity at the base of the Tertiary (Base North Sea Group deposits).

During many of these phases, the pre-existing rift-basins were inverted during reactivation of normal faults. Inversion-related uplift resulted in thinning of Cretaceous and Lower Tertiary deposits. As most faults run NW-SE, the more N-S or NNW-SSE oriented compression caused dextral strike-slip movements. Many differences can be seen in the structural style of the inverted basins, which are related to the present and thickness of Zechstein salt deposits, both in Dutch basins (ref.18) and in basins in NW Germany (ref.19).

Also, the Gronau Fault Zone was reactivated and inversion led to thrust faulting. Being located at the transition from the Central Netherlands Basin to the Lower Saxony Basin, inversion of this fault zone is unclear. The Central Netherlands Basin is suggested to have been inverted strongly during the Subhercynian and Laramide phases and also during the Pyrenean pulse. In contrast, the Dutch sector of the Lower Saxony Basin has only been mildly inverted, but the central sectors of this basin were strongly inverted during the Subhercynian and Laramide phases, creating thrusts and flower structures. During these compressional phases, probably most of the earlier Kimmerian vertical movements along the Gronau Fault Zone were compensated. Which type of structural style was active in the Gronau (and Boekelo) Fault Zone is difficult to say and may differ strongly from place to place, depending on the local presence and thickness Zechstein salt deposits.

These compressional phases were followed by “relaxation” and a more extensional regime came into existence. Regional subsidence took place during Middle Tertiary times, during which formation of the Cenozoic Rhine Graben system took place, both to the southwest of the area of interest (Roer Valley Graben), to the south (Lower Rhine Embayment) and to the east (Rhenish Massif and Leine Graben to the east of it).

Faults identified in the Twenthe-Rijn area

Faults evaluation is based on extensive analyses of the geology (gamma-ray logs and cutting evaluation) of all the wells in the Hengelo Brinefield, yielding a very good correlation where even small faults could be identified. These small-scale faults often form part of larger scale fault systems and identification of the small faults enables

the reconstruction of the geological model. A map showing the main faults, categorized into groups of maximum present-day offset, is presented in Appendix 4.

Various core analyses have identified the faults to be sealing. For example, cores retrieved from wells TWR-480 and TWR-495 showed gypsum filled fractures. In none of the core material retrieved have open fractures been identified.

4. Cavern Isolation Strategy

This chapter describes the considerations regarding isolation of the cavern, which is considered to have flow potential as future cavern brine pressure is likely to increase.

4.1. Cavern stability and safety

Cavern stability is a function of the tension in the cavern roof and loading of the pillars of rock salt between neighbouring caverns. Based on calculations by the Bundesanstalt für Geowissenschaften und Rohstoffe, Nobian applies the following stability criteria (ref.20):

- Remaining cavern roof shall consist of 5 m of Rot Salt C and Anhydrite layer. If salt D is present, at least 10 m combined thickness of salt D and Anhydrite remain.
- Cavern dimensions are limited to a cavern height of 40 m and roof span of 120 m.
- Salt pillars shall be loaded to a maximum of 30% of their calculated strength.

Each cavern in the Hengelo Brine field has been evaluated for cavern- and pillar stability. If cavern parameters are according to above criteria, the cavern is considered *stable*. Additionally, well-specific evaluations were prepared by RESPEC focusing specifically on pillar deformation under increased loading (ref.21).

Cavern safety is related to potential cavern migration. Conservatively, every cavern is evaluated for potential cavern migration by roof fall regardless of the roof stability analysis outcome. Safety analysis focusses on the maximum cavern migration and potentially resulting sinkholes. Only caverns where potential migration is limited to 40 m below Tertiary formations are considered *inherently safe*.

This document is only applicable to caverns which are considered *stable* and *inherently safe*. Caverns which do not comply with these statements require cavern-specific evaluations and potential backfilling.

4.2. Salt stress and cavern convergence

An evaluation of the maximum anticipated cavern pressure development is the second step of Nobian's abandonment design. Predicting maximum anticipated cavern pressure during the abandonment phase of a shallow cavern (<500m) is complex because pressure trends need to be extrapolated over long timescales while they are affected by various and varying processes over time. Within Nobian, the evaluation of the maximum anticipated cavern pressure is performed in cooperation with the Brine field Technology (BFT) department. Processes which are considered include, but are not limited to: brine thermal expansion, cavern convergence by salt creep and potential brine leak-off. In-situ aspects such as roof stability or existing hydraulic communication with the under- or overburden may also require a well-specific evaluation. This step in the design process relates to Mining Regulation article **8.5.1.3**:

When a well is abandoned, the operator shall place effective and durable barriers which prevent flow of subsurface gasses and fluids through sealing formations to other formations or surface.

Only when the maximum anticipated cavern pressure is known, can effective and durable barriers be designed which will prevent flow from a cavern to overlying permeable formations. Studies are currently (2021) ongoing to evaluate anticipated cavern pressure evolution for the first 100 years after abandonment. Furthermore, long-term pressure trends of shut-in caverns are not yet available due to the timescale of the processes. Therefore, assumptions related to maximum anticipated cavern pressure are very conservative until further information becomes available:

The **maximum anticipated cavern pressure** results from assuming a tight cavern as long as brine pressure does not exceed the minimum principal stress of the surrounding Röt salt layer. Salt creep will continue until the effective stress equals zero, where the effective stress ($\sigma_{t,eff}$) is defined by the difference between cavern pressure (P_{cavern}) and in-situ stress of the rocksalt (σ_t , assumed equal to the lithostatic gradient). When brine pressure exceeds the stress of the rock salt, permeation is assumed to occur as presented in Appendix 5.

The presented assumptions are valid because creep closure rate is a decreasing non-linear function of cavern brine pressure and permeation rate through the cavern wall and roof is an increasing function of cavern brine pressure. One can expect creep closure and permeation rates to reach an equilibrium. It is assumed such an

equilibrium occurs at the value of the lithostatic gradient, based on salt permeation tests as function of the effective stress (see Appendix 5, refs.22,23).

Based on the previously stated assumptions, the maximum anticipated cavern pressure is based on the minimum principal stress value, which occurs at the shallowest depth where rock salt is exposed to cavern brine. In the Twenthe-Rijn area, this is generally the depth of the last-cemented casing shoe above the cavern roof. However, the cavern roof may have been leached behind the last-cemented casing, in which case the shallowest exposure occurs at the shallowest depth of the cavern roof. A well specific evaluation of the pressure build-up may be possible if sufficient data is available. Such a well-specific evaluation shall be included in the P&A work program.

Salt behaves plastically under loading, yielding an approximately isostatic stress regime within the salt body. An extended leak-off test, or mini-fracture test, was performed on the Röt salt C section of well TWR-448, yielding a (minimum principal) stress of **2.1 sg** (see **Table 1** in section 4.4). For the Twenthe-Rijn brine field, calculations have been performed based on cavern TWR-355 (deepest cavern in the Hengelo Brine field to which this Isolation Strategy is applicable), to evaluate maximum anticipated cavern pressure during the abandonment lifetime of a cavern.

- Cavern pressure at depth of the last-cemented casing shoe (516.8 m):
 - $516.8 \text{ m} \cdot 2.1 \text{ s.g.} \cdot 0.0981 \text{ m/s}^2 = 106.5 \text{ bar}$
- Brine pressure at the top of the Isolation Window (377.0 m, at which depth the formation would fracture, see Appendix 6 and section 4.4):
 - $106.5 \text{ bar} - (516.8 \text{ m} - 377.0 \text{ m}) \cdot 1.20 \text{ s.g. (cavern brine)} \cdot 0.0981 \text{ m/s}^2 = 90 \text{ bar}$
- Pore pressure of the Röt Claystone (gradient of 1.12 sg):
 - $377.0 \text{ m} \cdot 1.12 \text{ sg} \cdot 0.0981 = 41.4 \text{ bar}$
- Pressure differential between maximum anticipated cavern pressure and pore pressure
 - $87.4 \text{ bar} - 35.1 \text{ bar} = \mathbf{48.6 \text{ bar}}$

Therefore, to comply with mining regulation 8.5.2.2.a, the first abandonment barrier above a cavern shall be placed such that cavern brine outflow is prevented when cavern pressure reaches the maximum anticipated cavern pressure, yielding a conservative pressure differential across the barrier of **49 bar**. Lower pressure differentials may be applicable for shallower caverns, which will be detailed in the well specific P&A work program if applied.

The maximum potential cavern pressure described above is conservative because:

- The cavern convergence process by salt creep, and resulting cavern brine pressure increase, is an extremely slow process for the shallow caverns mined in the Twenthe-Rijn area (<550m) and should be considered on a geological timescale (hundreds to thousands of years, ref.25).
- As cavern brine pressure increases, brine migration may occur via local flow paths caused by salt dilatation, cleavage planes, local heterogeneity or micro-scale fractures induced by the mining process. These potential flow paths would limit the pressure build-up to values (significantly) lower than the lithostatic gradient (see also section 4.5).
- In the conservative scenario where cavern pressure continues to increase to maximum values, the limiting factor is the (minimum principal) stress of the Röt Salt. When cavern brine pressure equals the in-situ stress of the rock salt, permeation processes will prevent further pressure increase (refs.22,27). The lowest in-situ stress value is at the depth of the last-cemented-casing shoe.
- Pressure monitoring of caverns in the Twenthe-Rijn brine field yields observed stabilized cavern pressure values less than 65% of the lithostatic gradient at the depth of the cavern roof. This value is of the same order of magnitude as tests performed at shallow caverns of Gellenoncourt (ref.24).
 - Additionally, during the first quarter of 2022 two relief wells were drilled into caverns 60 and 87 respectively. Cavern 60 was plugged and abandoned in 1988 and cavern 87 in 1980.
 - When penetrating the roof of cavern 60, the wellbore fluid changed-out from 1.25 sg drilling fluid to 1.18 sg brine and a significant fluid level drop in the well was observed. Therefore, cavern pressure was observed to be below halmostatic pressure (equal to a brine column to surface, and thus below 65% of the lithostatic gradient).

- When establishing hydraulic communication with cavern 87, the wellbore fluid changed-out from 1.25 sg drilling fluid to 1.18 sg brine and was then observed to be static, indicating the cavern was approximately at halmostatic pressure (and thus below 65% of the lithostatic gradient).

4.3. Cavern brine thermal expansion

As a result of water injection during mining operations, cavern brine temperature may be lower than the temperature of the surrounding rock salt. When production processes stop, cavern brine temperature slowly equalizes with the local geothermal gradient potentially causing brine thermal expansion. To evaluate thermal expansion, the in-situ rock salt temperature is assessed based on available wireline measurements. A final cavern measurement (sonar) is performed before barriers are placed within the wellbore. As part of the final sonar evaluation, a temperature measurement is included. A representative temperature log taken from brine within the wellbore and cavern TWR-495 is presented in Appendix 7. Shortly above the cavern roof, fluid temperature can be expected to be close to the in-situ formation temperature due to heating by the surrounding rock salt. The data presents an in-situ brine temperature at mid cavern depth of 22 °C and a maximum value of 23 °C. The data obtained yields a geothermal gradient of 0.031 °C/m and an average surface temperature of 9.7 °C. Extrapolating the geothermal gradient to an average mid-cavern depth of ca. 445 m yields a rock salt temperature of approximately 22.0 °C.

Based on temperature measurements on TWR-495, brine thermal expansion is considered negligible for Twenthe-Rijn caverns. At the time of the final cavern log, remaining temperature deficit is generally less than 0.5 °C if a well was suspended for more than 3 years. Consequently, cavern-brine thermal expansion generally causes less than 5 bar cavern pressure increase (applying thermal expansion rate of 4.4 10⁻⁴ /°C and standard cavern compressibility of 4.4 10⁻⁴ /MPa, (refs.27,28)).

4.4. Röt formation stress regimes

In order to comply with Mining Regulation 8.5.2.2.a (see Chapter 2), it is important to evaluate which overburden formations have sufficient strength such that they can hold pressure from underlying formations with flow potentials. For abandonment of the wells in the Twenthe-Rijn area, the only source of flow are the caverns which were developed in the Röt Salt formation, with maximum anticipated cavern pressures as described in section 4.2. For caverns which are considered “*inherently safe*” (caverns with no risk of causing a trough or sinkhole at groundlevel as per Nobian procedure, ref.26). Caverns with the potential to migrate upwards are not covered by this Isolation Strategy.

To evaluate if the entire Röt formation can act as barrier formation, mini-fracture tests were performed on the Röt Main Evaporate, Intermediate Röt Claystone and Upper Röt Claystone (refs.30,31). The data of the measurements were interpreted by Nobian using a “double-tangent” method, as presented in **Table 1** and **Figure 7** below:

Table 1: Results of extended leak-off test (mini-fracture test) of operations performed on wells TWR-403 and TWR-448 in the Twenthe-Rijn brine field (refs.30,31). The presented values are the averages of the results from both wells.

Formation	Formation breakdown	Fracture propagation	Tensile strength	Min. principal stress gradient
	[s.g.]	[s.g.]	[MPa]	[s.g.]
Upper Röt Claystone	7.9	3.6	8.6	2.4
Intermediate Röt Claystone	5.1	4.3	4.0	2.7
Main Röt Evaporite (Anhydrite)	4.9*	3.2*	2.7	2.0
Main Röt Evaporite (Salt C)	4.6	2.4	6.1	2.1

*Data was only obtained for the Main Röt Evaporite (Anhydrite) on well TWR-403.

Based on previous analyses performed by the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) on cores from the Röt section in TWR-480 (ref.32), MeSy Solexperts estimated the overburden gradient to be 2.50 s.g. at cavern depth, confirmed by GeoWulf (refs.4,30,33). At shallower depths, the overburden gradient is slightly lower due to a decreasing overburden density. The results indicate the minimum principal stress

gradient to be equal to, or to slightly exceed the vertical stress gradient for the claystones and to be slightly lower for the Main Röt Evaporites.

A further assessment of the local structural geology based on previous studies indicates the minimum principal stress of the claystone to exceed the overburden gradient can be explained by the reverse faulting regime of the Gronau fault zone (see 3.2 and Appendix 8), confirmed by cleavage planes found in cores retrieved from the Röt formation in well TWR-480 (refs.4,7). To determine the isolation window, the depth range where a suitable P&A barrier can be set, the data shown in **Table 1** is graphically presented in **Figure 7**.

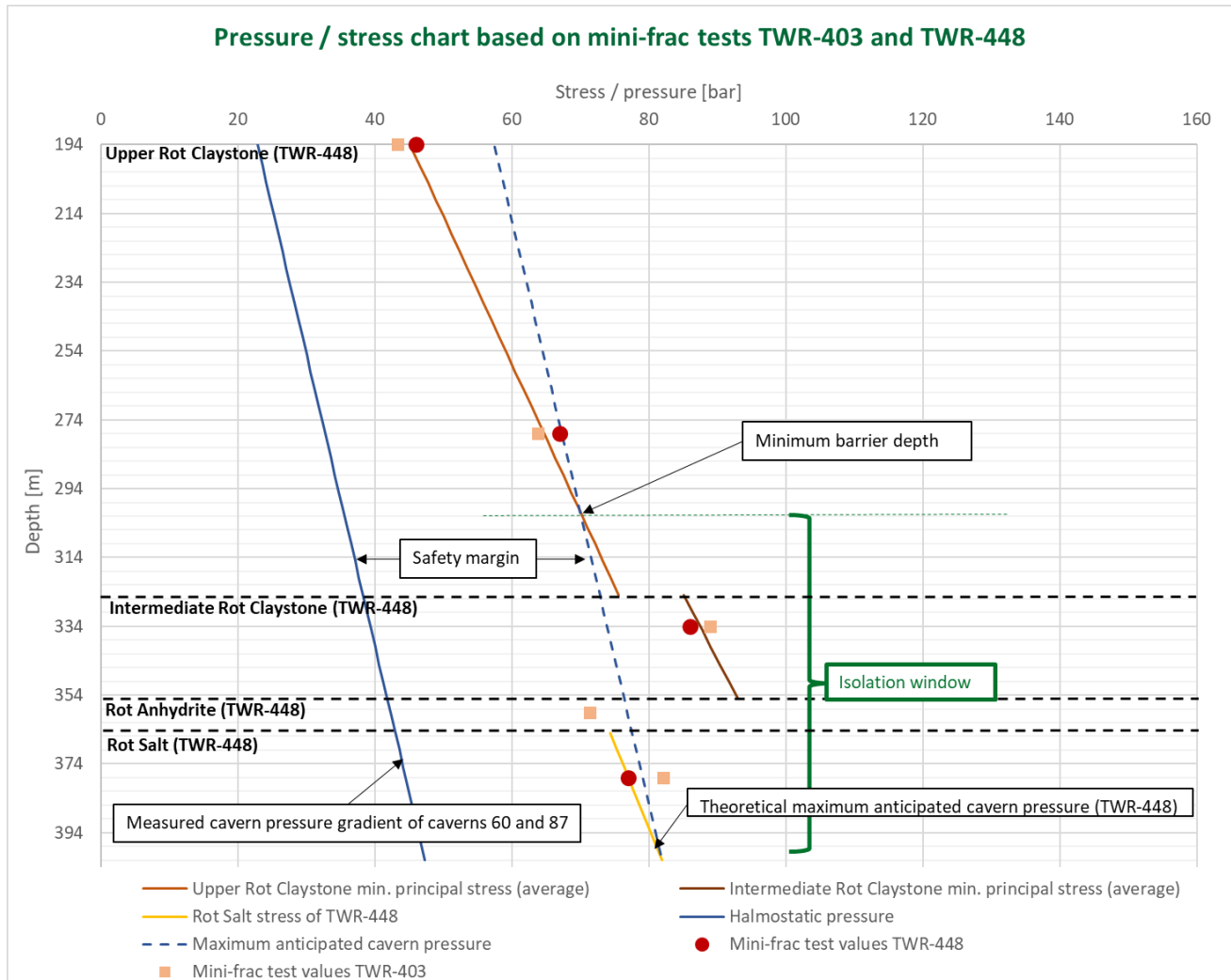


Figure 7: Cavern isolation window for well TWR-448 (example), based on minimum horizontal and vertical stress of the Upper Röt Claystone, Intermediate Röt Claystone and Röt Salt. Values were obtained from mini-frac tests performed on well TWR-448 (ref.30). The blue curve represents halmostatic fluid pressure (a 1.20 sg brine column to surface with 0 bar surface pressure, equal to pressure measurements on caverns 60 and 87). Finally, the dashed blue curve represents a shut-in cavern with brine pressure equal to the measured lithostatic gradient at 378m (test depth) and brine to surface for well TWR-448. The minimum barrier depth is defined as the depth where potential cavern brine pressure would exceed the minimum principal stress of the Röt Claystone. Additionally, depth corrected data from mini-frac tests on well TWR-403 are also presented (ref.31).

Although a suitable isolation window may be determined based on the formation fracture gradient (ref.35), a more conservative approach is to use the minimum principal stress value; because pre-existing faults in the Röt formation cannot be excluded and have even been observed in cores retrieved, e.g. from TWR-480, the formation strength may be overestimated when applying the formation fracture gradient. Therefore, Nobian uses the minimum principal stress as reference value for the Röt formation strength. From **Figure 7** it is observed that the minimum horizontal stress gradients exceed the overburden gradient, while only limited data is currently available (March 2022). More tests are required to establish if the high horizontal stress values found in well TWR-448 and TWR-403 are applicable for the entire Twente-Rijn brine field. For the time being, barriers will

generally be placed as deep as possible and juxtaposing the Röt Salt and Röt Anhydrite (RNRO1) members. A well-specific evaluation may be performed if in-situ data is available, which shall be included in the well-specific P&A design and work program.

For well-specific evaluations, an overburden gradient of 2.30 s.g. shall be used to determine the isolation window, being the lower limit of the various principal stresses.

4.5. Additional consideration: Solling formation

As stated in section 2.1, most wells in the Twenthe-Rijn area were drilled into the Solling formation underlying the Röt Salt before cavern development was started. Drilling into the Solling formation ensured the entire salt section was penetrated and salt reserves maximized. Several studies were performed related to the underlying Solling formation and its hydrological properties, such as the MSc. Thesis prepared by D. Vlieg (ref.36). Research was done following observations of hydraulic communication between neighboring caverns; increasing pressure in one cavern would result in a delayed increase in pressure in caverns in the vicinity (timespan in the order of hours).

The lithological evaluations by D. Vlieg (ref.36) suggest the Solling consists of an alternation of very fine to fine sandstones, an intercalation of argillaceous silt and sandstone and silty to sandy claystone overlain by a sandstone bed. The overall sequence is fining upwards, where samples become less silty and sandy. The Solling formation is separated from the Röt salt by an anhydrite layer. Although the solling formation is initially cemented with halite, cavern operations alter the composition and increase the formation permeability (especially during the initial leaching phase where fresh water is injected at the bottom of the cavern). Although difficult to measure, field trials which included measuring flow from one cavern to another indicated permeability values up to several Darcy (ref.36). Additionally, Geowulf performed core analyses on samples retrieved from the Solling formation in well TWR-480 and TWR-534 and concluded (ref.37):

In six of the seven wells studied, thin siltstone and sandstone levels are described in the upper part of the Solling Formation with a proven or interpreted halite cement. In previous studies these silty/sandy intercalations were concluded to have excellent reservoir properties but for the tight halite cement (B534, B536, B480, HEN-01).

[...] It is important to realize that the upper part of the Solling Formation is a section of claystones with only minor thin siltstone and sandstone intercalations (fig 2.5). For this study only the coarser clastic intervals were sampled.

For the wells which were drilled into the Solling formation and caverns which indicate hydraulic communication to neighboring caverns, the cavern is no longer considered tight. Instead, the maximum anticipated cavern pressure is lower than previously stated in section 4.2. From a conservative point of view, all caverns are assumed to be hydraulically tight. However, a well specific analysis related to the maximum anticipated cavern pressure may be performed, which shall then be included in the P&A Work Program when considering barrier design.

5. Overburden crossflow potential and isolation strategy

Mitigating risks towards the environment and, specifically, potable groundwater is an important aspect when abandoning onshore wells (ref.2). This chapter describes additional evaluations and observations related to the shallow overburden and hydrology.

5.1. Twenthe-Rijn geohydrology and REGIS model

The hydrology in the Twenthe-Rijn brine field area is set within the porous geological layers of the subsoil (Quaternary and Tertiary). Throughout the Twenthe-Rijn brine field, the depth of the base of the formations range from approximately 70 m to 156 m below ground level. This depth is benchmarked by the vast number of wells in the area which were drilled by Nobian (previously AkzoNobel and Nouryon) for the purpose of solution mining, but also by other public sources such as the REGIS model which was developed by TNO as described below.

The REGIS model has been further analyzed in the Twenthe-Rijn area to evaluate the local geohydrology in more detail. Multiple cross sections were picked within the model and these profiles were correlated to three actual wells that were used for an interpretation of the geohydrology. These three wells are the only wells within the Twenthe-Rijn area which were drilled to a sufficient depth to obtain a complete overview of the subsoil and geohydrology. An overview of the locations of the profiles and wells is given in **Figure 8**. The profiles are named REGIS 1-4, the wells are B34F0018, B34F0051 and B34F3880.

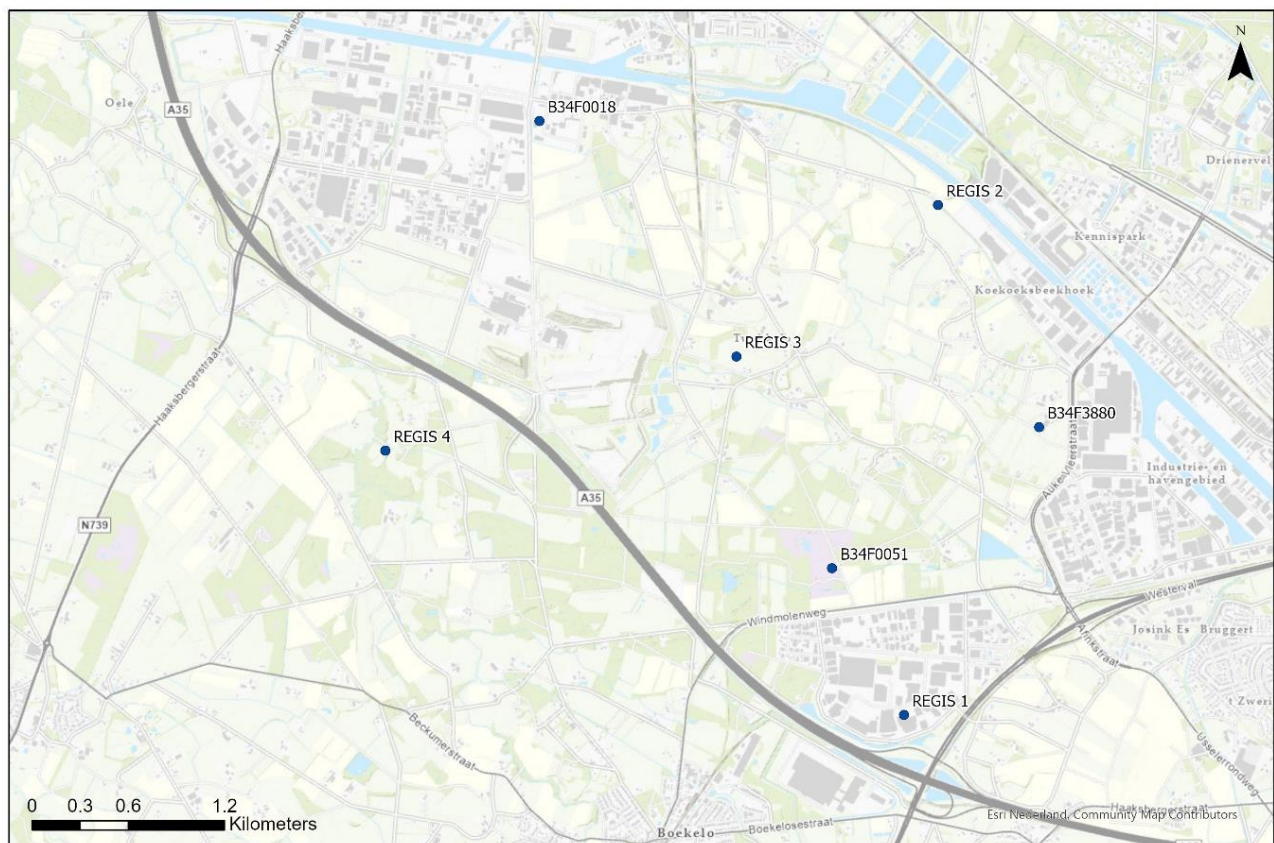


Figure 8: Overview of subsoil profiles and wells that were used for correlation and evaluation of the subsoil and geohydrology.

The REGIS data indicates that almost all groundwater flow is restricted to the upper sandy layers from 0 m to a maximum of 30 m below ground level. Below these sandy layers, a large clayey section is observed with a base at approximately 80 m to 130m depth below ground level, varying throughout Twenthe-Rijn area. The more clayey section is defined in the REGIS model as the “Dongen clay member” and, according to the REGIS data, within this member only limited flow is possible with fluid velocity values of $k_v = 0 - 5E^{-5}$ m/d and k_h of 0 m/d. Below the “Dongen clay member”, a thin sand layer is identified in the REGIS model as the “Dongen sand member”. Within this member horizontal and vertical flow is possible.

Below the layer identified by REGIS as the “*Dongen sand member*”, the REGIS data suggests no horizontal or vertical flow can be expected (permeability values are not presented). The data correlates well to the experience related to drilling and operating many salt exploration and production wells drilled in the Twenthe-Rijn area, where influx or losses by hydrostatic differences have not been reported below the “*Dongen sand member*”.

It should be noted that the interpretation of the Quaternary and Tertiary in REGIS does not fully correlate with the studies prepared by Geowulf regarding the Tertiary formations (refs.4,11), but the results are roughly comparable. REGIS distinguishes a clear separation of the geological layers (e.g. Drenthe, Dongen clay, Dongen sand, etc.) and suggests a lateral continuity of these layers, indicating no hydraulic communication between the quaternary layers and the Dongen sand member at the base of the Tertiary (from a shallow hydrology point of view). Studies performed by Geowulf demonstrate that this is not true within the Twenthe-Rijn area when considering well abandonment barriers to crossflow. The Tertiary formations are too unconsolidated to act as a barrier to crossflow and are of a sandier nature than may be expected based on regional evaluations. Furthermore, the lateral continuity is uncertain because the shallow layers of the Tertiary consist of an alternation of sandy clay, clayish sand, sand lenses and silt which have some interconnectivity. Nobian considers the detailed study performed by GeoWulf to be more accurate.

5.2. Infiltration areas and water production

Figure 9 below shows the infiltration areas and areas where water is produced in the vicinity of the Twenthe-Rijn brine field, which would require specific attention (production site Hasselo). From the presented map it follows that such areas are absent (see also the map of the Twenthe-Rijn brine field in chapter 2). Production at Hasselo will not be expanded in the future due to present groundwater contamination (ref.38). Furthermore, the infiltration area presented in yellow is to the East of production site Hasselo based on a 100-year flow duration to reach the production site, while the Twenthe-Rijn brine field is to the South; because groundwater flow is from East to West and production site Hasselo is North of the Twenthe-Rijn brine field, the risk of potential contamination of the produced water is extremely unlikely. A more detailed overview of water production site Hasselo is presented in Appendix 9.

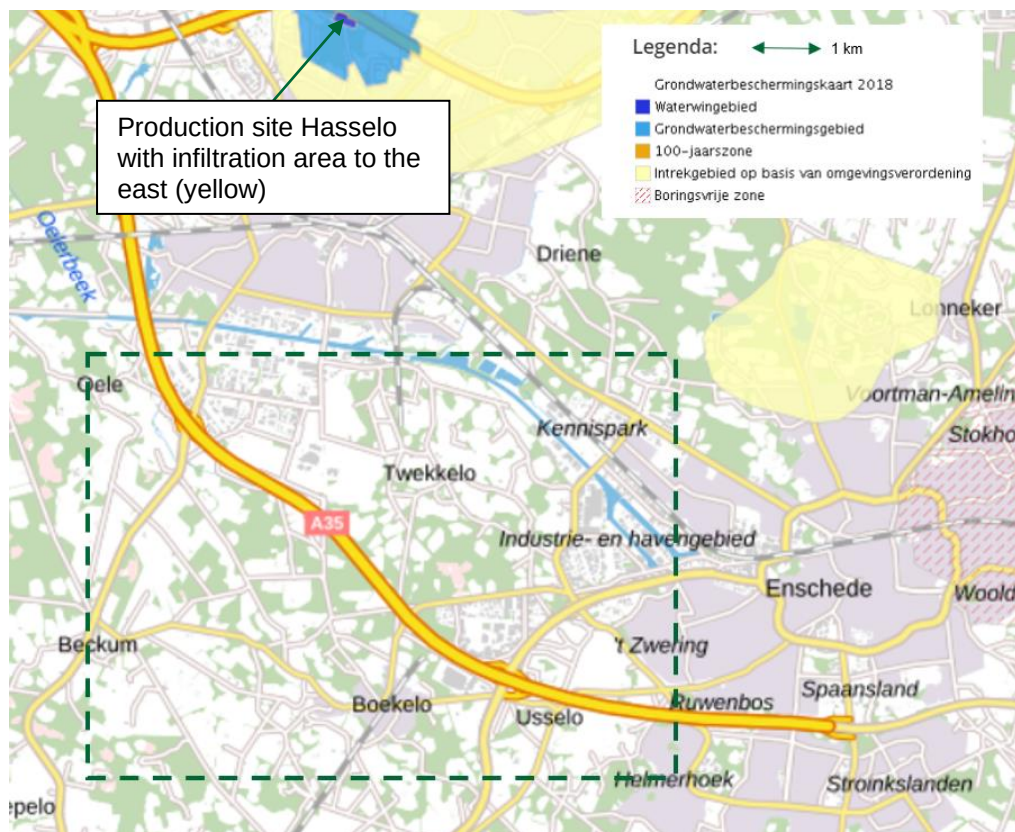


Figure 9: Map of the Hengelo area showing infiltration areas (yellow), groundwater protection areas (light blue) and water production areas (dark blue). The green square represents the map of the Twenthe-Rijn area presented in Figure 2, Chapter 2. Source: atlasleefomgeving.nl.

5.3. Twenthe-Rijn hydrology and artesian effects

Artesian wells that were drilled in the Twenthe-Rijn area

A potential source providing information on the hydrology in the Twenthe-Rijn area is related to the document “Artesian wells in the Hengelo brine field”. This document was in a poor condition and incomplete. Therefore, the report was further evaluated because flow potential by an artesian effect is indicated; the same document was used by GeoWulf as reference for “water gains” (ref.4, Table 2) and wrongly gave reason to believe the Muschelkalk to have flow potential in previous studies, as discussed in more detail in this section. Further investigation showed the document to be an attachment of a report prepared by the “Rijksinstituut voor drinkwatervoorziening” (ref.42).

In 1981 the geohydrology of the Twenthe-Rijn area was investigated in detail by the hydrologic department of the ‘Rijksinstituut voor drinkwatervoorziening’. The objective of the investigation was to assess the risk of soil contamination and potential consequences for the quality of drinking water in the Hengelo area. Groundwater flow was mapped in detail and measured in the field. Furthermore, all public and industrial groundwater extraction data was compiled and included in the study.

Attachment 1 of the reference report shows a S-N cross section of the geohydrology of the area. For completeness, a part of the schematic is included in appendix 10. Indicated in yellow is fair groundwater flow. Indicated in green is good groundwater flow.

The main conclusions of the report prepared by the Rijksinstituut voor drinkwatervoorziening are:

1. The main groundwater flow occurs in the top of the Hengelo basin. The base of this basin consists of the argillaceous deposits of the Tertiary. The sandy layers at the bottom of the Hengelo basin show good groundwater flow. The deposits up to the surface show fair groundwater flow.*
2. The sandy layers at the bottom of the Tertiary, just above the Muschelkalk, also show groundwater flow. The layer was initially identified as N1a of the North Sea Supergroup, and further specified as the Heers Sand member of the Dongen Formation.
3. The deep groundwater in the area can be considered semi-tension water.
4. The source of the groundwater is the moraine complex situated East of Hengelo between Oldenzaal, Enschede and the German border.
5. Groundwater flow is from the moraine complex [artesian effect], varying in direction from West to North-West.

* These layers were identified by Geowulf as part N2 of the North Sea Supergroup (see Chapter 0).

An East-West geohydrological overview is presented in **Figure 10**.

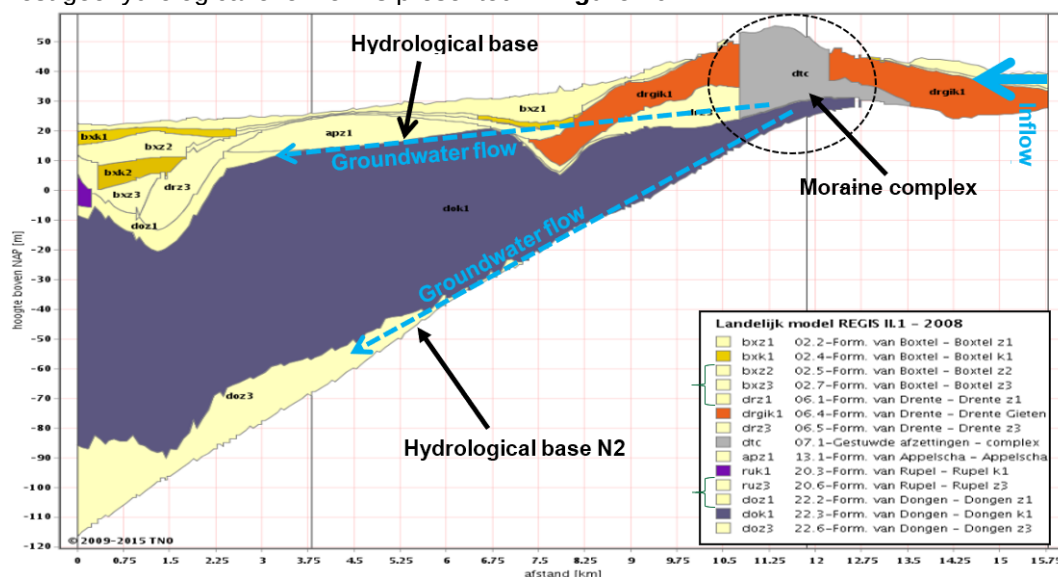


Figure 10: Geohydrological East-West overview. Influx of groundwater from Germany in the East. Filtration and separation of groundwater at the moraine complex near Oldenzaal-Enschede. Groundwater flows through the upper basin and the deeper sand deposits of N1a.

5.4. Well monitoring and observations

Nobian wells are generally not equipped with a manometer and the well configuration generally does not allow monitoring of annular pressures between the conductor and production casing. Therefore, hydraulic isolation of the annulus can generally not be concluded based on pressure trends. However, all wells operated by Nobian are monitored and (sustained) flow would be detected and documented. To date, such a scenario has not been reported.

Additionally, while performing pre-abandonment wireline evaluations (see Chapter 2), a bridge plug is set as deep as possible within the last-cemented-casing. Subsequently, the mechanical integrity of the wells is tested by pressure testing the wellbore to 25 bar wellhead pressure (a higher value than wellhead pressure during mining operations). If the pressure test fails, the well integrity is assumed to be compromised and additional evaluations are performed to identify the location of a leak-path. Observation pipes are installed in the vicinity of the wellhead to evaluate potential contamination of potable groundwater. So far, only very local contamination by wellbore fluids has been documented (subsequent spills have been reported and remediated). However, any contamination by crossflow of formation fluids through the overburden formations or annulus of a well have not yet been observed.

Finally, a CBL-VDL and ultrasonic measurement of the annular cement is obtained and evaluated. The cement log evaluations of the Twenthe-Rijn area generally show moderate to good cement across the sealing formations (Altena, Niedersachsen, Muschelkalk and Röt formation), while cement quality is (very) poor across the permeable North Sea Supergroup. The poor cementation in the North Sea Supergroup can very likely be attributed to the low formation strength (cement pressure exceeding the formation fracture pressure) and the presence of permeable layers. This assumption is further substantiated by observations during P&A operations in 2020 and 2021 within the Twenthe-Rijn area: 50 m windows were milled and underreamed in the last-cemented-casing juxtaposing the North Sea Supergroup. Window depths varied from ca. 34 m to 100 m and exposed virgin formation to borehole fluids (viscous silicate brine) and pressures. Mud losses were observed while the formation was exposed at all these windows and at various depths across any of the North Sea Supergroup members. Static losses were observed in the order of 1 m³/day to 8 m³/day with a fluid gradient varying from 1.10 s.g. to 1.20 s.g. Hydraulic loss rates were observed at various wells with a loss rate up to 48 m³/day with an Equivalent Circulating Density (ECD) of approximately 1.15 s.g. to 1.20 s.g. No losses or gains have been observed from any formations below the North Sea Supergroup.

5.5. Overburden barrier requirements summary

Considering that:

1. No hydrocarbons have been encountered while drilling any of the Nobian operated wells within the Twenthe-Rijn area;
 - Any recoverable blanket fluid that was used for cavern leaching operations is removed from the connected wells before a well is put in suspension or abandoned.
2. The North Sea Supergroup and Quaternary formations consists of an unconsolidated alternation of sandy clay, clayish sand, sand lenses and silt which have some interconnectivity and limited lateral extent (see section 5.1 and ref.11);
3. The North Sea Supergroup and Quaternary formations contain similar pore fluid throughout the different formations (Quaternary, N2, N1b and N1a) and members, originating from the same source: the moraine complex situated East of Hengelo.
4. The North Sea Supergroup has insufficient formation strength to act as a barrier formation as per NOGEPA definitions.
5. No fresh water is produced from the shallow hydrology in the vicinity of the Twenthe-Rijn brine field (see section 5.1 and **Figure 9**).
6. No contamination of groundwater by crossflow of formation fluids has been reported at any of the salt wells operated by Nobian within the Twenthe-Rijn brinefield.
7. No zone with flow potential has been identified below the North Sea Supergroup which requires isolation, apart from the cavern in the Rot formation from which salt was mined.
8. The cavern is isolated by a barrier placed within the Röt formation.
9. Any remaining wellbore fluids above the first barrier shall not be harmful to the environment and remaining wellbore fluids shall have a higher specific gravity than the pore fluid of the North Sea Supergroup and Quaternary as per Nobian procedure (ref.3) and NOGEPA standards (ref.2).
10. It is unlikely that any remedial cement operations across the North Sea Supergroup will result in an improved cement bond.

It is deemed that the risk of groundwater contamination is extremely low. Therefore, a barrier is not required within the North Sea Supergroup to prevent potential crossflow from the base of North Sea Supergroup member N1a to Quaternary formations.

A top plug ("*environmental plug*") as required by Mining Regulations 8.5.2.1.b, NOGEPA standard 45 and Nobian Cement Barrier procedure shall be placed across the North Sea Supergroup by setting a 50 m cement plug on top of a mechanical base within the last-cemented casing. Although verification of the top plug is not required as per Mining Regulations or NOGEPA standard 45, Nobian procedure is to visually verify the top of the cement plug.

6. Hengelo Brine field Isolation Strategy summary

Based on the geological and hydrogeological assessments, formations are subdivided in aquifers, flow potential, aquitards and barrier formations as shown below in **Figure 11**. The Isolation Strategy can be summarized as follows:

- Because insufficient reference data is available from the Twenthe-Rijn brine field to conclude on maximum anticipated cavern pressures during the abandonment lifecycle of the relevant caverns, conservative assumptions are applied as described in section 4.2.
 - Until more data is available, it is assumed that trapped cavern pressure of an abandoned cavern may increase to a value equal to the lithostatic gradient of the salt.
- Only one zone with flow potential has been identified: the cavern in the Röt Main Evaporite salt section. Furthermore, risks towards the environment related to crossflow are deemed extremely low. Therefore, in compliance with Dutch Mining Regulations and NOGEPA standard 45, one barrier is required to prevent crossflow between the cavern and various formations. The barrier shall be set within the isolation window as shown in **Figure 7**.
 - In general, the (most) conservative Maximum Anticipated Cavern Pressure related to cavern convergence in the Hengelo Brine field evaluated in this document is calculated to be **49 bar** (assuming a tight cavern, see section 4.2).
 - The difference in cavern temperature compared to the temperature of the surrounding rock salt is less than 0.5 °C after 3 years of suspension. Therefore, brine pressure increase related to thermal expansion of cavern brine is considered to be negligible (less than 5 bar, see section 4.3).
 - A well specific analysis related to the maximum anticipated cavern pressure may be performed, which shall then be included in the P&A Work Program when considering barrier design. E.g. when hydraulic communication with neighboring caverns via the underlying Solling formation exists.
- A top plug will be set across the North Sea Supergroup as per Mining Regulation 8.5.2.1. and NOGEPA standard 45. The top plug is not a pressure holding barrier and the cementation requires no verification (see section 5.5).

Twenthe-Rijn Lithostratigraphic Column						
Geology Group & Formation		Aquifer	Flow Potential	Aquitard	Barrier	Comment
Quaternary						Groundwater bearing zone
North Sea Supergroup (NL)	N2					The tertiary formations have varying flow properties.
	N1b					
	N1a					
Rijnland Group (KN)	Vlieland Claystone (KNNC)					Only found in wells: TWR-349-350-351 (pinch- out)
	Vlieland Sandstone (KNNS)					Only found in wells: TWR-348-349-350-351
Niedersachsen Group (SK)						
Altena Group (AT)	Sleen Formation (ATRT)					
Upper Germanic Trias Group (RN)	Muschelkalk (RNMU)					Potential barrier pending well specific evaluation
	Upper Röt Claystone (RNROU)					
	Upper Röt Evaporite (RNRO2)					
	Intermediate Rot Claystone (RNROM)					
	Röt Main Evaporite (Anhydrite) (RNRO1E)					
	Röt Main Evaporite (salt) (RNRO1)					Flow potential from cavern only
	Solling (RNSO)					Aquifer properties vary, depending on leaching of halitic cement and facies.

Figure 11: Lithostratigraphic column of the Twenthe-Rijn and Usseler Es area, indicating aquifers, flow potential, sealing formations and formations which can act as barrier to zones with flow potential.

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Appendix 1 – Depth of the base of the North Sea Supergroup in the Twenthe-Rijn area

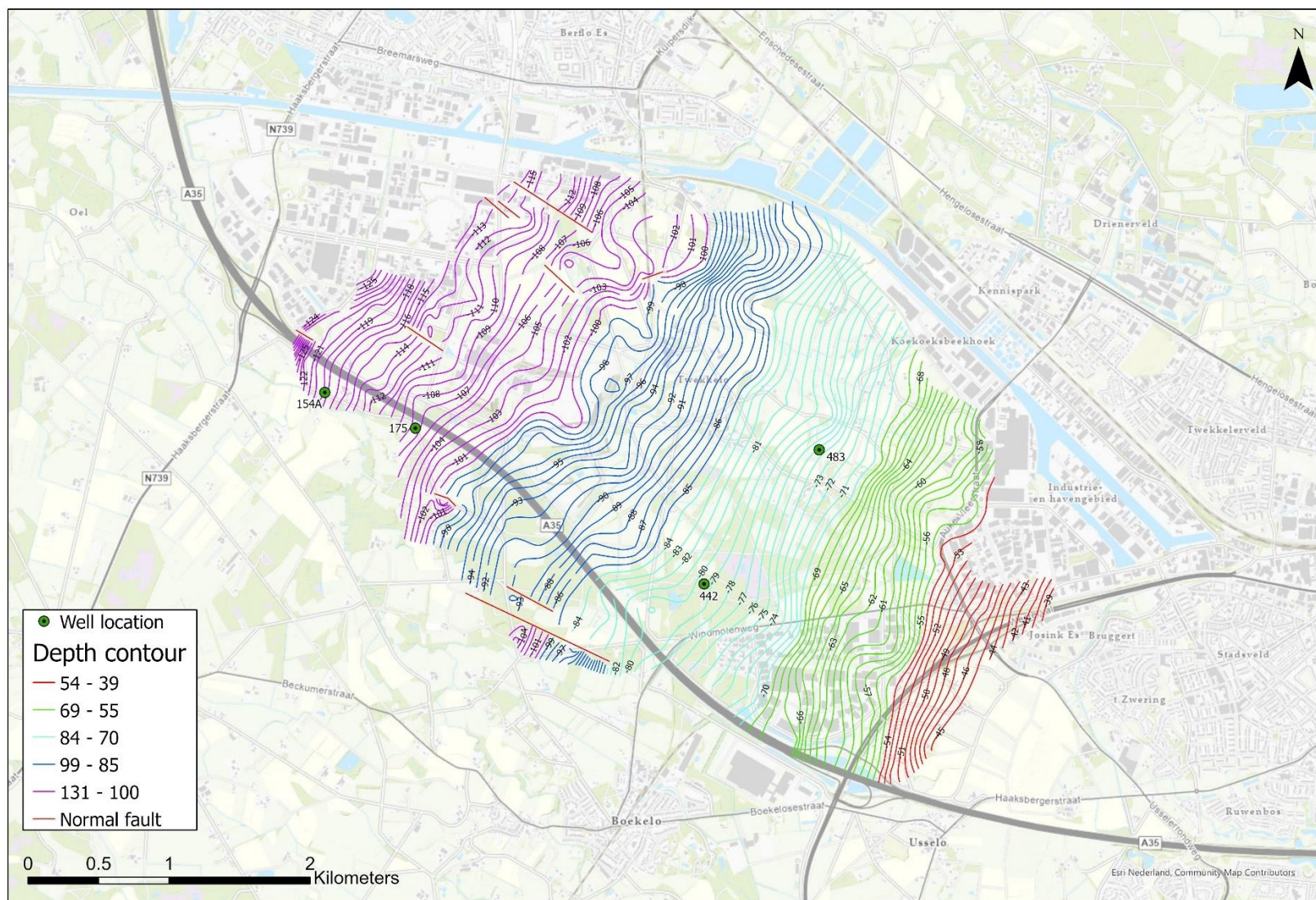


Figure 12: Depth base of the North Sea Supergroup throughout the Twenthe-Rijn area (area presented by phase 1,2 and 3 in Figure 2, chapter 2). Depth reference is meters below NAP.

Appendix 2 – Wells evaluated for aquifer properties of the North Sea Supergroup

List of lithological studies and wells studied			
wellname	strat sections	report	biostratigraphy
DED-02	N, SK, MU-O1	GL09.401	biostrat N, SK, MU
HEN01	N, SK, MU-SO	GL08.501	
BKM-01	MU-OU	GL09.401	
BKM-02	N, SK, AT, MU-SO	GL15.501	
1	N	GL08.501	
11	N	GL08.501	
106	N, MU	GL08.501	
154a	N, SK, MU-OM	GL08.501	
175	N, SK, AT	GL08.501	
186	N, SK	GL08.501	
386			
442	N, SK, MU-O1	GL11.901	
472	N, SK, MU-O1	course 1999	
478	N, SK, AT, MU-O1	GL07.101	
480	N, SK, AT, MU-SO	GL06.0406, GL06.601	
		GL14.901	biostrat N biostrat SK biostrat AT
482	N, SK, AT, MU-O1	GL08.501	
483			
495	N, SK, MU-SO	GL10.401	
534	N, AT, MU, SO	GL13.701, GL14.901	
536	N, SO	GL14.901, GL16.0901	
537	N	GL16.0901	
538	N	GL16.0901	
558	N, SK, AT, MU-B5	GL20.101	

Figure 13: The table above presents the wells that were evaluated for aquifer properties based on cores and cuttings. Additionally, relevant reference reports prepared by GeoWulf are listed in the third column.

Appendix 3 – Overview of locations of wells drilled in the Hengelo brine field

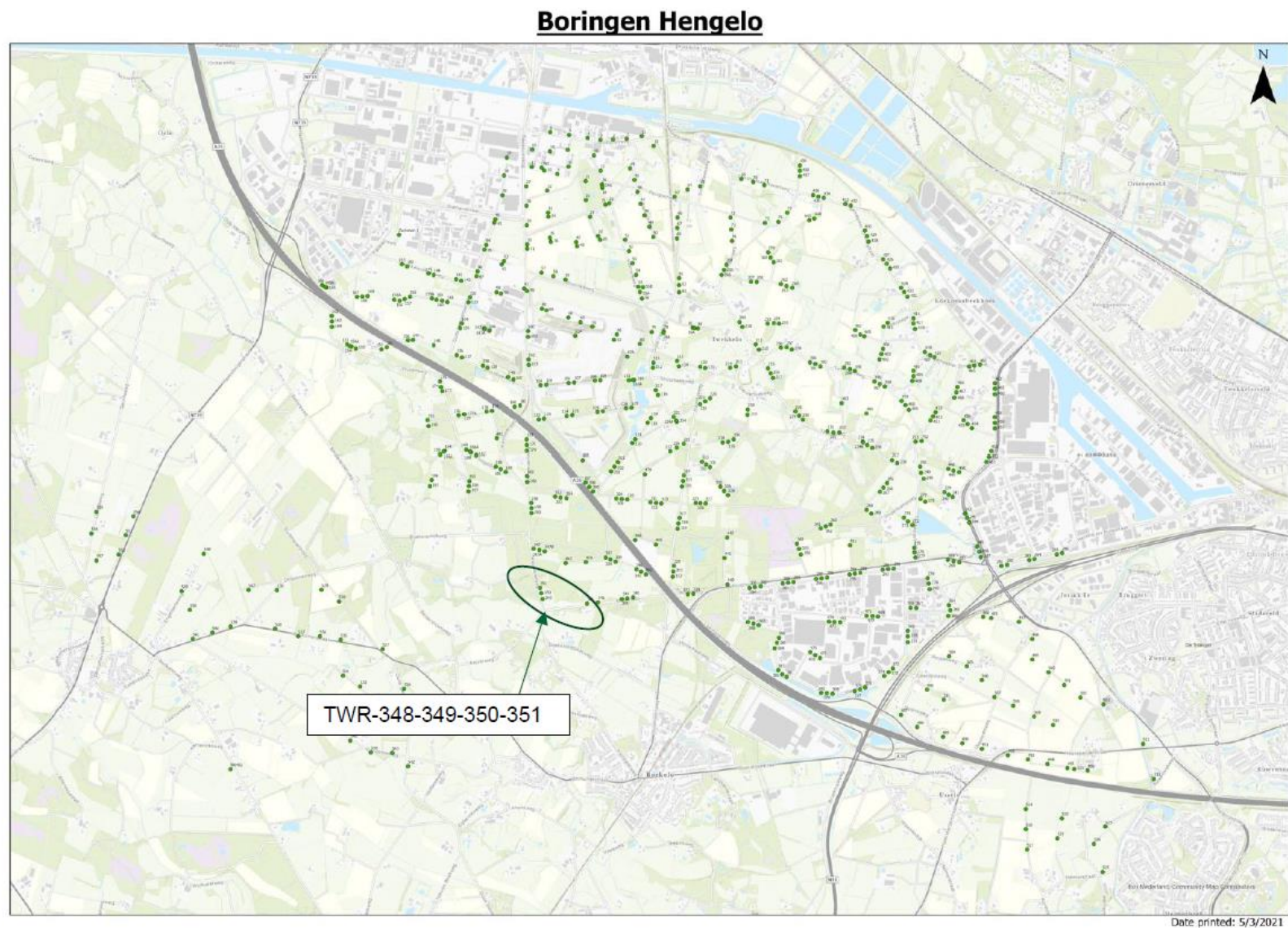


Figure 14: Overview of wells drilled in the Hengelo brine field, the only wells where the Vlieland formation was penetrated (near the Boekelo fault zone).

Appendix 4 – Map of faults identified in the Hengelo Brine field

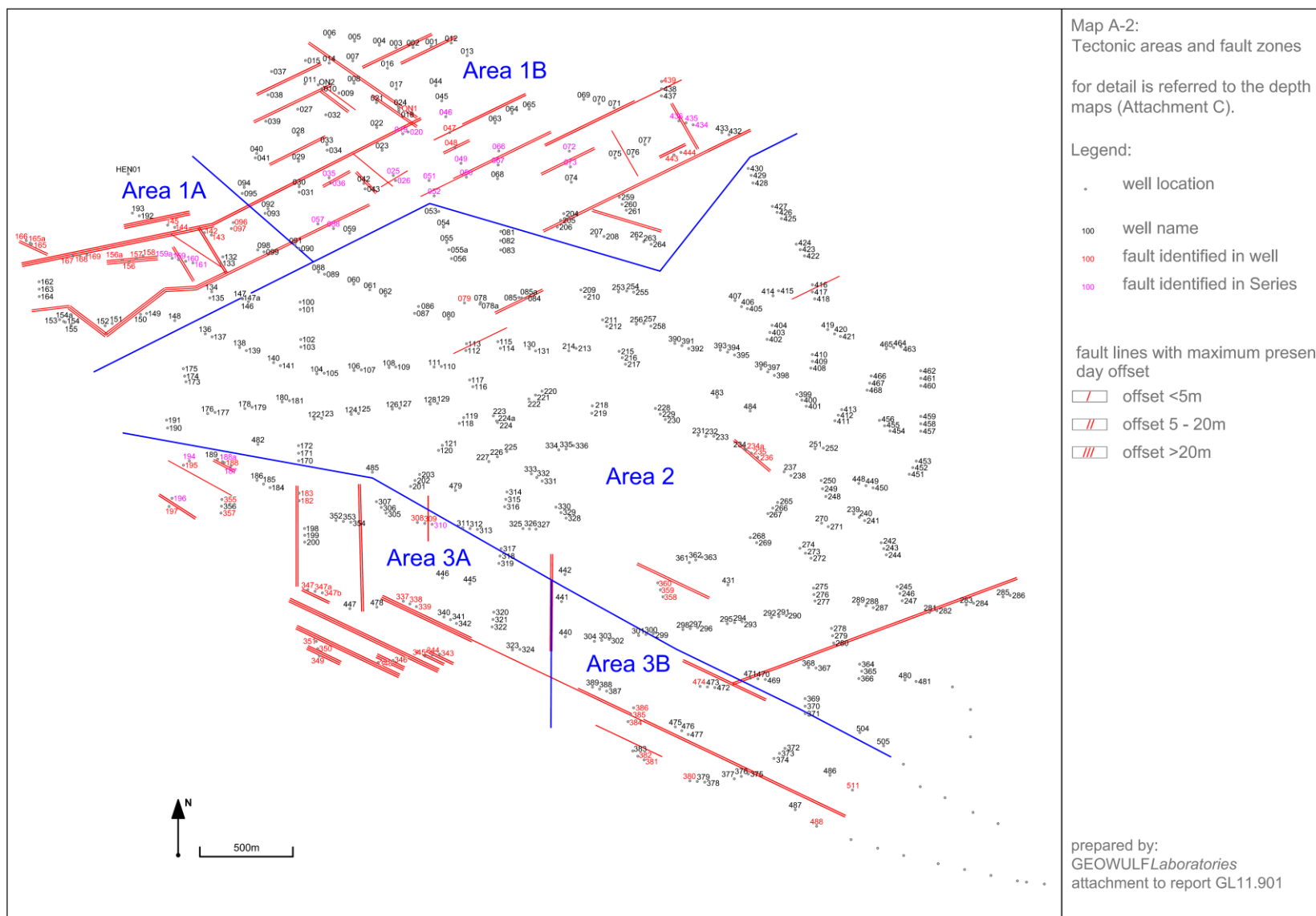


Figure 15: Faults identified in the Hengelo Brine field.

Appendix 5 – Salt permeation as function of effective stress

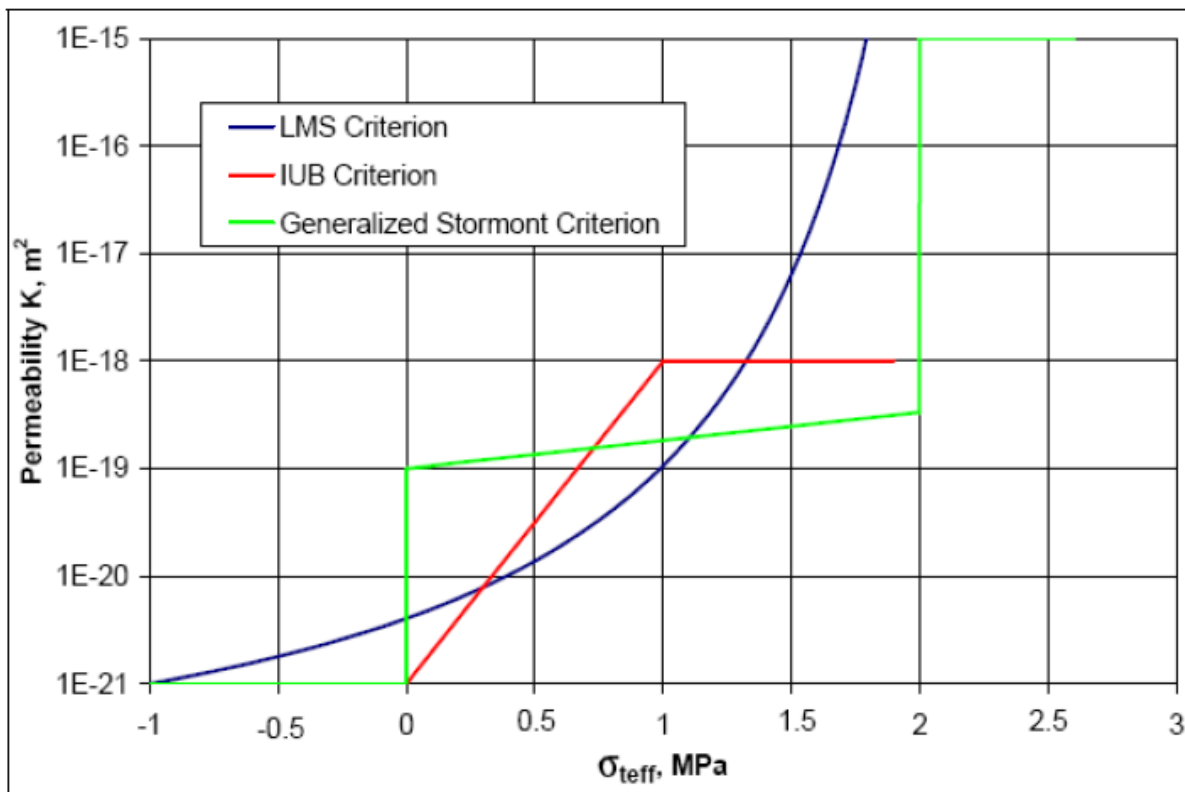


Figure 16: Three different criteria for the observed permeability of rock salt as function of effective stress in the direction of flow (ref.22). Effective stress is defined as $\sigma_{t,eff} = P_{cavern} - \sigma_t$. Within the rocksalt, tangential stress, σ_t , is equal to local in-situ stresses.

The description of the infiltration behavior of the rock salt under stress conditions as existing under cavern abandonment conditions is based on the results of the laboratory tests carried out within the SMRI 2001-1 research project “Salt Permeability Testing” (ref.39) as well as on the results of the Etzel field test (ref.23).

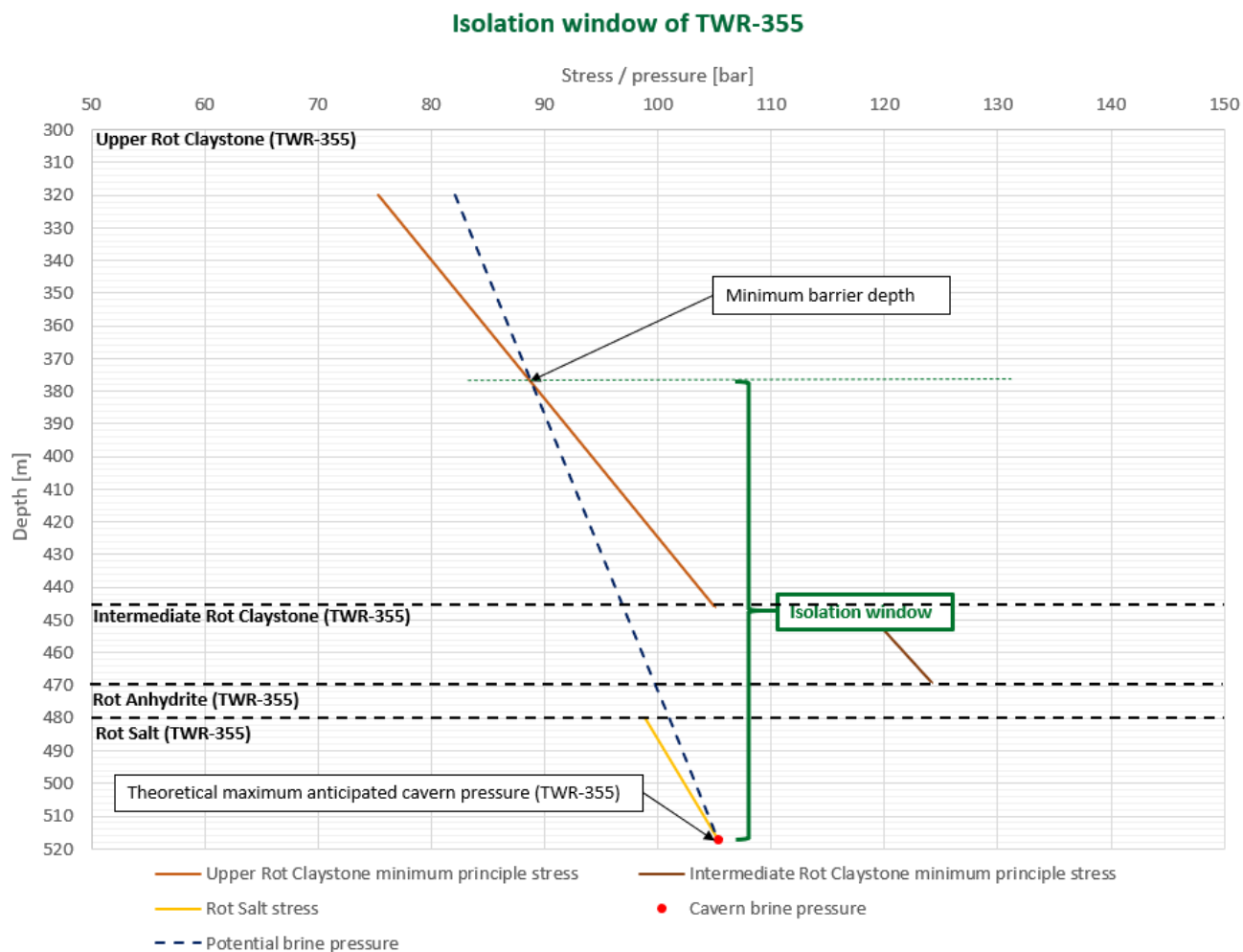
The review of the test results according to 2001-1-SMRI (ref.40) resulted in different proposals for the description of a stress dependent permeability development in rock salt, as presented in **Figure 16**. The LMS-criterion is suggested by LMS (Laboratoire Mécanique de Solides) itself at the end of the tests. Stormont’s criterion is developed in his review of the LMS tests (ref.41). The IUB (Institut für Unterirdisches Bauen) criterion has been derived from the results of the Etzel test.

The IUB criterion states that a raised infiltration of the cavern fluid starts as soon as one component of the local principal stress state acting perpendicular to the spreading direction of the infiltration is lower in level than the internal cavern pressure acting at that point in time, which is equal to the pore pressure at the cavern boundary.

The LMS criterion, which is similar to the IUB, criterion has been proposed by BÉREST et al. (ref.39). The difference of the LMS criterion to the IUB criterion originates from the definition of the maximum permeability which reaches an infinite value after exceeding a maximum value of σ_{teff} .

The criterion by Stormont (ref.41) distinguishes between a change in permeability due to tensile failure and pore-scale damage due to the limited tensile strength of crystal boundaries. The development between those boundary values can be described by a stress permeability model which considers the relationship between permeability and porosity.

Appendix 6 – Isolation Window of cavern TWR-355



The figure above presents the Isolation Window evaluation for cavern TWR-355, based on data obtained from mini-frac tests in the Twenthe-Rijn brine field and evaluations and assumptions presented in chapter 4 (specifically, section 4.4).

Appendix 8 – Cavern temperature measurements in the Twenthe-Rijn area

Figure 17 below shows the wireline temperature logs of cavern TWR-495. In the wellbore, the logs show a large variation. The cavern is accessible via two wells; production well TWR-495 and TWR-515, which was drilled as a monitoring well only and has never been used for production. There are two aspects which skew the data; before measurement, the cavern pressure was bled off causing warm cavern-brine to flow through the well before measurements were performed. For cavern TWR-495, it was easiest to bleed-off pressure from well TWR-495, so for most measurements that respective well temperature is above the geothermal gradient. Secondly, when the well was still in production (blue curves), the injection water temperature fluctuated throughout the year. Therefore, in some cases the injection water was warmer than the cavern brine.

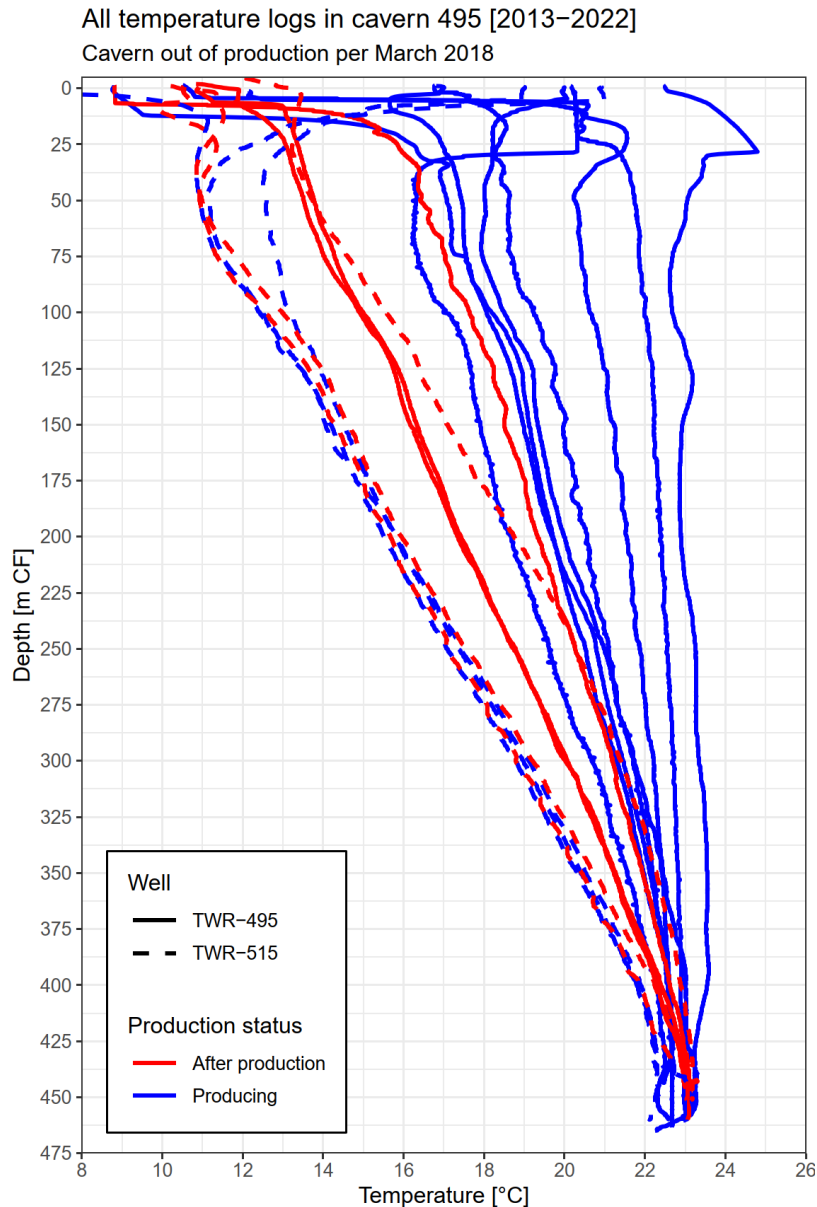


Figure 17: All temperature logs from wireline measurements in cavern 495 (cavern accessible through 2 wells TWR-495 and TWR-515)

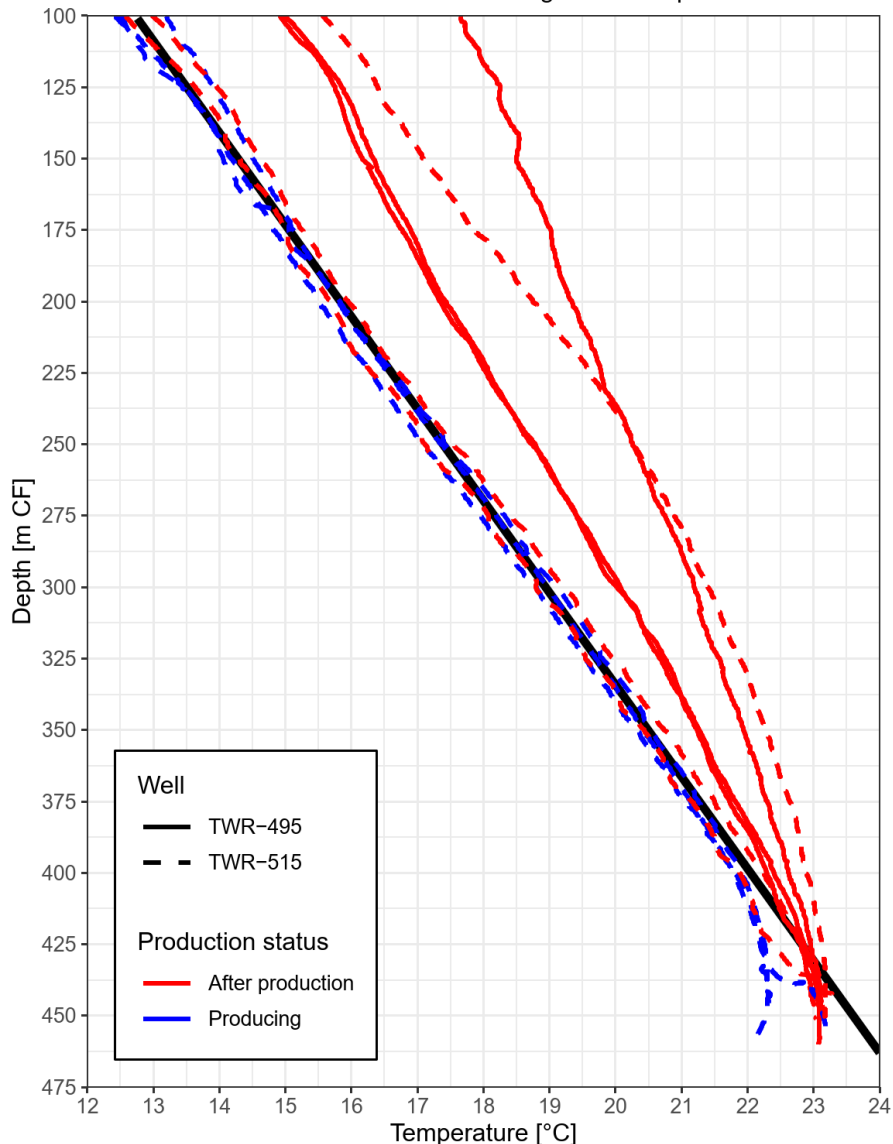
Considering the arguments stated above, some logs can be selected to determine the geothermal gradient. The major fluctuations happen in the top section, so when evaluating the interval between 100 and 350 m, the 5 logs from TWR-515 measured in 2013 (twice), 2016, 2018 and 2022 yield a fairly constant slope as presented in Figure 18. Linearly interpolating the data yields a geothermal gradient of 30.8 °C/km depth and a surface temperature of 9.7 °C.

Selected temperature logs to find local geothermal gradient

Pressure release happens generally at TWR-495.

This brings warmer fluid higher up.

Cooler lines from 515 seem constant trough time and production



Please note scale changes.
Regression line calculated between 100 and 350 m CF: $\text{Temperature} = 0.0308 \cdot \text{Depth} + 9.7^\circ\text{C}$

Figure 18: Selected temperature logs to determine geothermal gradient between 100 and 350 m. Please note the scale changes (x and y) compared to the previous figure.

Further evaluating the data presented Figure 18, the final expected temperature in cavern TWR-495 when equilibrium is reached is estimated. Figure 19 presents the temperature trends in cavern TWR-495 and the geothermal gradient. At the cavern roof, at a depth of 436 m, a temperature deficit is observed when comparing cavern temperature and the geothermal gradient. At the cavern mid-depth around 445 m, the temperature deficit is less than 0.5°C , 3 years after end of production from the cavern. It should be noted that the measurements were taken with different tools and no information is available regarding tool calibration. Therefore, small measurement errors are possible (less than several tenths of a gradient). However, the general trends present a clear overview.

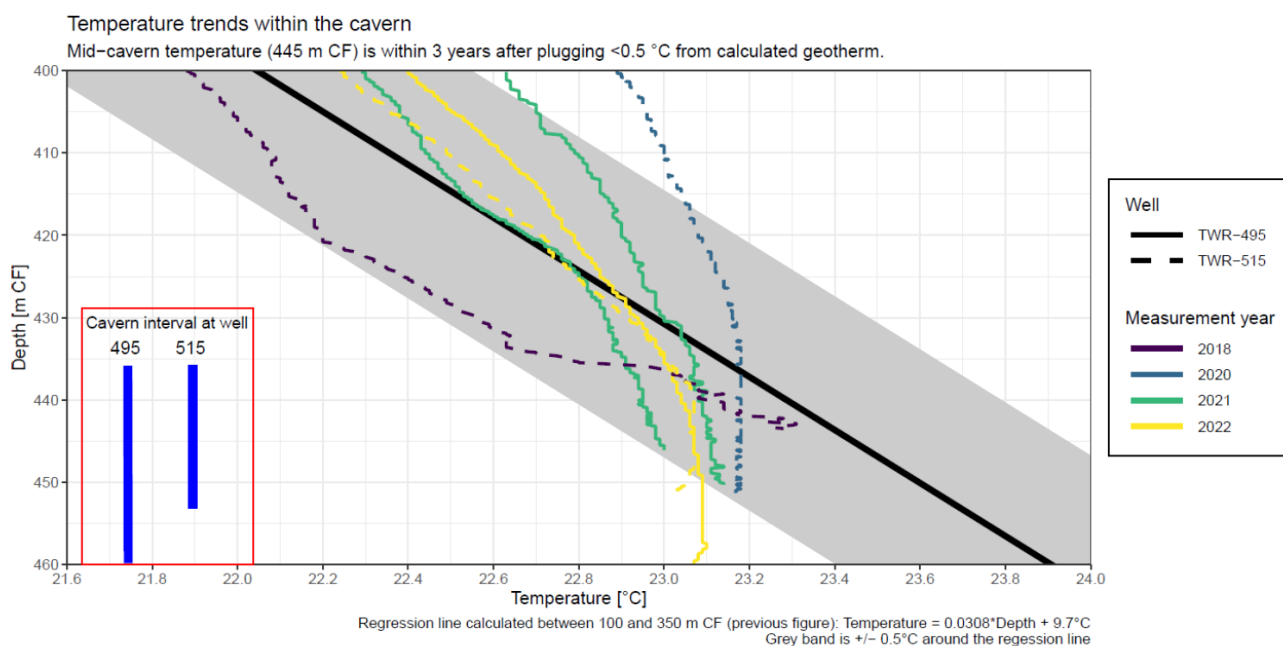


Figure 19: Temperature plots from cavern TWR-495 (solid curves) and TWR-515 (dashed curves) at the depth of the cavern. The roof of the cavern at well TWR-495 at the end of production is located at 436 m while the base of the cavern is at 457 m. Color codes are based on the year of the respective measurement. Cavern production was stopped in 2018 and the wells were suspended. The measurements from 2021 and 2022 indicate that within 3 years after production, the mid-point cavern temperature at 445 m is within a margin of 0.5 °C from the geothermal gradient.

Appendix 8 – Overview of major faulting in the Netherlands

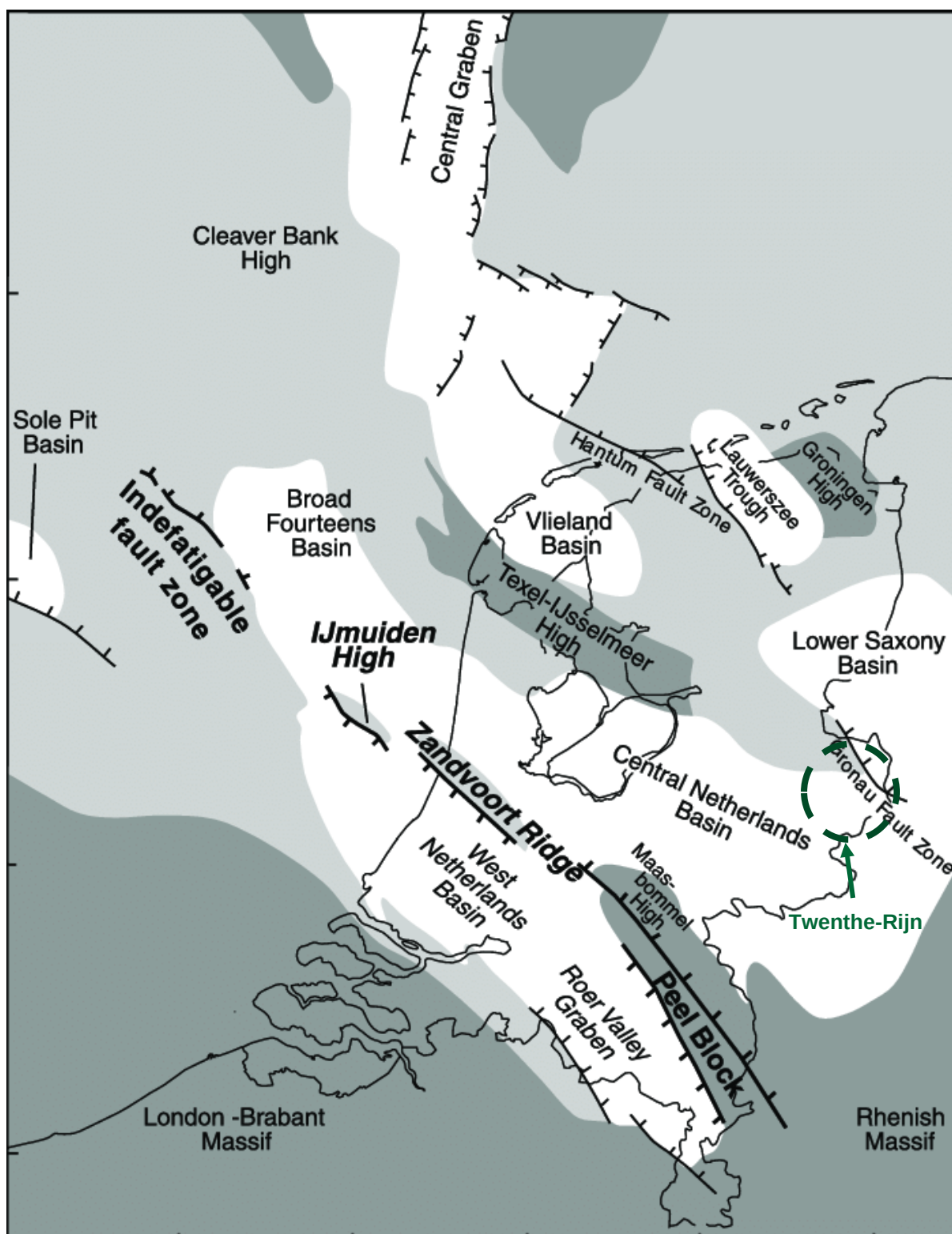


Figure 20: Jurassic-Cretaceous tectonic elements of the Netherlands (ref.43).

Appendix 9 – Water production site and infiltration area Hasselo

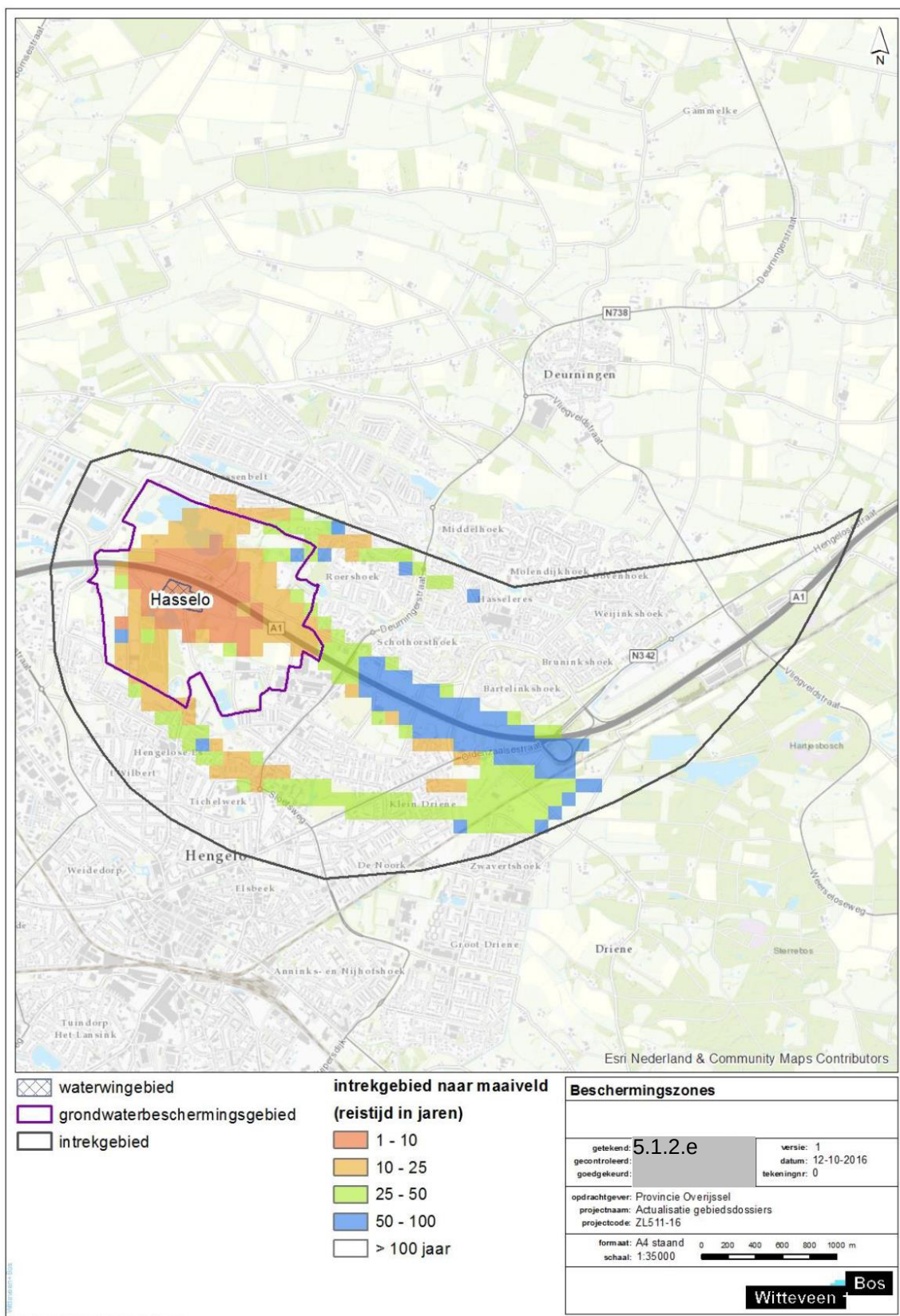


Figure 21: Production site and infiltration area Hasselo (ref.42). Production from the site will not be expanded due to (natural) groundwater pollution.

Appendix 10 - Cross section of the geohydrology in the Twenthe-Rijn area

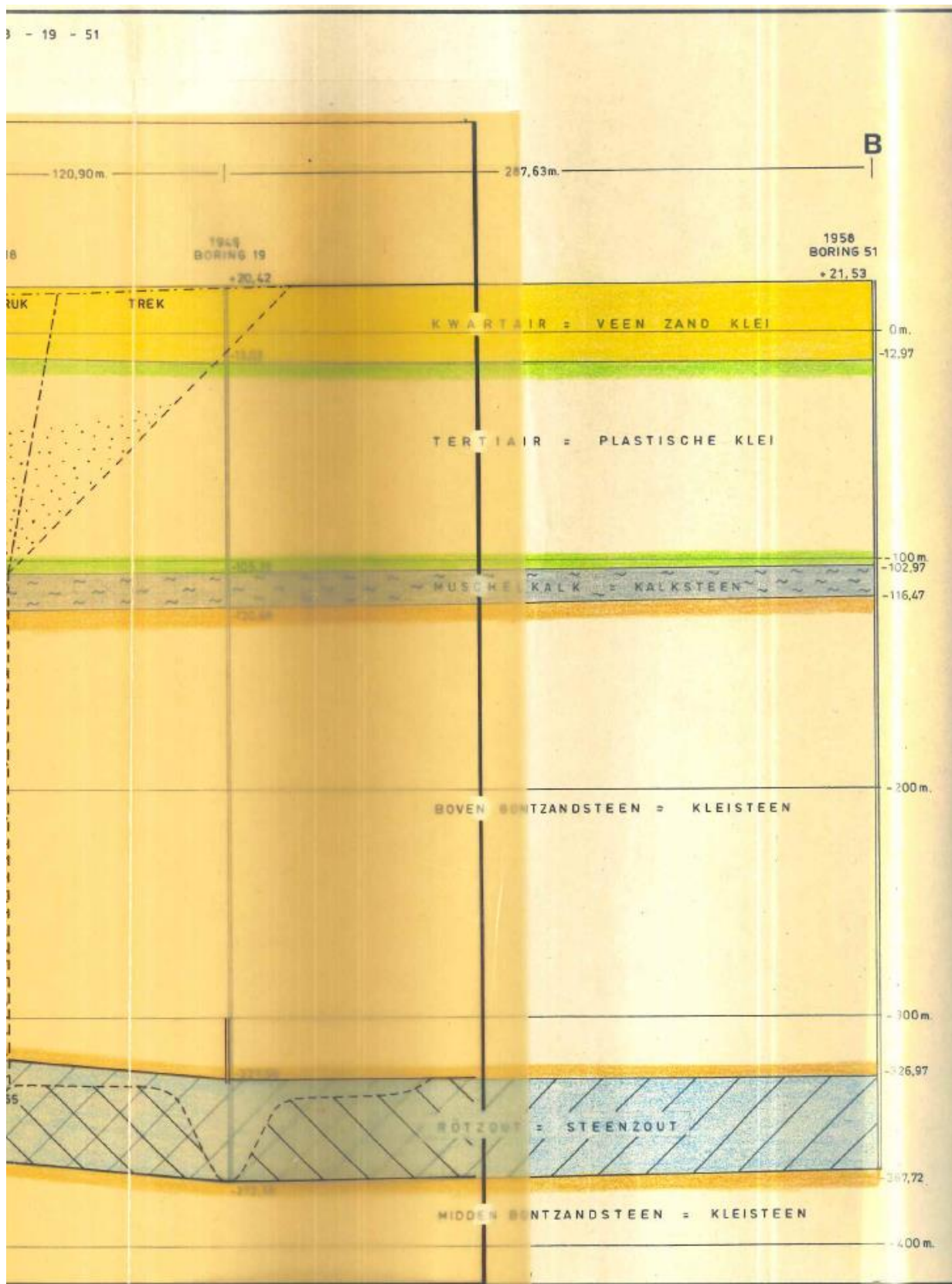


Figure 22: S-N cross section of the geohydrology of the area. Indicated in yellow is fair groundwater flow. Indicated in green is good groundwater flow (ref.42).

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