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Update Migration Study

Twenthe-Rijn – Phase 1-Part A+B+C

Reconstruction of cavern development, slurry filling, migration, and the link to subsidence

Report Part 1 – Fundamental principles used in reconstruction

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Contents

1 Introduction and structure

1.1 Background

The historic development of the Nobian cavern fields within the Twenthe-Rijn mining permit (incl. extensions) has been divided into five phases ("Fase" 1 -5) as shown in Figure 1 below.

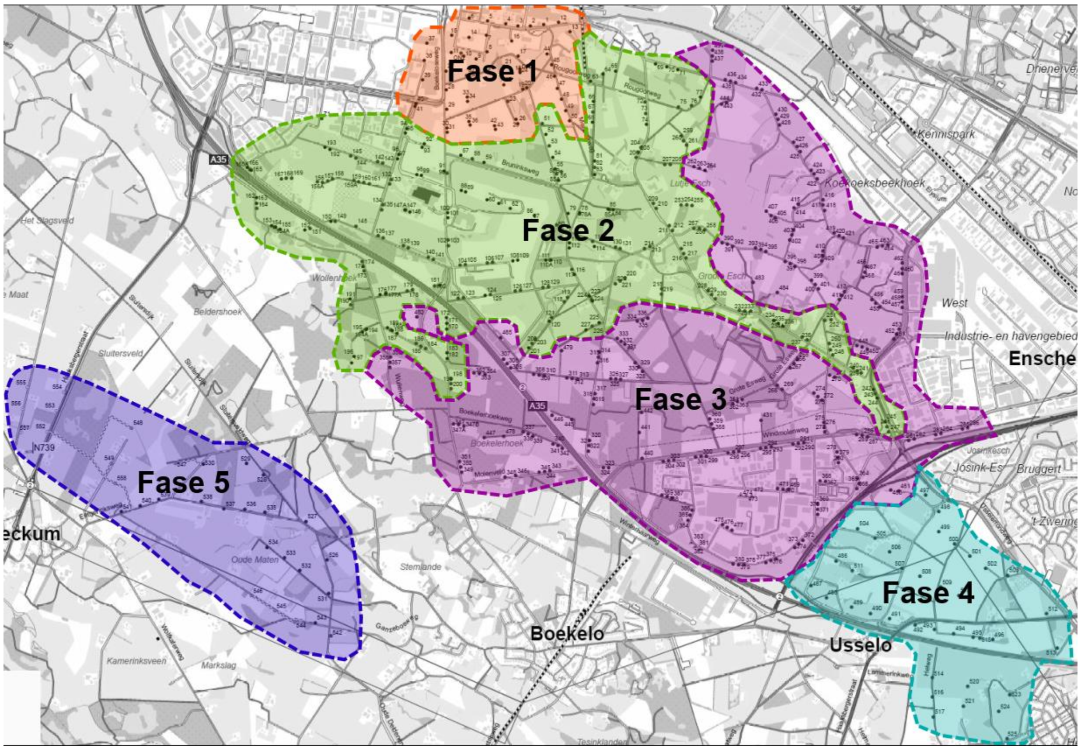

Figure 1: Historic development of Nobian cavern fields in the TWR permitting area, Twente, The Netherlands (Nobian, 20220919 – Opvolging werk Bekendam vs2.ppt)

For the caverns within the areas depicted "Fase 1" and "Fase 2" an update of the existing cavern migration assessments prepared by (late) Roland Bekendam is sought by Nobian. REinvent GmbH (Reinvent) and K-UTEC AG Salt Technologies (K-UTEC) were (sub-)contracted by Nobian to perform the study. Work was initiated in January 2023 and continues as this first report covering the overall study results is delivered.

The offered scope has been structured as proposed by Nobian and comprises three phases, each consisting of several parts, see paragraph 1.2. The reporting on Phase 1 will be covered by a total of three reports. This first report describes the fundamental principles used during Phase 1 of the study. As such, it introduces the reconstruction of cavern development by leaching, subsequent cavern migration and the principles governing resulting subsidence. This report is intended to support the understanding of the further two reports covering Phase 1 of the Update Migration study. The second report covers the reconstruction of cavern development (by leaching) and cavern migration. The final report for Phase 1 discusses the link between cavern development/migration and subsidence. It also proposes an algorithm for the prediction of potential subsidence caused by cavern migration in the Hengelo brinefield of Nobian which is an adaptation of the original Bekendam algorithm.

1.2 Scope of work

The scope of work for Phase 1, reconstruction of well documented cavern migration cases, was distributed over three parts:

Part A: Reconstruction cavern development.

Part B: Reconstruction of cavern migration process.

Part C: Effects at surface related to cavern migration.

The caverns studied in Phase 1 are:

- Reference Cavern 251-252-253
- Reference Cavern 320-321-322
- Cavern 15 (slurry filled)
- Cavern 33-34-35-36
- Cavern 37
- Cavern 49-50 (slurry filled)
- Cavern 64-65 (slurry filled)
- Cavern 69-70-71 (slurry filled)
- Cavern 72-75-76(-77) (slurry filled)
- Cavern 86-87
- Cavern (104-105)-106-107 (slurry filled)
- Cavern 167-168-169 (slurry filled)

The reference caverns and caverns in brackets (…) have been added during performance of Part A resulting initial data extraction work. The need for reference caverns for which multiple sonar images were available arose as very little information on the early stages of sump development and cavern development in multiple completion caverns (MCC) are available. The caverns in brackets have been added as they were at one point hydraulically connected to the caverns initially included in the scope of work. This connection dictated the spatial development in the last years of production.

The scope of work for Phase 1 - Part A has been defined as:

> The historic cavern development of ten (10) caverns, of which 7 are slurry-filled and 3 brine-filled, will be reconstructed based on the available historic data and information. The aim of Part A is to construct reliable cavern geometries for the 10 selected caverns as a basis for the activities in Part B of the study. The reliability of the reconstructed geometries is limited by the quality of the input data. No guarantee for the accuracy of reconstructed geometries can be provided due to the absence of validation opportunity (the caverns have already been migrated). Input data and information as well as output will be according to the document "20220919 – Opvolging werk Bekendam vs2".

The scope of work for Phase 1 - Part B has been defined as:

> Based on the reconstructed cavern geometries from Part A, the historic slurry filling (where relevant) and cavern migration processes for the 10 selected caverns will be reconstructed in Part B, incorporating further historical data and information where available. Input data and information as well as output for Part B will be according to the document “20220919 – Opvolging werk Bekendam vs2”.

The scope of work for Phase 1 – Part C has been defined as:

> Combining the outputs from Part A and Part B, the effects at surface from the cavern migration of the 10 selected caverns will be investigated in Part C. The main task of this part is to match the actual, measured, subsidence development to the reconstructed cavern geometries and migration processes stemming from Parts A and B with the aim of establishing one (or more) formula(s) that can describe the subsidence effect at surface from cavern migration of the 10 selected caverns. This formula should be applicable to other caverns in the TWR region. The support from a geotechnical/ geomechanical specialist will be required for part of the Part C and 5.1.2.e (K-UTEC AG Salt Technologies) has taken that role.

1.3 Structure of the report

This first part of the overall reporting for the Update Migration Study Phase 1 describes the fundamental principles used during the reconstruction of leaching and migration development of the 10 caverns included in the study. By explaining the fundamental principles first, the reader is supported in the understanding of the actual reconstructions described in the second part of the overall reporting.

The presentation of the fundamental principles used in the study are divided over three chapters. Chapter 2 covers principles used to reconstruct the leaching phase of the study caverns. Chapter 3 discusses the large- and small-scale processes controlling cavern migration and Chapter 4 concludes with an explanation of the link between cavern migration and subsidence. Chapter 5 provides a short summary and conclusions for this part of the performed work.

The reporting uses “,” to indicate a decimal and “.” as a 1000 separator.

2 Cavern development by leaching

2.1 Information sources for reconstruction

The information sources used for the reconstruction have all been provided by Nobian at the start of the study or on request. The used information can be split into six main categories:

1. Geological information
2. Information from well diaries (drilling and work-over information)
3. Production information
4. Sonar information
5. Slurry filling information
6. Subsidence data and information

Geological information was provided in the form of both detailed (historical) well logs and tabulated stratigraphy data taken from the so-called BPB- database ("BoorPuttenBeheer) owned and operated by Nobian. The tabulated data was primarily used as it is the most accurate and includes the most recent insights into the stratigraphy. The detailed information from the logs was used to gain insight into the composition of specific strata where necessary.

The drilling process for each well and information pertaining to subsequent maintenance to each well has been detailed in well diaries. These diaries are available for all wells in both an original and a (neater) copied version, all hand-written. The original versions were used for the investigation unless information was unclear in which case the copied diary was consulted. Information from the well diaries has been a valuable source for the reconstruction albeit sometimes limited and inconsistent. This is mostly likely caused by different people writing the diaries over a timespan of more than four decades.

Production data for the investigated caverns was provided by Nobian in the form of a series of PDF-files containing the original tabulated brine and salt production information. The relevant information was extracted from the PDF-files by hand and entered in a "Masterfile". The format in which the production data was recorded changes several times for the investigated period, e.g. recording just yearly production was later changed into monthly production figures. To enable the use of a consistent database, all production data entered in the Masterfile used for reconstruction was based on yearly figures.

Apart from the brine/salt production data, the so-called "Slurryberging- & Stromingstabel"-PDF file, shows what was injected or produced from each well on a quarterly basis from 1975 onwards. Using this file, it has become possible to estimate the contribution of water injection into a well to volume creation in the cases of connected wells. It is unfortunate that this information is not available for the investigated caverns before 1975 and this has limited the ability to reconstruct caverns in some cases.

Sonar images were used as a guide to the reconstruction and to assess the quality of the reconstruction by comparing production (reconstruction) volumes to the sonar volumes. The sonar images used were delivered as DXF-files and transformed to AutoCAD drawings before being used as reference files in the reconstruction of caverns. It has not been possible to transfer sonar images to "closed" 3-dimensional objects on which Boolean operators can be used. As a result, the true volume of a cavern which has been imaged using overlapping sonar images cannot be derived from the sonar information. Although the sonar images are not closed objects and volume determination is not possible in AutoCAD, the volume of single sonar images has been provided by Nobian. These volumes were determined by a custom algorithm embedded in the BPB database.

2.2 Stratigraphy

The representation of the overburden stratigraphy used in the cavern reconstruction process is presented in Figure 2. A detail representation of the salt bearing strata is included in this figure. The position of the strata interfaces has been based on the most recent data available in the Nobian geological database.

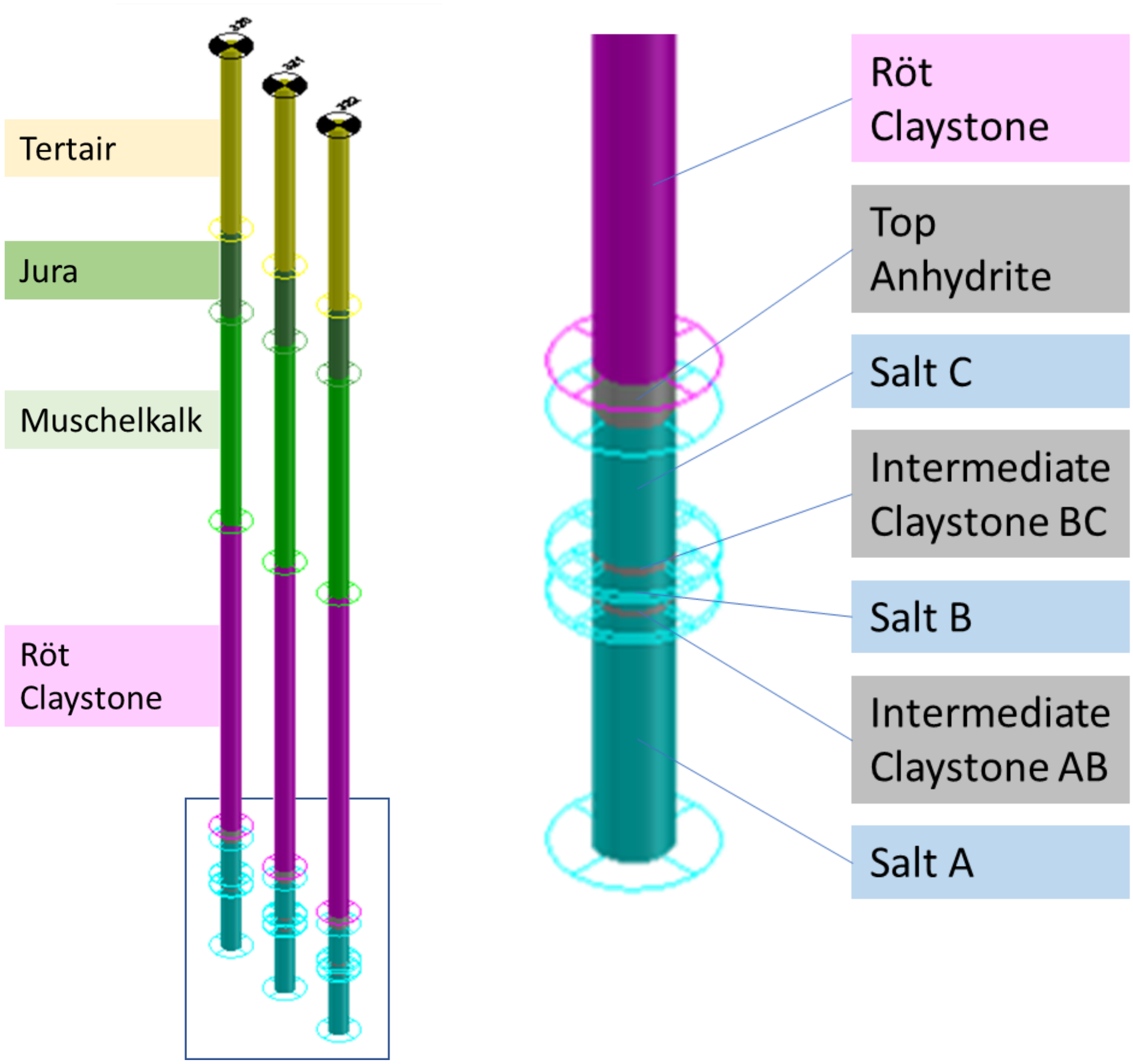

Figure 2: Stratigraphy of the overburden and salt-bearing strata at the brinefield

The defining characteristics of each stratum in the stratigraphy shown in Figure 2 are summarized in Table 1.

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Table 1: Defining characteristics of geological strata found in the study area (source: well logs, available at NLOG.nl).

Stratum	Defining properties for the reconstruction of cavern development and migration
Tertiary	Comprises mostly unconsolidated sand and clay. Tertiary sediments are not capable of spanning a large roof span. Consequently, when a cavern of sufficient diameter and height migrates upwards and reaches the bottom of the Tertiary, failure of the Tertiary sediments may occur leading to significant subsidence.
Jura	Rarely present in the study area (only at cavern 167). Comprises marl interbedded with limestone and contains gypsum nodules and shell fragments. Rocks of Jurassic age in the study area are assumed to have geo-mechanical properties similar to the underlying Muschelkalk and thus (temporarily) support a cavern roof span.
Muschelkalk	Comprises mostly marl with some limestone and gypsum nodules. Logs also mention sandstone and claystone layers as part of this stratum. Does not occur at all wells in the study area.
Röt Claystone	Forms the main overburden member overlying the saline strata. The Röt-Claystone comprises carbonate-rich mud- and claystones, as well as sandy claystones, with and without gypsum nodules. For most migrated caverns in the study area, the Röt-Claystone is the main stratum through which cavern migration has propagated.
Top Anhydrite	Comprises claystones and anhydrite, sometimes with rock salt interbeds ("Salt D"). It has been observed that the Top-Anhydrite can maintain a stable cavern roof span for considerable time (decades). Deterioration and/or collapse of the Top-Anhydrite is unpredictable considering the observations in the brinefield. In some cases, the Top Anhydrite collapsed during production, while in other cases, the Top Anhydrite has been stable for several decades after production has stopped. The collapse of the Top Anhydrite in some cases may have been triggered by the presence of faults in the overburden as established in some areas of the brinefield, e.g. around cavern 69-70-71 where a sinkhole was formed in 1991 after migration of the cavern. Collapse may also be initiated by water or weak brine being present directly underneath and enabling the formation of gypsum and consequential "scaling" of bedded layers of Anhydrite, claystone and salt. As Anhydrite has a very low and temperature independent solubility, it has acted as a natural "blanket medium" for cavern development, i.e. acting as the maximum depth underneath which leaching takes place, see also paragraph 2.8.
Salt C	Upper main salt production member for the caverns in the study area. Comprises rock salt with a low percentage of insolubles (assumed 5 m.-%).
Salt B	Minor salt production member, sometimes very thin (< 5 m). Rock salt from this member may have fallen to the bottom of the cavern in combination with collapsing intermediate rock benches after which dissolution of the salt is slowed by the relative high salinity of brine near the bottom of a cavern.
Salt A	Lower main salt production member for the TWR caverns. For the caverns in the study area, leaching of the Salt A member is often limited by the absence of a controlled (oil) blanket, forcing the leaching upwards and into the Salt B and C members.
Intermediate Claystone benches	Salt members are separated by intermediate rock benches comprising claystone, anhydrite and dolomite. Once sufficiently exposed, these benches collapse and the (insoluble) material sinks to the bottom of the cavern. During cavern development, the material from the intermediate rock benches, combined with the insolubles from the rock salt, will (partly) fill the initial sump volume of the cavern.
Bottom Anhydrite	Lowest member of the saline strata comprising mainly Anhydrite. Due to the low solubility of the anhydrite in this member, it can be assumed that cavern development has always taken place above this stratum.

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2.3 Cavern Volume

The reconstruction of cavern development and migration has been performed using AutoCAD 2023 CAD modelling software. Caverns were modelled and referenced in 3-dimensional space by representing produced salt in tons as cavern volume in cubic metres. A conversion factor coupling tons of salt produced to cavern volume has been derived. This factor has been used for all reconstructed caverns in this study. The input parameters for the conversion are:

Table 2: Input parameters Tonnage-Cavern volume conversion

Density water	0.998	t/m³
Density Brine	1.201	t/m³
Density Salt	2.165	t/m³
Density Insolubles	2.7	t/m³
Insolubles	5%	(m.-%)
Brine concentration	312	kg/m³
Water concentration	889	kg/m³

A brine concentration of 312 kg/m³ has been used for all stages of cavern development by leaching. In reality, the brine concentration at the wellhead will not have been constant, especially during the sump development where undersaturated brine may have been produced. The calculation of the conversion factor however relates to the brine concentration in the cavern which will have been saturated at 312 kg/m³ at least at the end of cavern development by leaching. The volume conversion thus uses a constant value for brine concentration despite the variance at the wellhead.

Using the input parameters listed in Table 2, the composition of 1 cubic metre of in-situ rock salt (before cavern development by leaching) can be calculated:

Table 3: Composition of 1 m³ of in-situ rock salt before cavern development

1 m³ Rock Salt In-Situ					
Total Mass	2.19175	t			
of which Salt	2.082163	t	→	0.96	m³
of which Insolubles	0.109588	t	→	0.04	m³

The composition of 1 cubic metre of cavern space after cavern development by leaching can be calculated next:

Table 4: Composition of 1 m³ of cavern space filled with saturated brine after cavern development

1 m³ Cavern space filled with brine		
Total brine volume	0.96	m³
Total insolubles	0.04	m³
Salt in brine	0.299	t
Water in brine	0.840	t
Insolubles in brine	0.110	t

Based on this composition, it can be calculated how much water it takes to create 1 cubic metre of cavern space by leaching and what the resulting brine yield is:

Table 5: Water requirement and brine yield for 1 m³ of cavern space

To leach 1 m³ of cavern space		
Salt to be disolved	2.082	t
Water required	5.933	m³
Water required	5.921	t
Total brine yield	8.003	t
Brine remaining	1.152	t
Brine produced	6.851	t
Brine produced	5.704	m³

The conversion of the production in tons to cubic metres of cavern space created can now be calculated from the values in Table 5 and the brine concentration in Table 2:

Table 6: Conversion factor production tonnage to cavern volume created.

Production per 1 m³ cavern space	
1.780	t salt produced
0.562	m³ cavern space / ton salt produced

Using this conversion factor, the historic records containing the annual production figures can be converted to the corresponding volume creation over time.

A challenge in the determination of spatial distribution of cavern space is the fact that many of the studied caverns at one point in time achieve a hydraulic connection with one or more adjacent caverns. In the production records, the brine yield of all connected caverns was recorded as if it was a single cavern as no means of distinguishing between where brine originated exists. It is observed from well diaries however that, in practice, caverns were mostly operated in their original production configuration also after a hydraulic connection was established. The way of recording brine production can therefore lead to uncertainty with regards to the spatial distribution of volume in the final years of production for each cavern if a connection with an adjacent cavern is established. For those cases, a best estimate has been prepared which will be cavern specific and thus described in the second report of this series on the actual reconstruction.

2.4 Insolubles in rock salt

The rock salt mined in the TWR area has a very high purity and contains approximately 5 m.-% insolubles. For this study, it is assumed that the insolubles are equally distributed in the rock salt. As the insolubles are liberated by leaching of rock salt, they sink to the bottom of the cavern and settle mainly in the sump area. The characterisation of this insoluble material is difficult as it remains in the cavern. However, as part of a Master thesis project in 2012, a small amount of the insoluble material was liberated in the laboratory of the Department of Applied Earth Sciences at the TU Delft by leaching of rock salt core material from the TWR area. Figure 3 shows the thus extracted insoluble material after separation in three grain-size fractions.

Figure 3: Different fractions of the insoluble material. A is the fine fraction with grains smaller than 2 mm. B is the fraction with fragments up to approximately 5-6 cm and C is the coarse part with larger rock fragments. (Ball point pen used for scale). (http://resolver.tudelft.nl/uuid:dda45cb7-e64d-4e23-b616-90457d01997a , page 18)

The extracted insoluble material from the core material was tested on consolidation properties during this thesis project. From these tests an initial porosity of 33% has been established for freshly settled material without any (self-weight or forced) consolidation. Further testing in an oedometer cell demonstrated that the porosity decreases to approximately 28 % under a load of 120 kPa[1]. For the reconstruction of caverns, a conservative bulking factor for the insoluble material of 1,3; corresponding to a porosity of 25%, has been chosen based on these oedometer test results.

It is likely that some cementation of settled (and consolidated) insoluble material takes place through the crystallisation of sodium chloride and the hydration of anhydrite to gypsum. Anecdotal evidence of a competent sump material is available through the well diaries which note that a drill string of several tens of tons mass can stand on top of the sump material without significant penetration taking place. As such, it is assumed for the study that the sump material forms a solid base for falling rock masses in case of cavern migration and/or for backfill material. Consolidation of the insolubles under the load of bulked overburden in a migration scenario is conceivable, this has not been considered however to err on the safe side in terms of bulking factor estimation.

2.5 Sump development

The initial development of a cavern from an open-hole section of the production well is meant to form an “undercut” for the leaching process, a so-called “sump”. In the current mining practice in the TWR area, a blanket medium is used to control the depth of the sump thus forcing leaching in an outward rather than an upward direction. The caverns included the herewith reported study have generally not been developed using a blanket medium except for caverns 86, 104 and 167 where small amounts of blanket medium (up to approx. 20 m^3) were used at some wells. Due to the absence of a blanket medium or a way to measure/control blanket medium level, depth control of the sump was not possible. The depth of the sump development was mainly limited by the intermediate rock benches between Salt A and B and/or Salt B and C. The current and historic practices are illustrated in Figure 4 below.

[1] http://resolver.tudelft.nl/uuid:dda45cb7-e64d-4e23-b616-90457d01997a , page 100

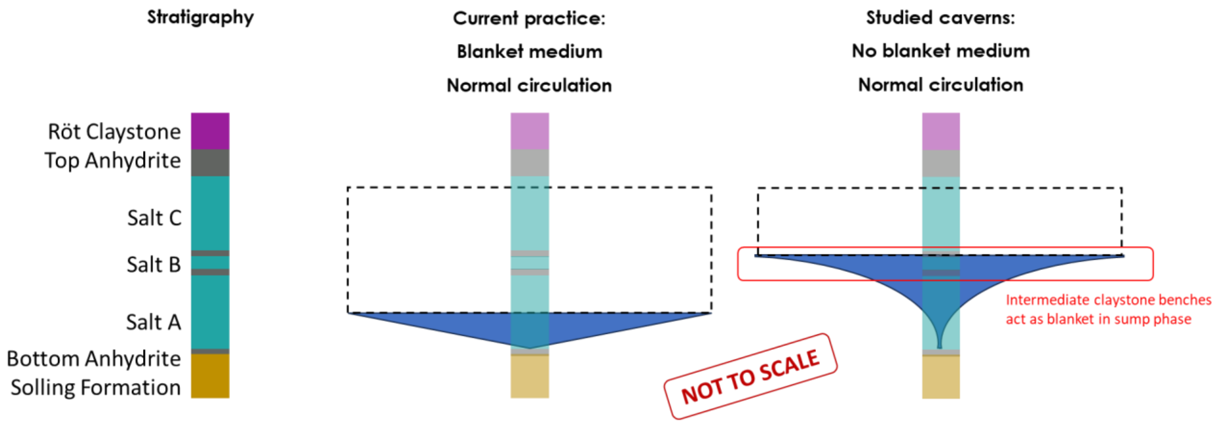

Figure 4: Current and historical cavern sump development using top injection (left with blanket medium, right without)

Whereas the current practice allows for a shallow cone shaped sump, the absence of a blanket medium during sump development for the studied caverns has usually resulted in a (vortex) funnel-shaped sump. Consequently, the cavern development is higher in the saline strata, often leaving out a large part of Salt A as a production member. The original shape of the funnel-shaped sumps has not been observed in available sonar images for two reasons:

1. Sonar technology at the time could not capture the outermost contour of a sump where the cavern height is only a few decimetres due to the limited resolution of the sensor array.
2. A funnel-shaped sump quickly fills up with insoluble material and material from intermediate rock benches. The funnel-shaped sump relies on the use of the "top injection" leaching configuration, i.e. injection of fresh water at the top of the cavern and production of brine near the bottom of the cavern. Most of the studied caverns have been developed using this configuration.

In some of studied cases, notably caverns 33-34 and 35-36 the "bottom injection" leaching configuration was used in which fresh water was injected near the cavern bottom and brine produced from the top of the cavern. This has led to a more cylindrical-shaped sump development as shown in Figure 5.

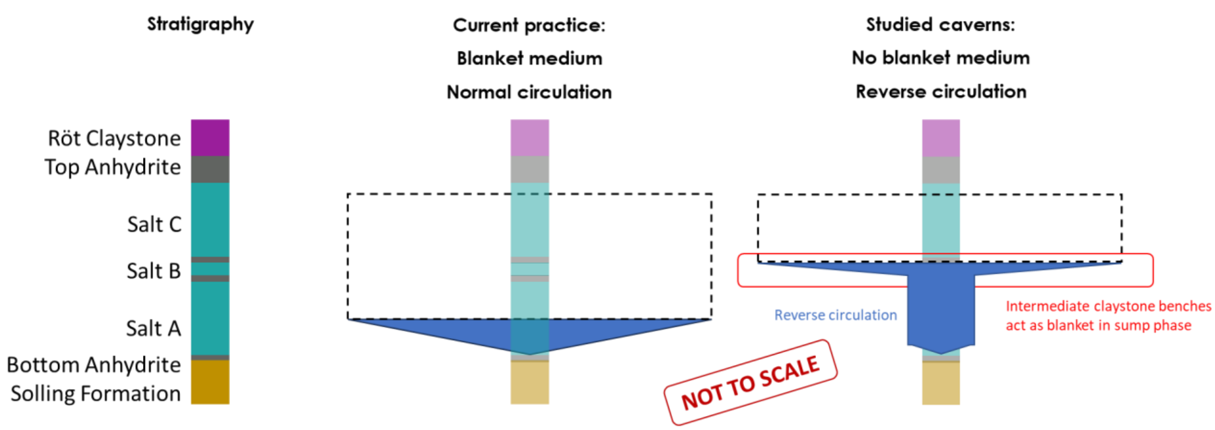

Figure 5: Current and historical cavern sump development using reverse circulation (left with blanket medium, right without)

As with the top injection, also the sump development using bottom injection circulation often reached the intermediate claystone benches which then acted as a blanket and forced an increase of the cavern span as shown in Figure 5. The eventual sump span (contour) largely dictates the further cavern development contour and thus forms the basis for the reconstruction of the further cavern volume development by leaching after the sump had formed.

2.6 Sump development by forced leaching

The sump development methods described in paragraph 2.5 rely on leaching under "normal" pressure conditions. This means that the water is pumped into the developing sump at just enough pressure to displace the produced brine and transport the brine back to the salt plant. In the 1960's and 1970's several caverns in the TWR area were developed using an alternative method namely the "forced leaching" method. This alternative method used high pressure water injection during sump development to shorten the time needed to establish a hydraulic connection between two or more wells drilled as a planned cavern ("Series").

The method comprised the following steps:

1. Two or more wells were drilled in a line, between 40 m and 95 m apart, to the bottom of Salt A.
2. Wells were cased and cemented to a level just above the bottom of Salt A
3. A "high pressure" pump was used to pump water from the water pipeline infrastructure into one of the wells making up the planned series. A blanket medium may have been added at some point during the water injection to control the depth of sump development to some extent.
4. Water injection was not combined with producing brine, i.e. all brine produced by leaching was left in the cavern at this stage.

Pumping continued until a hydraulic connection with (one of) the other well(s) was established. The forced leaching by high pressure water injection could take months and formed an undercut for further cavern development. This process is illustrated in Figure 6 below.

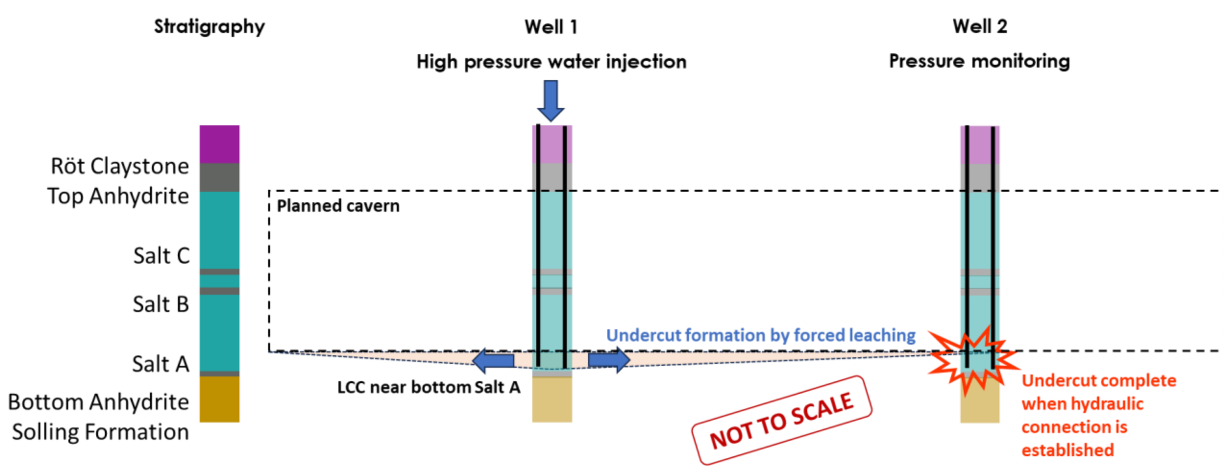

Figure 6: Forced leaching method to create a sump (undercut) in months rather than years

No records for the forced leaching exist other than short notes in the well diaries stating start date and date of hydraulic connection with adjacent wells and some more information in memos/notes. It is therefore unknown exactly at which well(s) the pump was located during the forced leaching. From oral tradition it is known that only one high pressure pump was used. The forced leaching was thus likely performed in sequence at multiple wells in a series. This can also be concluded from notes in the well diaries. Once the hydraulic connection between the wells was established, the cavern development would be initiated by connecting one well to the water infrastructure and the adjacent well(s) to the brine pipeline infrastructure as any other multiple well cavern.

The expected advantage of this method was a faster undercut development than the traditional sump method in which adjacent single well caverns could take years to connect and allow operation as a series. Although to some extent this worked out well, the method was unpredictable in terms of the shape and direction of the undercut. In some cases, a planned hydraulic connection was never established between wells using forced leaching and traditional sump development was subsequently applied instead. In other cases, an unplanned hydraulic connection with another well or a connection to only one of two or three planned connections was established.

For the four caverns in the study where forced leaching was successfully applied to form an undercut, this method resulted in irregular shaped caverns with often a large span in one or more direction(s). A top view of these caverns (sonar images) is presented in Figure 7, the possible initial contour of the undercut is marked by a red dotted line in these pictures.

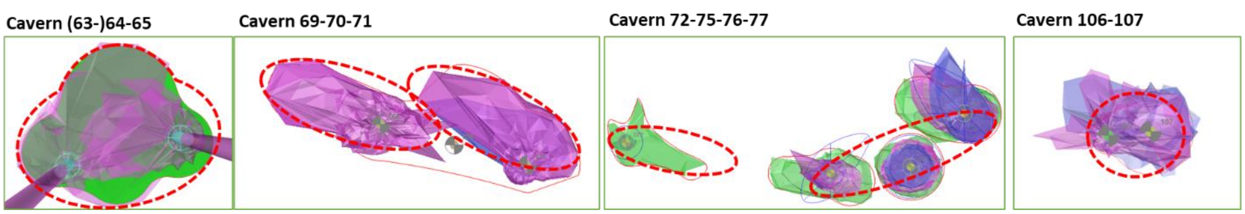

Figure 7: Examples of caverns which were developed from an undercut established by forced leaching

As can be seen from this figure, no consistent shape or extension of the initial contour can be derived from the studied caverns which challenged the reconstruction significantly. The reconstruction of these caverns required a detailed integration of all available data sources and a high degree of iterative work to determine the most probable cavern shape. Furthermore, in the case of cavern 72-75-76-77, cavern volume must have been created by leaching which is not visible in later sonar images. The true cavern extend is thus not clear in this case and assumptions on the position of "missing" volume had to be made during the reconstruction.

2.7 Cavern development

The cavern development after the sump phase without the use of a blanket medium is governed by the largest contour (span) of the sump and the thickness of the remaining rock salt above the sump. Without the influence of collapsing intermediate rock benches, see paragraph 2.8, cavern development broadly follows the pattern illustrated in Figure 8. In the dominantly used "top injection" configuration water is injected in the top of the cavern and consequently first causes a rise in the roof depth near to the well.

As the water is saturated with salt, it slowly sinks and flows outward and along the cavern walls to the bottom where it is produced as saturated brine. The leaching progress shown in Figure 8 considers a single well configuration. In practice, most of the studied caverns were initiated as single well caverns but planned and operated as multiple-well caverns. Wells were located sufficiently close to each other to ensure the single caverns would eventually connect by leaching, preferably early in the combined cavern lifetime.

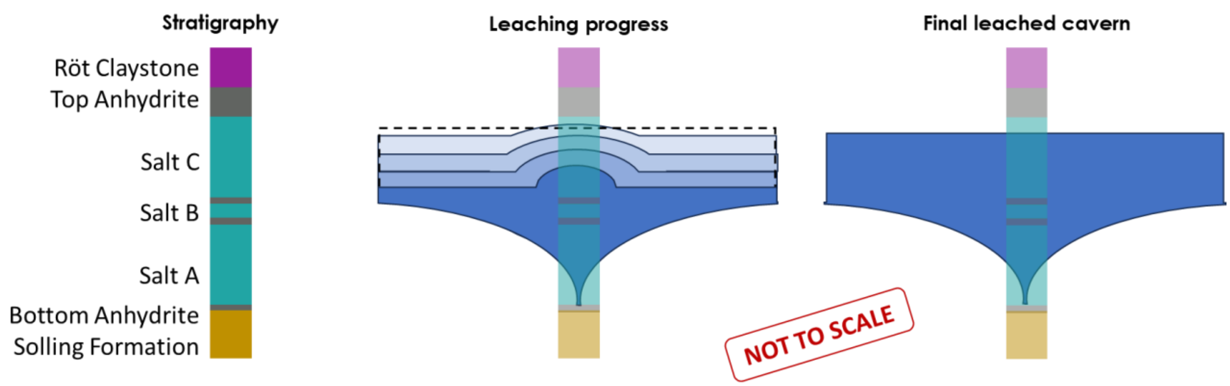

Figure 8: Leaching progress during cavern development (simplified, excluding the effect of collapsing intermediate benches)

After a connection was established, the wells were operated as a pair alternating water injection and brine production between wells. By further manipulating the depth of injection/production, the cavern shape, in particular the depth of the roof was controllable to some extent. With the absence of a controlled blanket medium however, the cavern development of the studied caverns was largely controlled by the geological conditions, i.e. the presence and location of insoluble strata such as the intermediate claystone benches and the Top Anhydrite.

2.8 Intermediate rock benches

The salt members Salt A, Salt B and Salt C in the TWR area are separated by (nearly) continuous intermediate claystone benches as described in paragraph 2.1. Although rock salt may be present in these benches, they are considered insoluble and do not contribute to cavern volume development by leaching in the reconstruction. As they are undercut during cavern development, they will eventually collapse when the undercut reaches sufficient span. The process of undercutting the benches is illustrated in Figure 9 (left picture).

At which undercut span the benches fail is mainly dependent on bench thickness, composition, and the presence of fracture and fissures within. A consistent relationship has not been established during the study. As the intermediate claystone benches collapse, rock material sinks to the bottom of the cavern and collects in the sump area. For the reconstruction of the cavern development, a conservative bulking factor of 1,1 has been assumed. This means that the intact volume of the claystone benches is increased by 10% after collapse and collection in the cavern sump. This is illustrated in Figure 9 where the added volume at the top of the cavern by collapsing rock benches and the consequential rock fill in the sump has been indicated by the red shaded areas in the right picture.

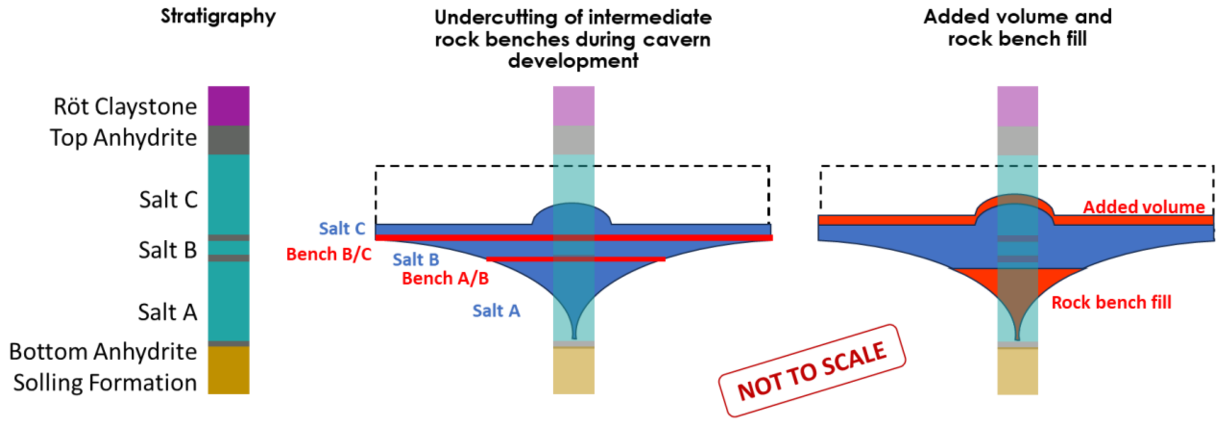

Figure 9: Undercutting and collapse of intermediate claystone (rock) benches (l), added volume and sump fill (r)

Depending on the situation, the collapse of the lower intermediate claystone bench (A/B) may have been (immediately) followed by a collapse of the overlying Salt B and upper intermediate claystone bench (B/C). In these cases, Salt B will not have contributed much to cavern volume development by leaching as the intact rock salt sank to the sump area where a very high brine saturation is normally present and leaching potential is limited. Where this has been suspected from notes in the well diaries it has been considered during the reconstruction and will be noted in the second report of this series on the actual cavern development and migration reconstruction.

2.9 Minimum cavern roof depth by leaching

Generally, during the reconstruction of cavern development by leaching, the top of Salt C, i.e. the bottom of the Top Anhydrite, has been taken as the vertical limit for volume creation, i.e. the minimum cavern roof depth by leaching. In practice this means that as soon as the cavern development reached the Top Anhydrite, any further cavern volume must have been created in a horizontal direction outwards from the cavern wall, increasing the span over which the Top Anhydrite is exposed by leaching. This is illustrated in Figure 10 below.

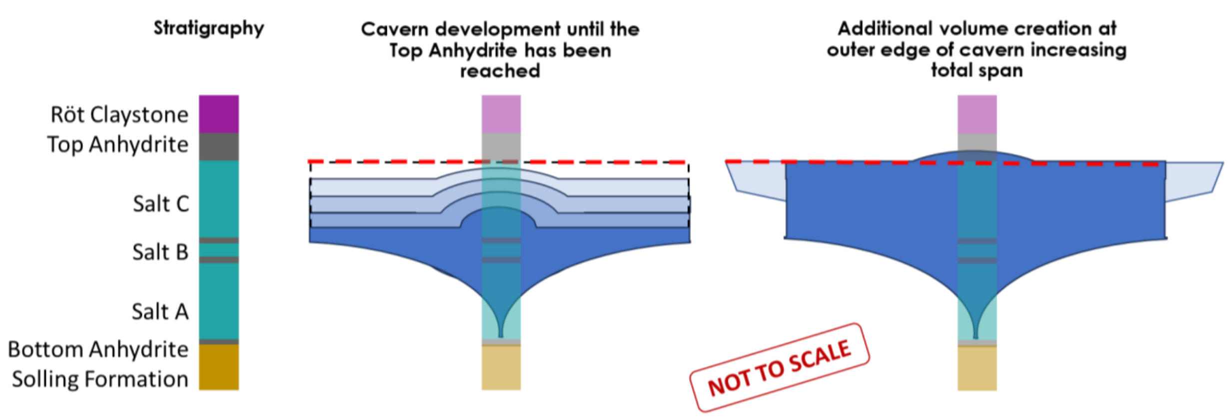

Figure 10: Vertical limitation of cavern development by Top Anhydrite (l) and subsequent outward development of the cavern (r)

As the Top Anhydrite is initially very stable and it is largely insoluble, it acts as a blanket medium and forces the cavern development outward. In many cases this has led to a hydraulic connection with adjacent caverns in a late stage of the cavern lifetime. However, the outward development of the cavern over a limited height could have undercut the Top Anhydrite over a large area in a short amount of time. This may have caused a collapse of the otherwise stable Top Anhydrite over a large area in some of the studied caverns (notably cavern 35-36).

The composition of the Top Anhydrite is not consistent for the studied caverns. In some cases, additional thin beds of rock salt may be present often indicated as “Salt D”. For the reconstruction of cavern volume development by leaching, rock salt included in the Top Anhydrite has not been considered for brine production for two reasons:

1. Rock salt included in the Top Anhydrite member can only be leached after liberation by removal of the underlying Anhydrite layers. As the Anhydrite is both stable and insoluble, the preferred leaching direction will be outward, not upward, see Figure 10.
2. Removal of the Anhydrite layers separating the cavern from “Salt D” can only take place by (gradual) deterioration by water or weak brine (see paragraph 2.1) and/or delamination and subsequent collapse of the Anhydrite layers, likely taking down any rock salt within. Rock salt liberated in this manner will sink to the cavern bottom where it cannot dissolve due to the high salinity of the brine in this part of the cavern.

As a result, the reconstruction of the cavern development used the Top Salt C interface as the minimal depth where volume creation by leaching can take place. A higher roof means (the onset of) migration.

3 Cavern migration by collapse of overburden strata

3.1 Migration and bulking factor

The migration of a cavern is defined as the progressive delamination and subsequent collapse of layers of bedded overburden rock, particularly the Röt Claystone directly overlying the evaporite strata. The Top Anhydrite overlying the salt members acts as stable cap for a cavern due to its mechanical properties. However stable, the Top Anhydrite can delaminate and subsequently collapse in the following situations:

1. The presence of faults and fault systems in some areas of the brinefield may have triggered the collapse of the Top Anhydrite for some of the studied caverns, e.g. around cavern 69-70-71 where a sinkhole was formed in 1991 after migration of the cavern.
2. Collapse may occur when the span of a cavern with a roof containing bedded Anhydrite exceeds the maximum allowable span as determined by the internal strength and thickness of the Top Anhydrite as well as the vertical load acting on it. Depending on the internal structure (bed thickness, presence of fissures, etc.) of the Top Anhydrite, it can be imagined that a collapse can be gradual (layer by layer) or sudden (several layers at once) after the failure criterion has been reached.
3. The Anhydrite is exposed to "fresh" water or unsaturated brine for a long period of time which would promote the formation of Gypsum in fissures/bedding planes by hydration of Anhydrite. This process is paired with a volume increase of the formed mineral which can cause delamination and fracturing of the Anhydrite. A gradual deterioration of the cavern roof in this manner may cause a later (sudden) collapse of the Top Anhydrite.

For the reconstruction of cavern migration, the migration process is initiated by the collapse of the first layer(s) of Top Anhydrite. As the strength of the Röt Claystone is generally lower than the strength of the Top Anhydrite, migration, once initiated, will progress upwards.

The actual collapse of overburden material will be preceded by delamination of the overlying (bedded) rock layers. GEOWULF Laboratories (GEOWULF) has analysed series of gamma rays logs over time for several of the studied wells in the brinefield. It was concluded by GEOWULF that delamination can be recognised as a progressive thickening of small lithological units with depth. From these analyses, delamination has been observed to be present 20 m to 40 m above the residual cavern roof. For the reconstruction, a conservative value of 40 m has been used as a result.

The rate at which the migration process progresses has been estimated by Bekendam at approximately 10 m per year. The current study generally confirms this value, however, it is likely that this rate has been highly variable with migration progressing rapidly in some years, while holding for others. The variance in strength/competency of small lithological units within the Röt Claystone/Muschelkalk and/or the absence/presence of faults may have caused this variation. The migration will stop once the migrating cavern void has effectively filled itself by the bulking of collapsed overburden material.

The bulking of overburden material after collapse is quantified by the so-called bulking factor (BF) which is defined as the ratio of the bulked volume of rock collecting on the cavern bottom over the volume of intact rock before collapse. The bottom of the cavern is formed by the insolubles that collected in the sump area. The migration process and bulking factor are illustrated in Figure 11.

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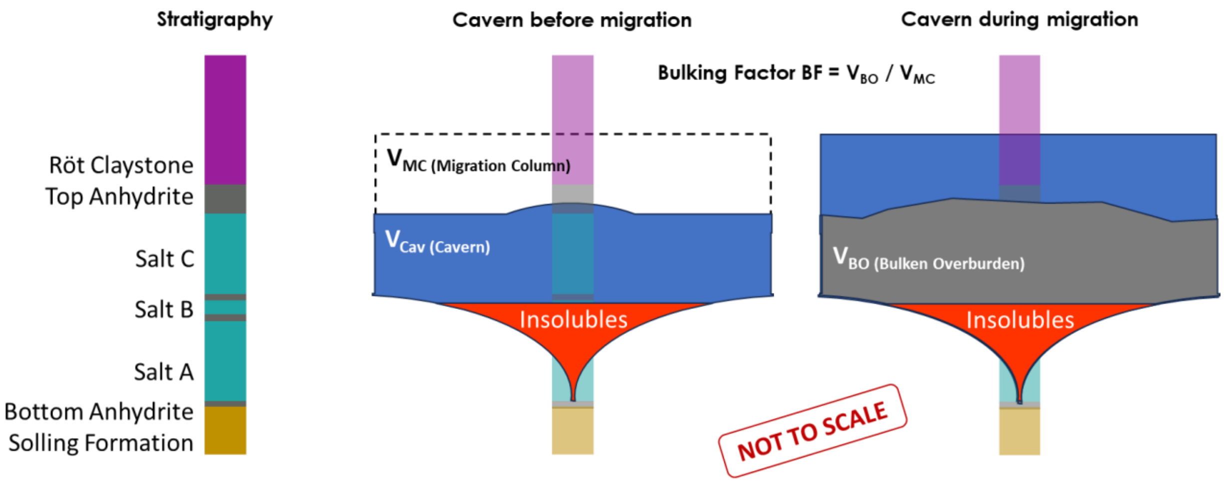

Figure 11: Cavern migration and bulking factor

The bulking of overburden on the bottom of the caverns causes the residual cavern to continuously decrease in height and volume. The migration will progress until the bulked overburden starts to support the migrating cavern roof and further collapse of the residual cavern roof is prevented. The bulking factor thus principally determines how far upward a cavern can migrate due to collapse. As the delamination of the overburden precedes the collapse by 40 m, the top of the migration column will be at a depth of 40 m above the final depth roof of the residual cavern. This is illustrated in Figure 12 below.

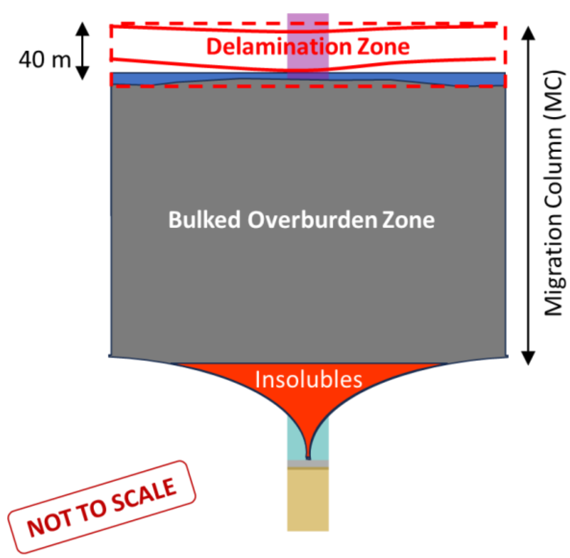

Figure 12: Definition of Migration Column comprising Bulked Overburden Zone (BOZ) and Delamination Zone (DZ)

The Migration Column (MC) as used in the volume reconstruction study thus comprises two parts:

1. Bulked Overburden Zone (BOZ) where the original stratigraphy of the overburden is not or hardly recognisable in Gamma Ray logs;
2. Delamination Zone (DZ) where the original stratigraphy of the overburden is recognisable and a thickening., i.e. delamination of the layers decreases to zero at the top of the MC.

When the collapse of the roof cannot progress due to the limited residual cavern height, delamination of the remaining overburden will continue for some time as the column of bulked overburden consolidates. The top of the delamination zone will not likely change as no more collapse takes place, only a redistribution of porosity can thus be expected.

The described progression and end of roof collapse are illustrated in Figure 13 below.

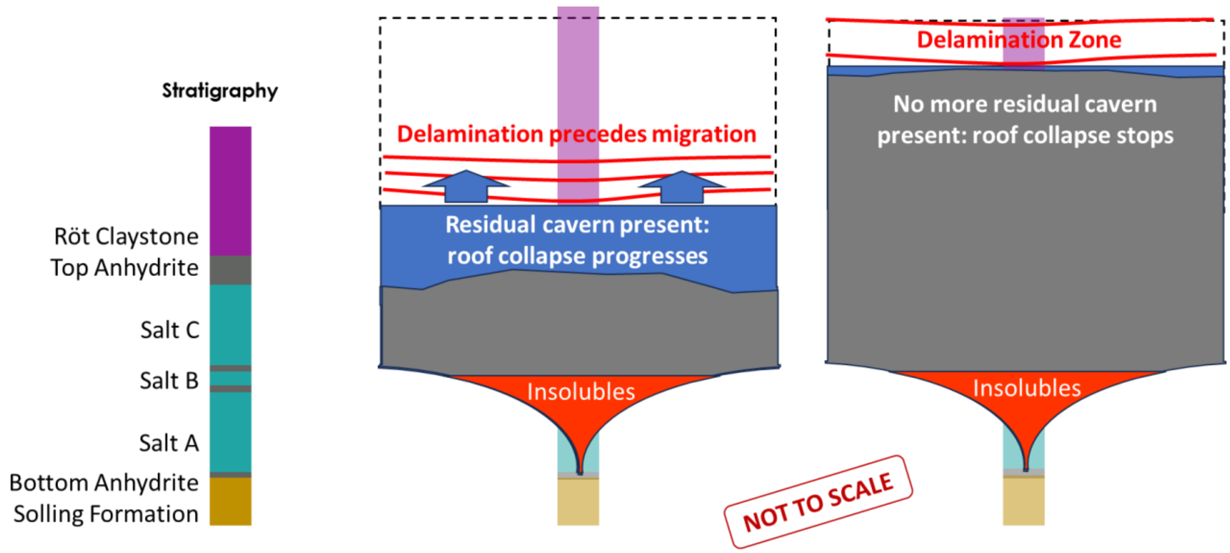

Figure 13: Cavern migration by progressive roof collapse preceded by delamination (l); end of roof collapse migration as residual cavern height is near zero (r)

3.2 Arching and bulking factor

In the work by Bekendam, the bulking factor of 1,11 was established from 1-dimensional assessment of migrated caverns based on the vertical displacement of geological markers determined from gamma-ray logs. The Bekendam method of determination of bulking factor does not consider the original volume and shape of the cavern and relies on a cylindrical migration column. The observed migration of the studied caverns does not fit that model in all cases and a new approach was therefore developed to allow reconstruction of most observed situations. In this new approach both the volume of the original cavern and the possibility of an “arching” effect during migration are introduced as parameters in the reconstruction. The differences between the Bekendam and current approaches are illustrated in Figure 14 below.

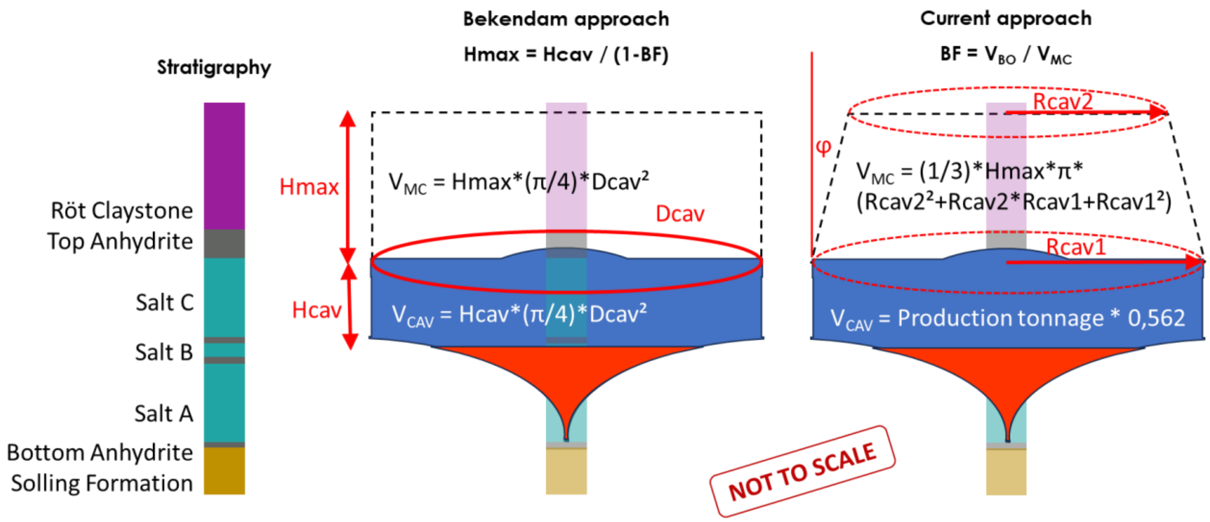

Figure 14: Bekendam approach without arching versus current volume-based approach with arching

The new approach enables variation of the arching angle (φ) and consequently allows better manipulation of the migration column shape following the observed migration column shape. The importance of migration column shape is illustrated by Figure 15 below.

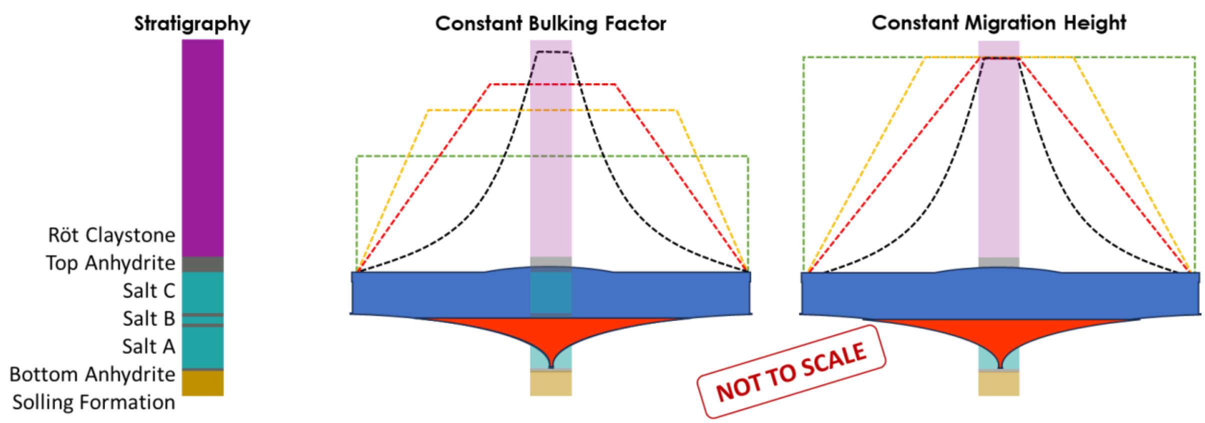

Figure 15: Influence of migration column shape on bulking factor (l) and maximum migration height (r).

Referring to this figure two situations can be clarified. First (left picture) the situation where a constant bulking factor is applied, and the shape of the migration column determines the maximum height of the migration (left picture). A cylinder-shaped migration column (green shape) will result in a less conservative prognosis for migration than a truncated cone (yellow and red shapes). In case a migration column has an inverted “vortex funnel” shape (black shape), the migration height can reach even higher than for the truncated cone shape. Second (right picture) the situation where the migration height is known (e.g. from delamination information), and the shape of the migration column will determine the historical bulking factor. In the right picture in Figure 15, the green shape could for example represent a BF of 1,11 whilst the red shape represents a BF of 1,25.

To enable the selection of an applicable migration column-shape several migration columns for the studied caverns have been reconstructed and analysed in terms of bulking factor and maximum migration height. This analysis showed that apart from the “intrinsic” arching that may be expected as the strongly bedded overburden strata collapse, it is likely that also the shape of the (residual) cavern is in part responsible for the migration column shape.

The intrinsic arching can be expected due to redistribution of stresses in the delaminating cavern roof, forming an arch over the cavern as shown in Figure 16 (left picture). The overburden load is redistributed in an arch spanning to the cavern pillar. Within this arch zone a compressive stress can be expected while underneath the arch tensile stresses are causing delamination as shown.

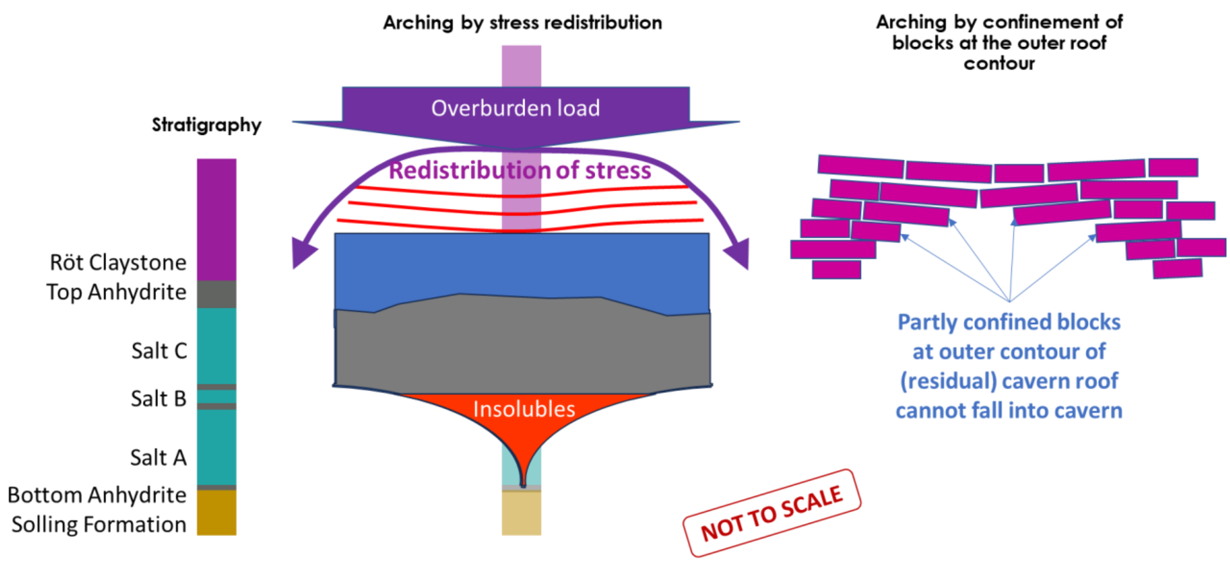

Figure 16: Intrinsic arching of roof collapse due to redistribution of stress (l) and confinement of blocks (r)

Arching may also occur due to small scale geometries where blocks of delaminated overburden rock are prevented from collapse by being partly confined by over- and underlying layers at the outer contour of the cavern roof, as shown in Figure 16 (right picture). Only unconfined blocks can fall into the cavern while partly confined block may remain in their original position. This mechanism also decreases the span over which collapse can take place and the shape of the migration may change due to this effect.

The (observed) additional influence of the (residual) cavern shape on the migration column shape is illustrated by the examples in Figure 17. Two extreme cases are shown in this figure:

- (Left picture) migration column shape over a cylindrical cavern
- (Right picture) migration column shape over a cavern with an inverted cone shape

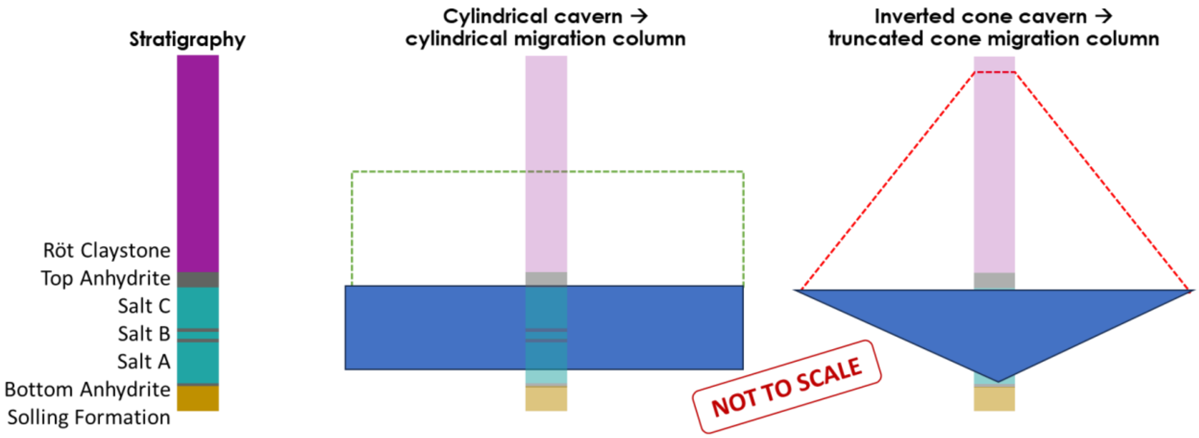

Figure 17: *Shape of cavern determines migration column shape: cylindrical (l) and cone-shaped (r)*

The left picture shows the likely migration column shape for a cylindrical cavern with a similar cavern height at each location in the cavern not considering intrinsic arching mechanisms as described prior. All material released from the cavern roof during migration can sink straight down to the bottom of the cavern. Consequently, the bottom rises as a near horizontal plane. The height of the cavern is reduced by the bulking of overburden material as the migration progresses and the height at any location in the cavern remains similar.

The right picture shows the likely migration column shape for an inverted cone-shaped cavern with a large cavern height at the centre and a near zero height at the outer contour. Material released from the centre of the cavern roof will sink straight down and collect on the cavern bottom. Material released from the outer contour of the roof however cannot fall straight down as the cavern height is zero at the contour. Consequently, as the roof line collapses, material from the outer roof contour will soon support the "wall" of the migration column. As the wall is supported at the outer contour, the unsupported span of the residual cavern reduces, and the migration column diameter thus also reduces forming a truncated cone as shown.

In practice, the reduction of the diameter with migration height will most likely not be constant thus forming an inverted vortex funnel as shown in Figure 15. This shape is difficult to capture in a mathematical formula and even more difficult to select shape parameters for. Consequently, in the prognosis algorithm under development, a truncated cone will be used to define the migration column shape. An analysis of the studied migration columns will enable the selection of an appropriate set of shape parameters and a corresponding bulking factor, see the third report in this series on Phase 1 of the Update Migration Study for more details.

With two basic cavern shapes defined, it can be imagined that combinations of the cavern shapes shown in Figure 17 are possible, for example a cylindrical cavern with an inverted cone bottom. This is shown in Figure 18 in the left picture. As the top part of the cavern is cylindrical, the initial migration column shape will also be cylindrical. However, as the average height of the cavern decreases with the progression of migration, the cavern height at the outer contour will reduce to zero. At this point a transition in migration column shape can be initiated as shown. The remainder of the migration will form a truncated cone until the cavern volume is (near) zero and the roof collapse stops as a result.

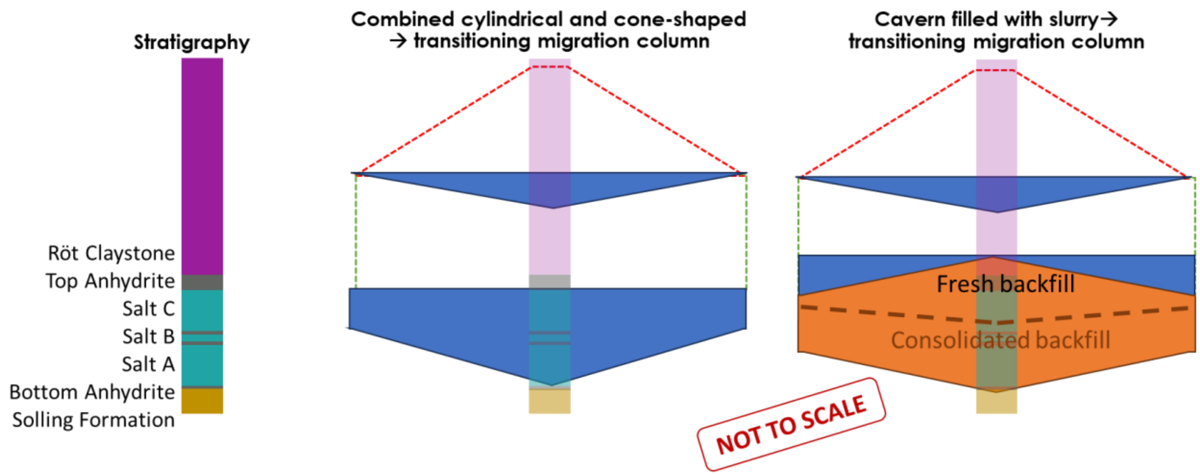

Figure 18: Shape of cavern determines migration column shape: combination cylinder and cone (l) and filled cavern (r)

Another possible scenario where a transition in the migration column shape can be expected is a cavern backfilled with slurry. The backfill will form a heap with a cone-shaped top as shown in Figure 18 in the right picture. As the migration progresses, the increasing load of bulked overburden on the backfill will cause the backfill to consolidate. As the thickness of the backfill in the cavern is largest at the centre, the consolidation potential of the backfill will also be the largest at the centre of the cavern. The original cone-shaped top of the backfill heap will thus transition into an inverted cone due to consolidation of the backfill. As the migration progresses, the shape of the residual cavern will likely also transform to an inverted cone as a result and the migration column shape will transition from a cylinder to a truncated cone.

The final presented scenario is a cavern which has an asymmetrical sloped bottom as shown in Figure 19. Initially the migration column shape will be cylindrical as the top part of the cavern is a cylinder. As the average cavern height is reduced by the bulking overburden, an asymmetrical residual cavern will form. Once the cavern height is reduced to zero at a part of the outer contour, the migration wall at this point will be supported by bulked overburden and the roof span will start to decrease. The migration will therefore be directed towards the area where the cavern height is largest and an asymmetrical migration column forms. This asymmetry can also cause the residual cavern progressing upwards to follow a path outside of the well path. A residual cavern is therefore not always visible from the well which has been considered during the reconstruction of cavern migration of the studied caverns.

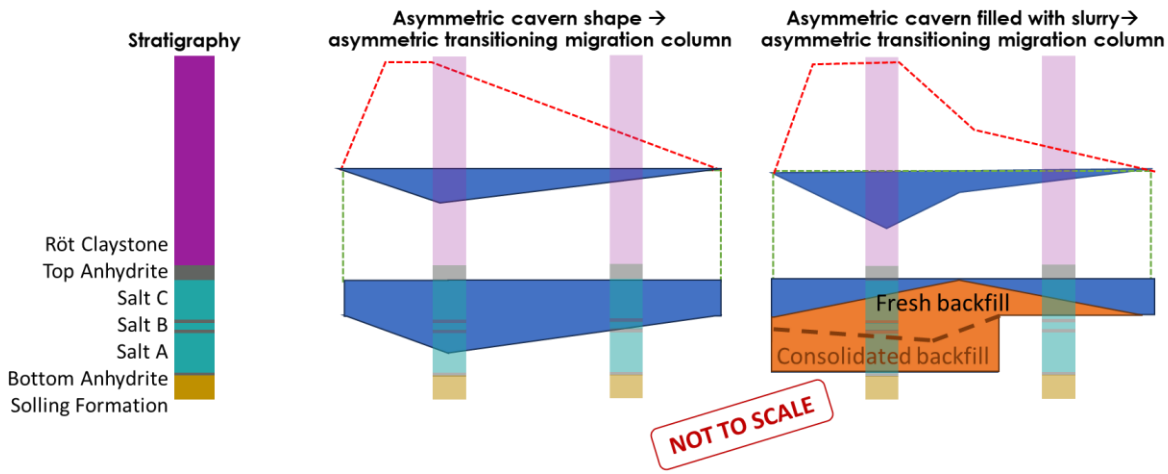

Figure 19: Shape of cavern determines migration column shape: asymmetric cavern (l) and asymmetric filled cavern (r)

An asymmetrical residual cavern can also form over a slurry filled cavern with a sloped bottom or a step as shown in Figure 19, right picture. Due to the varying thickness of the fill at different locations in the cavern, an uneven consolidation under the load of bulked overburden during migration can be expected. As in the previously described scenario, this can lead to an asymmetrical residual cavern and consequently a transition in the migration column shape as shown.

The presented scenarios are intended to form a framework along which the caverns in Phase 2 of the Update Migration Study will be classified. Depending on the shape of the cavern, an expected migration column shape will be determined, and the selected shape parameters applied. The classification of the total population of caverns for which an update of the subsidence prognosis is sought will avoid some prognoses to be overly conservative whilst others are not conservative enough as observed for the Bekendam method due to the 1-dimensional approach.

4 Subsidence

4.1 Overview

The development of (unsupported) underground space for any purpose will always cause subsidence to some extent, this has been sufficiently demonstrated in the wider civil and mining industries. In the case of salt caverns, subsidence can be caused by several mechanisms as shown in Figure 20. The effect of each of the shown causes is cumulative. The first cause for subsidence over a salt cavern is creep of the rock salt resulting in cavern convergence. The convergence volume will be transferred to subsidence over a large area around the cavern. The second cause will start to play a role once the cavern is migrating and no longer surrounded by rock salt. The overburden is not able to creep as the rock salt but will deform due to the changes in stress within the overburden as the migration progresses. The deformation is also translated to subsidence causing the subsidence rate to slightly rise.

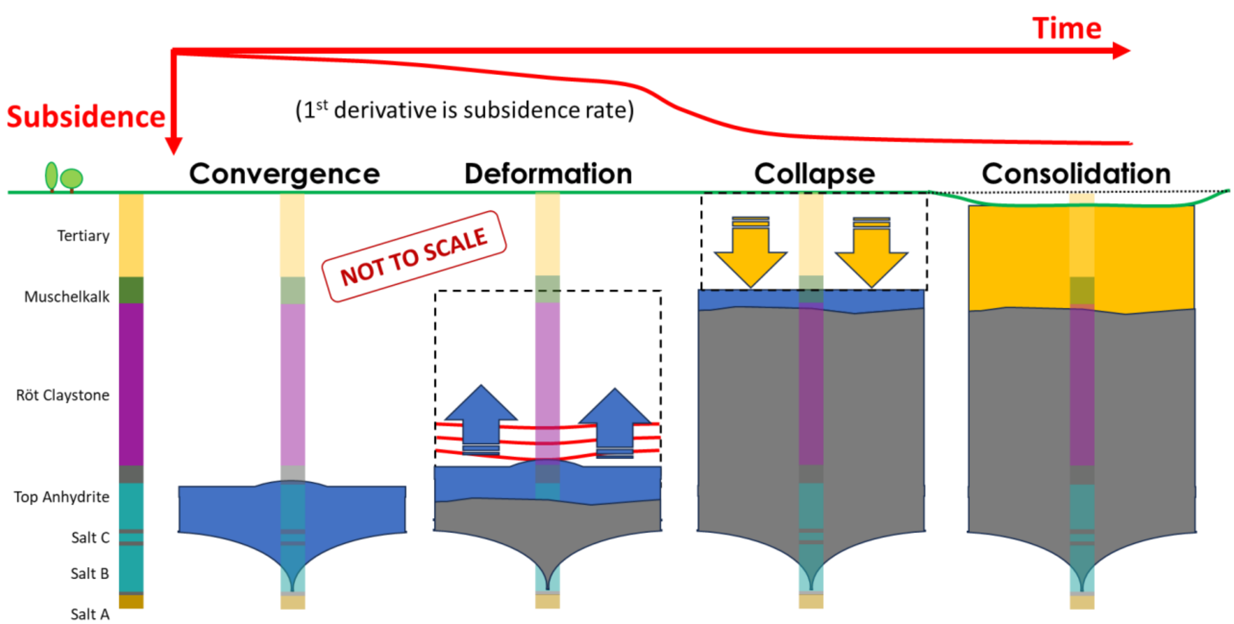

Figure 20: Causes of subsidence over migrating salt caverns: convergence, migration, collapse and consolidation

Once the migration column has progressed to a depth nearing the bottom of the Tertiary, the final rock layers forming the roof over the residual cavern will first bend and then collapse if sufficient cavern height is present. The (sudden) collapse will cause a strong deformation of the Tertiary and cause significant subsidence at the surface as the unconsolidated soils of the Tertairy fall into the residual cavern. A trough or sinkhole may form as a result of the collapse of the final competent rock layers.

The final cause of subsidence is the consolidation of the bulked overburden in the migration column as shown in the picture on the far right in Figure 20. Consolidation of the bulked overburden is transferred to a slow and diminishing subsidence which will continue for tens of years after the collapse of the final competent rock layers.

For the studied cases, only a few caverns demonstrate the full progression of migration and consequent subsidence as shown in Figure 20. Other caverns have migrated, but the migration has stopped well before any collapse of the final roof beam could occur. In these cases, the subsidence caused by the collapse of the final competent rock layers is not present. Consolidation of the bulked overburden thus directly follows the deformation stage. This is illustrated in Figure 21 below.

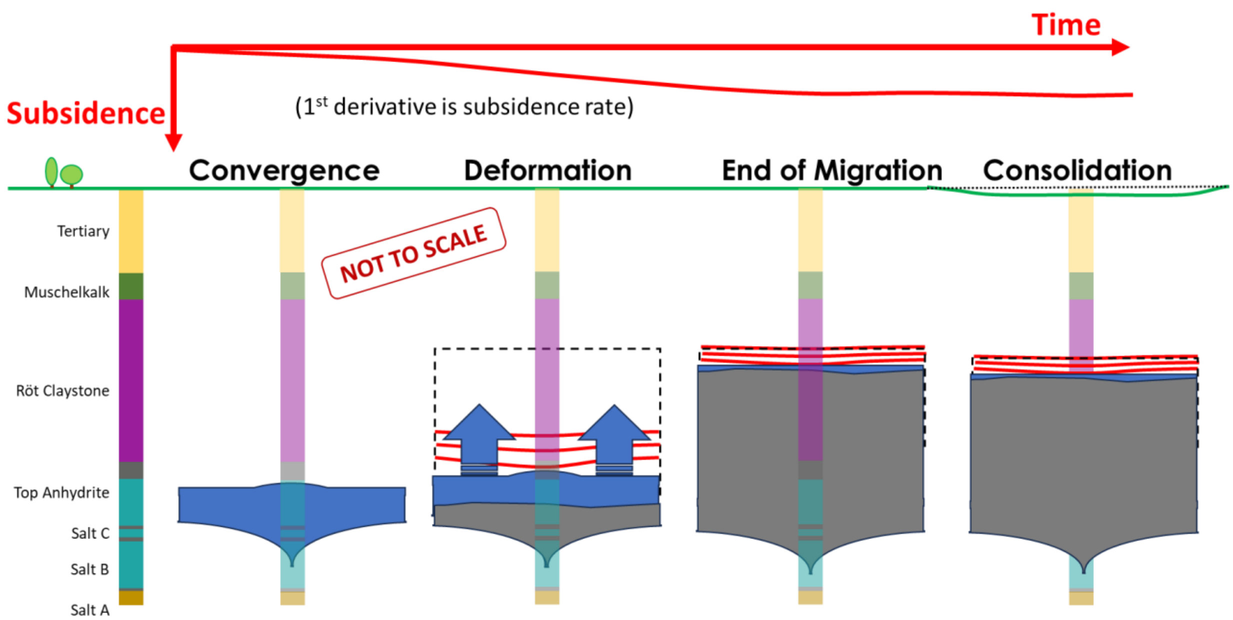

Figure 21: *Causes of subsidence over a cavern for which migration stops well below the final competent rock layers*

The overall progression of subsidence can thus be separated in five stages following the cause of subsidence:

- Stage 1 – Rock salt creep induced
- Stage 2 – Overburden deformation induced
- Stage 3 – Induced by the deflection of the final competent rock layers
- Stage 4 – Induced by the collapse of the final competent rock layers
- Stage 5 - Induced by the consolidation of the bulked overburden.

Stages 3 and 4 may not occur when the cavern migration ends well below the final competent rock layers. In the following paragraphs each of these stages is further detailed.

4.2 Stage 1: Salt creep induced subsidence

The subsidence caused by the creep of rock salt is designated as Stage 1 subsidence. The transferral mechanism for salt creep is illustrated in Figure 22 below.

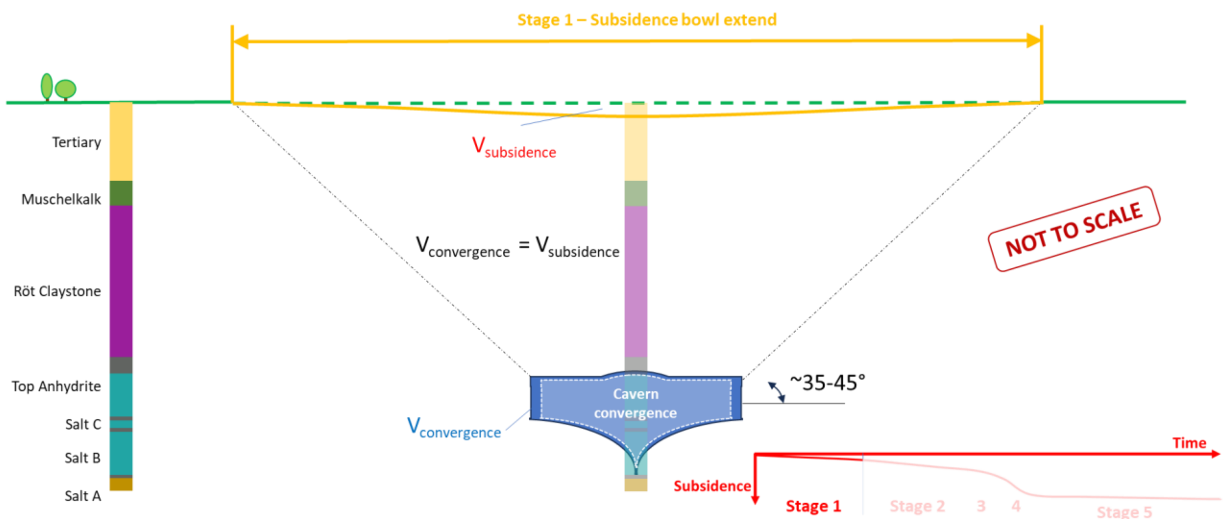

Figure 22: Stage 1 subsidence caused by rock salt creep and consequent cavern convergence

The volume loss in the cavern caused by the creep of the rock salt can be translated to a subsidence bowl at the surface of the same volume. The area of influence for Stage 1 subsidence is large and determined by an angle of 35-45° from horizontal taken from the outer contour of the cavern. As the caverns in the TWR area are relatively shallow, the subsidence rate for Stage 1 is very low.

When a cavern does not migrate, the Stage 1 subsidence caused by gradual convergence of the cavern due to salt creep is the not the only cause for subsidence that can be expected. In the oldest areas of the brinefield pillar deformation has also caused subsidence over caverns that not necessarily migrated. Pillar deformation is a form of salt creep but caused by under-dimensioning of the pillars surrounding the caverns. Pillar deformation causes additional subsidence on top of the subsidence caused by gradual cavern convergence and has thus caused in increase in subsidence rate over these caverns without migration taking place. Stage 1 subsidence is not subject of the current Update Migration Study and is not considered in the reconstruction.

4.3 Stage 2: Overburden deformation induced subsidence

Once the cavern roof is no longer comprising rock salt and/or intact Anhydrite, i.e. after the cavern development by leaching has reached the Top Anhydrite and some deterioration/collapse of the Top Anhydrite has passed, the deformation of the overburden is added as a cause for subsidence. This Stage 2 subsidence is therefore the addition of rock salt creep induced subsidence and overburden deformation induced subsidence as shown in Figure 23 below.

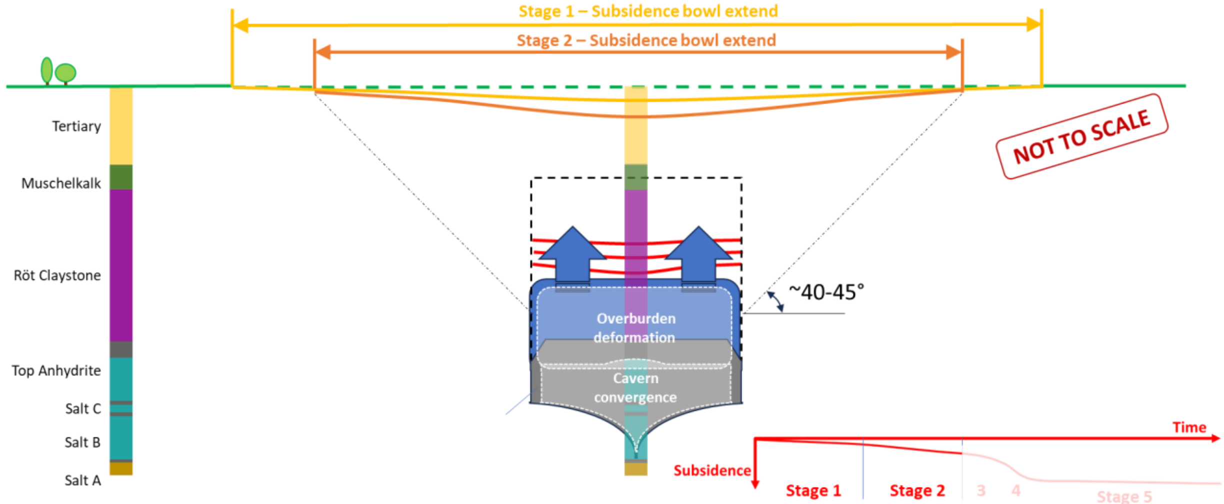

Figure 23: Stage 2 subsidence caused by deformation of overburden rock around a migrating cavern

The area of influence of the Stage 2 subsidence will be smaller than the area for Stage 1 subsidence as the average depth of the total void space (original cavern + migration column) is decreasing with the progression of migration. The shrinking of the area of influence will cause an increase in subsidence rate at the centre of the subsidence bowl. The outer edges of the Stage 1 subsidence bowl are less affected by the deformation of the overburden.

The migration of the cavern will progress until nearly zero residual cavern volume is left and roof collapse of the residual stops. In the case the migration does not approach the Bottom of the Tertiary, the Stage 2 subsidence will be followed directly by subsidence caused by the consolidation of the bulked overburden and of backfill in the cavern when present.

When the migration does reach a depth nearing the Bottom of the Tertiary, the last layers of competent rock will deflect and cause Stage 3 subsidence. This is further discussed in the next paragraph.

4.4 Stage 3: Deflection of Top Rock induced subsidence

A migrating cavern which nears the Bottom of the Tertiary, i.e. the “Top Rock”, will start to cause Stage 3 subsidence caused by the deflection of the final competent rock layers above the residual cavern. This is also the moment where delamination of the competent rock layers is translated directly into subsidence. The deflection mechanism is illustrated in Figure 24. The final competent rock layers over a residual cavern near to the Top Rock carry the overlying load of the Tertiary sediments. The bearing capacity of these lyers will be dependent on the span of the residual cavern and the internal strength of the material, e.g. Röt claystones or Muschelkalk marls. The presence of fissures and fractures in these layers will also influence the bearing capacity. As the thickness of the remaining competent rock layer over the residual cavern is reduced by migration, deflection will become prominent as a precursor for collapse when sufficient cavern volume remains.

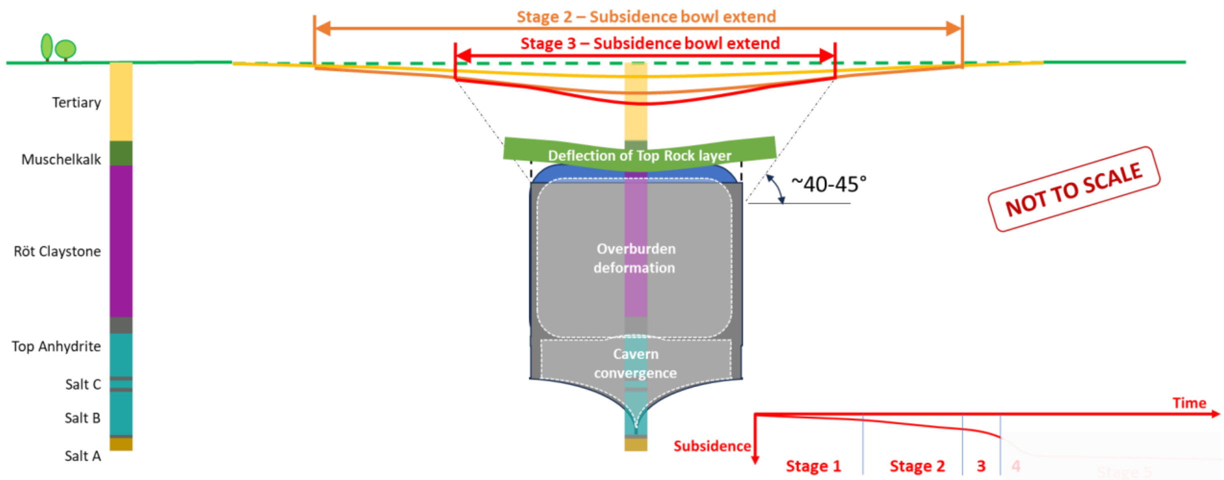

Figure 24: *Stage 3 subsidence caused by bending of the final competent rock beam over a migrating cavern*

Bekendam used a constant criterium for the thickness of the final competent rock layers of 40 m. This value was based on the observation that the migration of cavern TWR-015 reached a depth corresponding to 40 below Top Rock and deflection of the beam was not observed. The current study interprets the information pertaining to the migration of cavern TWR-015 differently, resulting in a migration reconstruction which places the final depth of the roof of this cavern considerably deeper. The basis for the Base Tertiary minus 40 m criterium ("BT-40") is thus no longer considered valid.

For the update of the subsidence prognosis a new criterium for the minimum beam thickness will be used. This criterium should at least consider the span of the residual cavern when it approaches the Top Rock as it can be expected that the span will dictate the capacity of the beam to bend. The lithology and structure could also be considered, i.e. corresponding Röt Claystone or Muschelkalk (or Jura in rare cases) as well as the presence of faults and fissures. The selection of the parameters defining the new criterium will be based on the results of the migration reconstruction for the caverns included in the study.

The area of influence for Stage 3 subsidence is smaller than the Stage 2 area of influence as the cause of the Stage 3 subsidence is considerably shallower than the average depth of the void determining Stage 2 subsidence. The subsidence rate at the centre of the subsidence bowl will thus further increase due to the cumulative effect of Stage 1, 2 and 3 subsidence causes.

The Stage 3 subsidence will transition into Stage 4 subsidence once the maximum deflection capacity of the final competent rock layers has been reached and they collapse into the cavern when sufficient cavern height is present. A sinkhole or trough will form as result. When the deflection of the Top Rock reaches the bottom of the residual cavern without collapse taking place, the Stage 3 subsidence will transition directly into the last subsidence stage caused by the consolidation of the bulked overburden in the void space (i.e. Stage 5 subsidence). Stage 4 subsidence will not take place in this situation.

4.5 Stage 4: Collapse of Top Rock induced subsidence

Once the final layers of competent rock over a residual cavern which reaches the Top Rock with sufficient cavern height collapses, Stage 4 subsidence is caused by the (rapid) deformation of the Tertiary soils. This process is shown in Figure 25. It has been observed from the provided information (e.g. regarding the 1991 sinkhole at well TWR-070) that the area of influence of the Stage 4 subsidence is initially limited to the maximum extent of the residual cavern, an 80° to 90° angle has (historically) been proposed. In the weeks/months after the initial (sudden) deformation of the Tertiary, the area of influence for Stage 4 subsidence becomes gradually larger area as Tertiary soils are drawn into the collapse zone. A ~40-45° angle has been used historically and in literature to delineate the maximum extend of this second part of Stage 4 subsidence.

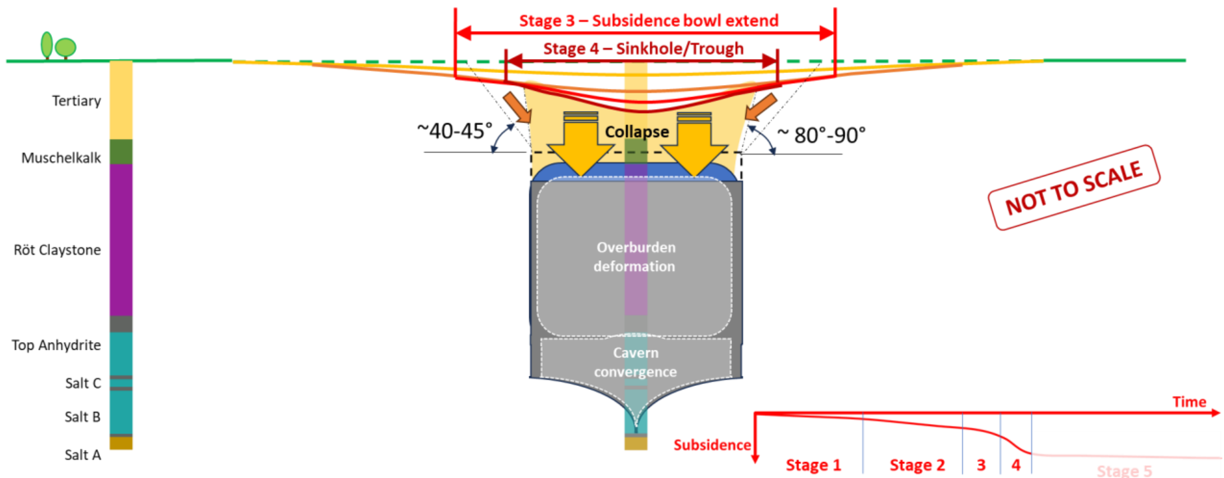

Figure 25: Stage 4 subsidence caused by collapse of the final competent rock beam over a migrating cavern

Bekendam used a 1-dimensional criterium based on residual cavern height to differentiate between a potential sinkhole and a trough type Stage 4 subsidence. The current study will adapt this approach by using a volume-based calculation and incorporating the span of the residual cavern as it approaches the Top Rock, see also the previous paragraph and the illustrations in Figure 26.

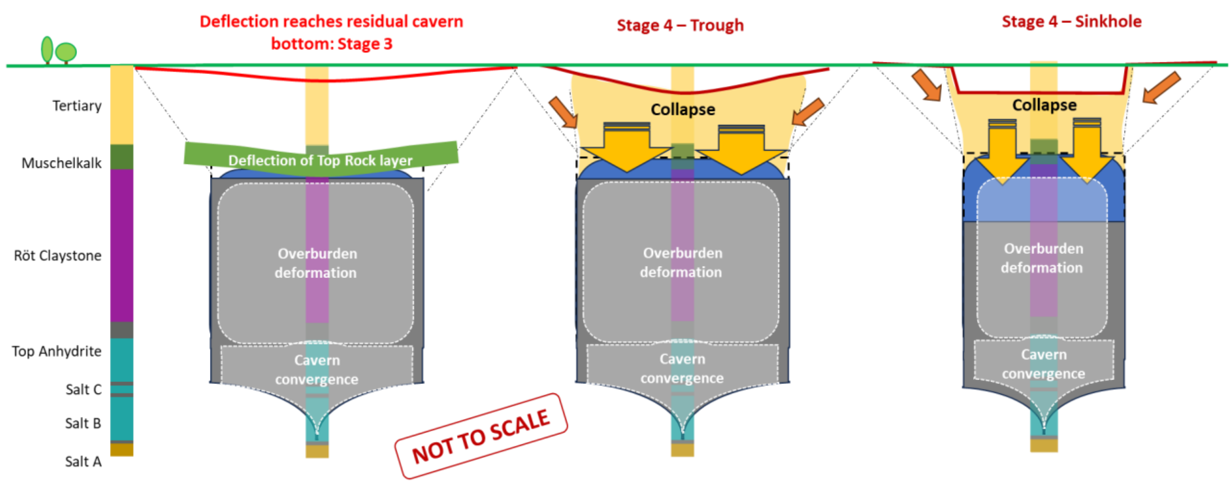

Figure 26: Stage 4 subsidence, differentiation between trough and sinkhole subsidence based on cavern span and height

In this figure three example situations are shown:

- (Left picture) A wide residual cavern with insufficient height has reached the Top Rock. The final rock layers will deflect until they touch the cavern bottom. Collapse of the final rock layers does not occur, and Stage 3 subsidence is followed directly by Stage 5 subsidence caused by consolidation of the bulked overburden (and backfill if present).
- (Middle picture) A residual cavern with sufficient span and height to allow collapse has reached the Top Rock and the final rock layers collapses. As the residual cavern has sufficient span for collapse but a relatively limited height, the collapse of the Top Rock translates the deformation of the Tertiary soils over a large area and a trough develops at the ground surface. The area of influence for this type of Stage 4 subsidence will gradually increase over time as the flanks of the initial deformation column are sliding into the centre of the migration column.
- (Right picture) A residual cavern with sufficient span and height for collapse has reached the Top Rock. As the residual cavern has sufficient span for collapse and a relatively large height, the collapse of the Top Rock translates the deformation of the Tertiary soils over a more concentrated area a sinkhole develops at the ground surface. The area of influence for this type of Stage 4 subsidence will also gradually increase over time as the flanks of the sinkhole cave in and the flanks of the initial deformation column slide into the centre of the migration column.

The presence of faults and fault systems in the vicinity of a cavern may also influence the differentiation between the formation of a trough or a sinkhole. It can be imagined that a faulted roof beam may cause roof collapse despite Top Rock thickness. The presence of faults and fault systems has been mapped in detail for the TWR area allowing for a case-by-case approach during planned potential subsidence prognosis study (Phase 2, see Chapter 1).

4.6 Stage 5: Consolidation of bulked overburden induced subsidence

The final stage for any cavern which has migrated to some extent, is caused by the gradual consolidation of bulked overburden in the migration column. This is illustrated in Figure 27 below.

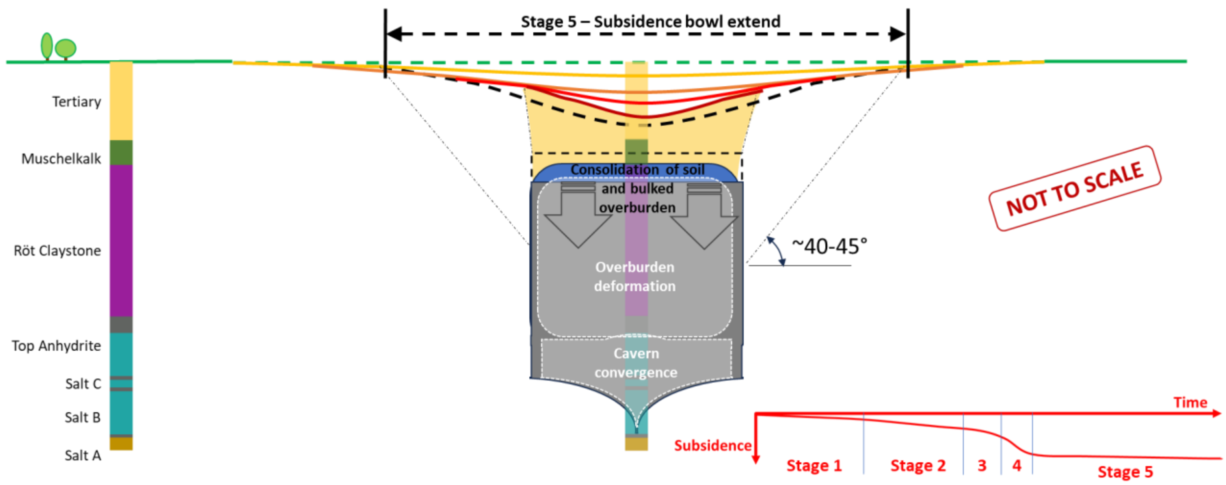

Figure 27: Stage 5 subsidence caused by consolidation of bulked overburden in the migration column

The extend of Stage 5 subsidence will be defined by a ~40-45° angle taken from average depth of the migration column. The subsidence rate will be small and diminishing with time.

5 Summary and Conclusions

This first of three planned reports which cover the overall reporting for the Update Migration Study Phase 1 describes the fundamental principles used during the reconstruction of leaching and migration development of the 10 caverns included in the study. These principles have been deducted from the available information and countless iterations performed during the reconstruction of cavern leaching and migration processes for the studied caverns. Furthermore, analogues from industry (mainly SMRI and personal experience with sinkholes in the Dead Sea area) were used as inspiration and as a validity check. The understanding of these fundamental principles will greatly support the reader during the review of the actual reconstructions described in the second part and the link between migration and subsidence discussed in the third part of the reporting cycle for Phase 1 of the Update Migration Study. The second and third part of the reporting cycle will refer to this document to ease review.

The presentation of the fundamental principles used in the study has been divided over three chapters.

Chapter 2 covers principles used to reconstruct the leaching phase of the study caverns. This chapter describes the several phases of cavern development starting with formation of a sump. Different methods of sump development have been used over the years, each with their own effect on further cavern development. Limitations to (vertical) cavern development are formed by the insoluble layers between salt beds and the Top Anhydrite overlying the salt strata. These layers have acted as a blanket medium controlling the depth to which cavern development took place. The main conclusion for this chapter is the observation that cavern migration should be considered when the Top Anhydrite has significantly deteriorated and/or collapsed. A prolonged exposure of the Top Anhydrite to fresh water / undersaturated brine may expedite the deterioration process due to the formation of gypsum in interbed voids and fissures within the beds comprising the Top Anhydrite.

Chapter 3 discusses the large- and small-scale processes controlling cavern migration. The chapter starts with a discussion on the Bulking Factor and how it is estimated in the current study as opposed to how it was estimated historically. The current methodology uses a 3-dimensional cavern shape as the basis for migration rather than using only the cavern height as an input parameter for vertical migration extent, i.e. a 1-dimensional approach. Furthermore, the possibility of arching is introduced in the methodology to account for a non-cylindrical migration column shape. Non-cylindrical migration column shapes have been observed in some of the studied cases. The introduction of a truncated cone as a mathematical model for the migration column, rather than a cylinder, will enable a more accurate representation of the actual migration column shape. Intrinsic arching caused by redistribution of stresses in the overburden and by partly confined rock blocks in the outer contour of the residual cavern roof contour is discussed. In addition to intrinsic arching, the hypothesis of an arching effect due to the cavern shape is introduced. The effect of arching on the migration column shape is particularly worth of attention as it may greatly influence the depth any migration can reach. The 3-dimensional approach of the current study is deemed a critical improvement over the former 1-dimensional approach based on (average) cavern height alone. This is illustrated by the observation that the 1-dimensional approach has under-estimated subsidence in some cases (e.g. cavern 69-70-71) and over-estimated subsidence in others (e.g. 86-87). The introduction of the truncated cone should mitigate this risk for the prognosis update when sufficient validation of the model parameters is possible through the reconstruction process.

Chapter 4 provides an explanation of the link between cavern migration and subsidence. The assessment of historical subsidence in combination with the reconstruction of cavern migration has led to an adjustment in the nomenclature of observed subsidence phases. The formerly used Phase I, II, IIb, III and IIIb phases are redefined as Stages 1 through 5.

Stage 1 subsidence is caused by salt creep and consequent convergence of the cavern and/or pillar deformation and is not further considered in this study. Stage 2 and 3 subsidence are caused by respectively the deformation of the competent rock layers in the overburden as the cavern migrates upwards and the deflection of the final competent rock layer, i.e. the Top Rock as the residual cavern approaches the Base Tertiary. If the migration of a cavern stops at a depth well below the Base Tertiary, Stage 2 subsidence is followed directly by Stage 5 subsidence caused by the consolidation of the bulked overburden in the migration column. When a residual cavern of limited height approaches the Base Tertiary, deflection of the Top Rock may reach the residual cavern bottom before it collapses. In this case Stage 3 subsidence is directly followed by Stage 5 subsidence. When a residual cavern with considerable height approaches the Base Tertiary. Stage 4 subsidence will develop when the final competent rock layers collapse and fall into the residual cavern. With the collapse of the final competent rock layers, the Tertiary soils will (suddenly) deform and a trough or sinkhole is formed as a result.

The final subsidence stage over a migrating cavern is always Stage 5 subsidence caused by the consolidation of the bulked overburden within the migration column. As the consolidation progresses over several tens of years, subsidence is continued albeit at a diminishing rate.

The adapted classification of migration stages and their translation to surface subsidence is the key subject of this chapter, specifically the introduction of Stage 3 subsidence, describing the deflection of the last competent rock layers. As the formerly used “BT-40m” criterium has lost it foundation due to a new interpretation of the migration processes at cavern 15, a new criterium is required. This new criterium should at least include both cavern span and residual cavern height to suit the current 3-dimensional approach. Sufficient validation of a new criterium from the reconstruction study is a prerequisite for its possible application in the updated prognosis model.

The overall conclusion of the Update Migration Study up to this point is that the historic migration processes observed in the Hengelo brinefield cannot be sufficiently represented by a 1-dimensional algorithm as previously used. A new approach thus introduces a 3-dimensional algorithm as the basis for potential subsidence prognosis over migrating caverns. By considering a 3-dimensional shape rather than just a cavern height, a more accurate prognosis should be possible avoiding severe under- or over-estimation of potential subsidence, especially over caverns with an irregular shape. It is thus recommended to differentiate between “regular” shaped caverns and “irregular” shaped caverns during the prognosis update. The prognosis of regular-shaped caverns can be largely based on a simple volume calculation using an appropriate bulking factor, whilst the irregular caverns will require an extra step in which the potential migration column shape is derived from, for example, the observed geological conditions, the operational history and/or the geometry of the original cavern. Also, the presence of faults and fault systems should be considered in this classification.

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