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Salt production

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ABSTRACT

In the Netherlands salt deposits are present within the Permian and Triassic intervals. The salt units in the upper Permian Zechstein Group attain especially great thicknesses (up to 1000 m) in the north of the country and the adjacent offshore areas. Salt is produced by solution mining in the eastern and northern Netherlands: rock salt from the Triassic Röt Formation and the Permian Zechstein Group and magnesium salt from the Zechstein Group. Total production amounts to 5.5-6.7 Mt/yr of rock salt and 0.25-0.30 Mt/yr of magnesium salt. Exploitation takes place between appx. 500 and 3000 m, the mining of Permian rock salt in the Barradeel concessions being the deepest worldwide. The rock salt is mainly used for the manufacturing of chlorine; most of the magnesium salt is used to produce magnesium oxide. The lifecycle of a salt mining concession can be divided into five phases: exploration, development and production, suspension, abandonment, and after-care. Optionally, a sixth phase, in-between production and suspension, can be to use the salt caverns (large brine-filled cavities in the salt that develop during production) for storage of a gas (natural gas, nitrogen, hydrogen, air) or a liquid (oil products). The environmental effects of salt mining are largely comparable to the mining effects of oil and gas operations in the Netherlands. Mining can result in ground subsidence, excess noise levels from drilling and production processes and production of saline wastewater. These effects also include the requirement for pipelines and cables installation as well as the (temporary) change of mostly agricultural land usage, hence changing the landscape to a limited extent.

<< Nobian salt storage in Hengelo (eastern Netherlands).
Photo: Nobian.

Introduction

Salt belongs to a group of chemically deposited minerals which crystallize by evaporation of salt-rich lake or sea water (called 'brine') in a lagoon, lake or shallow sea and which has limited or no connection to the ocean most of the time. Their chemical compositions reflect the original composition of water, although the brine changes in composition after precipitation of certain salts. Fresh influxes of seawater from the ocean at times, re-dissolution of salt near or at surface due to rainfall (and precipitation elsewhere) and temporary aerial exposure locally change the natural order of precipitation of the minerals in time or creates iterating cycles, the evidence of which can be observed in the stratigraphic record as sequences of evaporites. These sequences of evaporites thus result from variations in the chemistry of the brine from which they were deposited. The word salt is used as a general name for evaporitic salts, like gypsum/anhydrite ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}/\text{CaSO}_4$), halite (NaCl), sylvite (KCl), carnallite ($\text{KClMgCl}_2 \cdot 6\text{H}_2\text{O}$), kainite ($\text{KClMgSO}_4 \cdot 3\text{H}_2\text{O}$), kieserite

($\text{MgSO}_4 \cdot \text{H}_2\text{O}$) and bischofite ($\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$). Many more salts exist, but usually not in large volumes or concentrations from natural deposition. The largest known and also economically most important salt occurrences on earth are of marine origin.

The upper Permian Zechstein salt is the most widespread and thickest salt formation in the Netherlands and in Western Europe. It contains rock salt, potassium-magnesium salts and thick sulphates (Bouroullec & Geel, 2025, this volume). Apart from the Zechstein, salt occurs in the Permian Upper Rotliegend Group, in the Triassic Röt, Muschelkalk and Keuper formations (McKie & Kilhams, 2025, this volume) and locally in the Upper Jurassic Weiteveen Formation. Salt has been exploited in the Netherlands since 1919, by means of solution mining. Currently, in three clusters of concession areas, i.e. the Twenthe-Rijn cluster, the Barradeel-Havenmond cluster and the Adolf van Nassau cluster, rock salt is mined from a single concession (Fig. 16.1; Table 16.1).

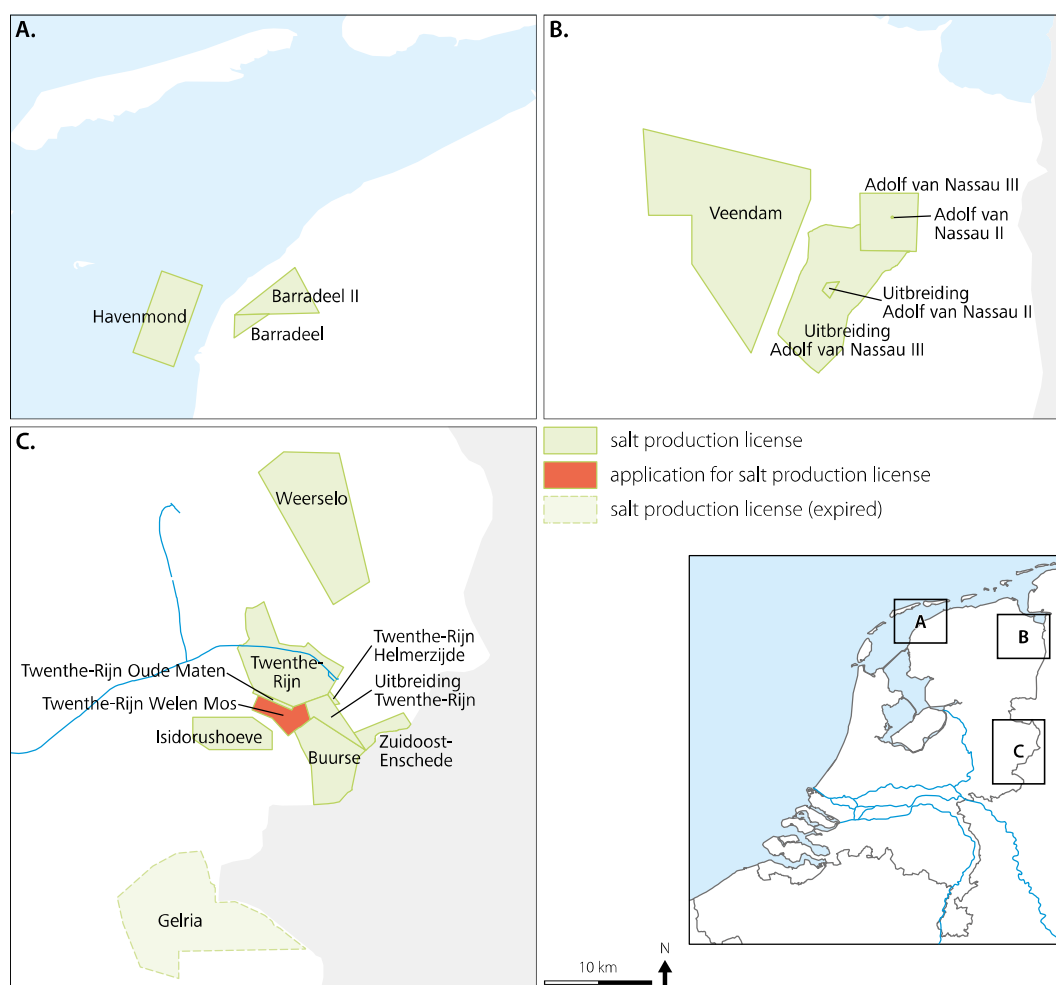


Figure 16.1. Overview of salt concessions in the Netherlands (reproduced from MEACP, 2022).

Table 16.1. Salt production and salt concessions in the Netherlands.

Concession	Owner	Salt formation	Depth	Annual production ¹
Adolf van Nassau ²	Nobian	Z2 Salt (diapir)	500-1600 m	2600 (2735) kt NaCl
Barradeel	Frisia	Z2 Salt (layered)	2500-3000 m	158 (174) kt NaCl
Buurse	Nobian	Röt Salt (layered)	300-400 m	42 (1440) kt NaCl ³
Havenmond	Frisia	Z2 (layered)	2600-3000 m	65 (0) kt NaCl
Isidorushoeve	Nobian	Z1 Salt (pillow)	600-1100 m	- ⁴
Twenthe-Rijn ⁵	Nobian	Röt Salt (layered)	300-550 m	2643 (2710) kt NaCl
Veendam	Nedmag	Z3 Salt (pillow)	1400-1800 m	246 (296) kt MgCl ₂
Weerselo	Nobian	Z1 Salt (complex)	400-1000 m	- ⁴
Zuidoost-Enschede	SGW ⁶	Z1 Salt (pillow)	- ⁴	- ⁴

1 Production 2020 (2019)

2 Including Uitbreiding Adolf van Nassau

3 Salt production stopped in 1953

4 No salt production has taken place

5 Including Uitbreiding Twenthe-Rijn, Twenthe-Rijn Helmerzijde, and Twenthe-Rijn Oude Maten

6 Salzgewinnungsgesellschaft Westfalen

History

Rock salt was discovered in the eastern part of the Netherlands during the 1880s in a drinking-water well (Wassmann & Brouwer, 1987). Later, during the drilling campaign of the *Dienst der Rijksopsporing van Delfstoffen* (National Agency for Exploration of Minerals) between 1903 and 1923, more deposits of rock salt and of potassium-magnesium salts were discovered in the east of the Netherlands (Van Waterschoot van der Gracht, 1909, 1918). In 1919, rock-salt production in the Buurse concession (Fig. 16.1c) from solution mining of salt belonging to the Triassic Röt Formation was started by the *Koninklijke Nederlandse Zoutindustrie* (KNZ, now Nobian) following heavy taxation on German salt exports. In 1936 production started in the Twenthe-Rijn concession (Fig. 16.1c), located close to the newly constructed Twentekanaal, a canal that connects the three largest cities of the Twente region (Almelo, Hengelo and Enschede) to the national network of rivers and canals and which allowed better transport facilities. In the same period, the Gelria concession (Fig. 16.1c) was granted for the exploitation of rock salt and coal. To protect the underlying Carboniferous coal reserves, the production of rock salt was restricted to conventional room and pillar mining, which made it uneconomic. The production of rock salt in the Buurse concession was discontinued in 1953 and salt production in the east of the Netherlands was continued in the Twenthe-Rijn area only. In 2012 the Isidorushoeve concession was granted for salt extraction from Z1 Zechstein salt (Bouroullec & Geel, 2025, this volume), following the gradual depletion of the Twenthe-Rijn Röt salt concession.

In the north of the Netherlands several salt domes were discovered while drilling for oil and gas during and after

the Second World War; others were inferred based upon gravity anomalies (Bentz, 1947; Mulder, 1950). More salt domes and pillows were interpreted from seismic surveys during the 1950s to 1980s. This resulted in the granting of new concessions for the production of rock salt to KNZ (Adolf van Nassau in 1954 with an extension in 1967 and Weerselo concessions in 1967) and of potassium-magnesium salts to Billiton (now Nedmag; Veendam concession, 1980). The presence of magnesium salts within some of the salt pillows was also proven thanks to drilling of gas wells from the 1960s onwards, when the pure MgCl₂ salt bischofite was found exclusively in this area between the towns of Veendam and Slochteren in the concession Veendam (Fig. 16.1b).

In 1996 the company Frisia started its salt mining operation near Harlingen-Franeker in the Barradeel concession (granted in 1991 with an extension in 2003 – Fig. 16.1a, Table 16.1). In 2012 the Havenmond Concession was granted. At the Havenmond concession (Fig. 16.1a), salt is extracted from below the Wadden Sea. The first Havenmond well was drilled from the salt factory site (at Harlingen harbour) with a deviation to 3 km offshore where the cavern is being developed. Mining from the Havenmond concession commenced in 2020. Note that carnallite salt layers were identified at the top of the Zechstein Z2 salt but they are not commercially exploited here.

Salt mining lifecycle

The lifecycle of a salt mining concession, and its associated caverns, can be divided into six phases: 1) Exploration and field design; 2) Development & Production; 3) Storage

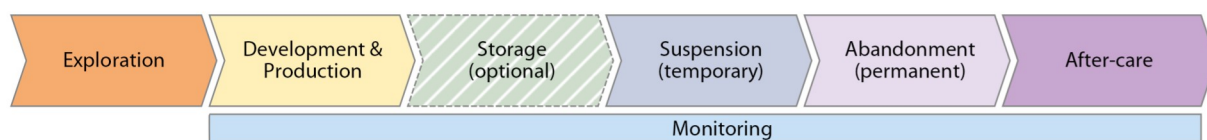


Figure 16.2. The lifecycle of a salt mining concession can be divided into six phases: 1 = Exploration; 2 = Development & Production; 3 = Storage (optional); 4 = Suspension (temporary); 5 = Abandonment; 6 = After-care. The (optional) storage phase only applies when the caverns are used for storage of gas or liquids.

(optional); 4) Suspension; 5) Abandonment; and 6) After-care (see Fig. 16.2).

In the first phase, the subsurface must be explored to confirm the presence of rock salt volume and structures in which caverns can be developed. This must be matched with suitable above-ground locations where facilities can be constructed, and where the necessary infrastructure is present or can be developed. With this aim an exploration permit is applied for. When granted, exploration work will be performed. Examples of exploration work are seismic data acquisition and interpretation and the drilling of an exploration well (including coring, logging and analyses and interpretation of these data). When the presence of the salt deposit has been confirmed, the application for the concession (mining permit) starts. At the same time the cavern field and its infrastructure will be designed. When the concession has been granted and the field design completed, the extraction plan (*winningsplan*) is sent to the authorities for approval and the environmental permits are applied for. After the permits have been granted the second phase of the field lifecycle starts.

In the second phase, drilling and construction of brine transportation and processing infrastructure is executed and production from the caverns starts. During this phase, a cavern is gradually increased in size by continuous leaching, while control measures and monitoring are carried out to ensure that it develops in a geomechanically stable fashion. In this process the amount of salt dissolved in the extracted brine gradually increases, until it reaches a fully salt-saturated level. Production continues until the cavern reaches its final shape according to the extraction plan.

In the optional third phase, gas or liquid storage can be implemented. After a period of production, when the cavern has reached a certain volume, it can be repurposed for storage by converting the former brine well to a storage well and replacing (a part of) the brine in the cavern with a gas (e.g. natural gas, nitrogen, hydrogen, air) or liquid (e.g. oil products). This process is called 'debrining'. This optional third phase can last for several decades, during which the stored product is injected and withdrawn in a cyclic manner depending on market dynamics (Juez-Larré et al., 2025, this volume) or remains untouched for a long time (in the case of storage for strategic reserves)

Afterwards, the stored product must be removed from the cavern, and brine (or water) must be injected again, either to restart a phase of production (second phase), or to safely suspend the mining operation (fourth phase) and initiate abandonment procedures (fifth phase). Note that suspension is a temporary measure applied to a cavern and can be undone. Suspension of a cavern involves removing the brine production string, shutting off the well, periodically in case of pressure build-up, and, when deemed safe, installing a cement plug downhole. Abandonment is commonly done at cavern and/or well pad level, is permanent and involves removing all surface infrastructure (well sites, brine transport and processing infrastructure, etc.) and returning the land into its original state.

After abandonment, the sixth and final phase is that of after-care, during which the surface continues to be monitored for years at least until site-specific subsidence cannot be measured or is constrained within the range of natural subsidence of 1-2 mm per year. In the next sections, the individual phases of the salt mining lifecycle are further detailed.

Exploration

The first phase in the lifecycle of a salt mining concession is the exploration phase. The most important topics for exploration are to confirm 1) the presence of salt, 2) the surface situation and 3) the distance to necessary infrastructure. A large enough salt volume should also be available for the long-term economic viability of the mining operation.

The geometry, volume and depth of the salt structures are important parameters to determine if mining is technically feasible and economically viable. Large volumes and shallow depths are favourable from a mining cost perspective. Proximity to sea-harbours can however favour deeper salt targets as well, limiting the need for long land pipelines to harbour-bound salt plants. This can save costs on salt transport to international clients who can be reached by larger ships, such as in the case of the Barradeel concession, with its production plant located in the Harlingen harbour. When locations with promising salt structures are identified, the surface situation is assessed. Agricultural land, or in combination with commercial estates represent favourable surface situations for the development

of a salt mine. Protected areas (nature, drinking water) and residential areas are less suitable for mining activities. Another important topic is the distance to necessary infrastructure. For regular solution mining this means access to water, electricity, pipelines for water and brine and a salt plant to process the brine to salt, or a large body of brackish or salt water (e.g. sea, estuary) to dispose all of the remaining brine. Note that this practice is currently not allowed under Dutch law since it is seen as a waste of natural resources, therefore brine production in the Netherlands is always coupled with salt production. Salt plants are in general located near canals or seaports to enable transport by ship. In the case of cavern development for storage of methane, hydrogen or compressed air the distance to main gas and electricity infrastructure is also important.

For the first step of the exploration phase assessment of all existing subsurface data is done and a new evaluation is carried out, for example involving reprocessing and reinterpretation of existing seismic data. Once the most promising location has been identified, drilling of an exploration well is often the logical next step. Core material from such a well is preferred since it enables the direct assessment of the quality and creep properties of the salt and increases understanding of the stratigraphy and internal structure of the salt deposits.

Salt structures and occurrence

On a geological timescale, and when buried below 500 m, salt behaves in a visco-plastic way, whereas other sedimentary rocks show brittle deformation. Rock salt compacts already during early stages of burial to a tight mass with a constant density of 2168 kg/m³, slightly depending on the quantity of impurities such as anhydrite, carbonate and clay layers. Other sediments show an increase in density with depth owing to cementation and the reduction

of pore volume as a function of overburden and pore pressures. Consequently, in near-surface positions, where sand and clay typically show densities of 1200 to 1400 kg/m³, halite is relatively heavy, whilst below 500 m it is lighter than the surrounding rocks. This results in an unstable situation. Under the right conditions, the salt rises while solid rocks sink (Trusheim, 1963; Kockel, 1990; Remmelts, 1995). This process of flowing and rising salt is called diapirism. Salt will initially flow mainly in a lateral sense, forming what is known as salt pillows (Fig. 16.3). Above a pillow, the sedimentary cover does not become pierced, but in the next stage a pillow can evolve into a salt diapir. The Zechstein salt in the Netherlands has formed many diapirs (Fig. 16.4), which indicates that the boundary conditions for diapirism have been met on a wide scale in the geological past. However, in the northwest of the Netherlands the salts remain almost undisturbed. A more in-depth explanation of salt tectonics, and its role in the geological history of the Dutch subsurface can be found in Bouroulec & Ten Veen (2025, this volume). Salt can be mined from different types of salt structures, and different internal tectonic styles can be recognized in them. In literature a separation is commonly made between bedded (layered) salt, salt pillows and salt diapirs, which represent increasing states of salt deformation (Fig. 16.3; Trusheim, 1963).

In **bedded salt** the top and bottom of the layer are parallel to the interbedded elastic carbonate and anhydrite beds, reflecting the original depositional geometry. Salt layers may be discontinuous due to faults with significant offset, especially in areas with relatively thin depositional salt. In most cases the faults will be salt smeared, in similar fashion to clay smeared faults, by which process the faults will be barriers to fluid migration. In contrast to paleo basement highs where the salt is often thin, basinal areas can have salt thicknesses that generally exceed the throw of most faults. Even with bedded salt the internal individual salt layers can be deformed due to salt lateral migration, expressed by flow folds with horizontal axial planes (Lotze, 1957). They occur on the decimetre to decametre-scale. Potassium-magnesium salts, with interbedded layers of halite, usually show strong folding. With the exception of possible faults, exploration in bedded salt can be relatively simple due to the often large extent of continuous (semi-)horizontal layers. Possible trends in depth or thickness can be interpreted from one well to the next. The salt occurrences in the Twenthe-Rijn, Buurse and Friesland (Barradeel/Havenmond) concessions are examples of layered or bedded deposits (Fig. 16.1; Table 16.1). In the Twenthe-Rijn and Buurse concessions, 50 to 100 m of rock salt occur in the Triassic Röt Formation at depths of 200 to 600 m (Harsveldt, 1980, 1986). In the Friesland

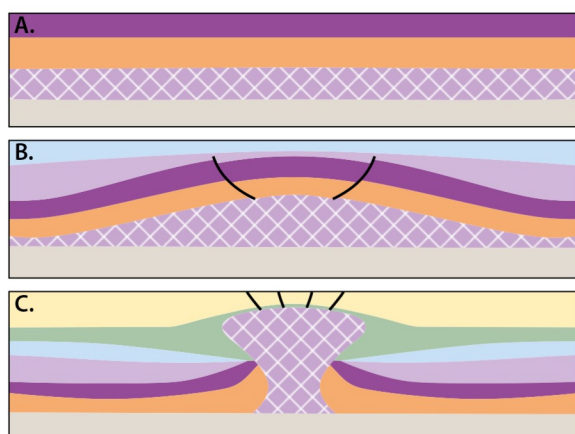


Figure 16.3. Types of salt structures. a) Original salt layer, end Middle Triassic. b) Salt pillow, Late Jurassic. c) Salt diapir, present-day situation. Modified after Trusheim (1963).

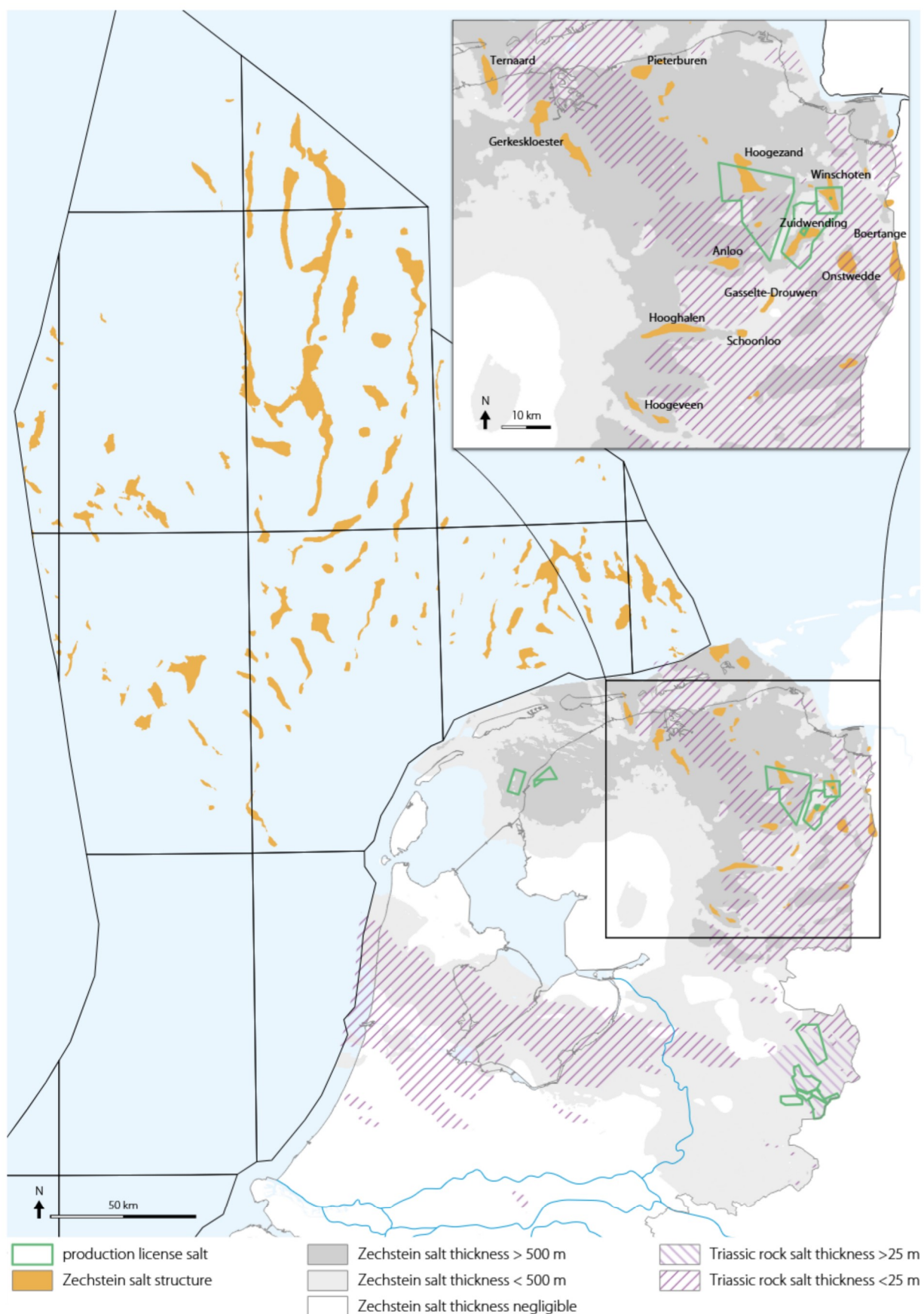


Figure 16.4. Map displaying salt occurrences of the Permian (Zechstein) and the Triassic (Röt) in the Netherlands. Zechstein salt diapirs are displayed in orange. Elongated salt walls (e.g. in the northern offshore) are related to major sub-salt faults, whereas circular diapirs developed at intersections of fault trends.

concessions, bedded rock salt occurs in the Z2 (Stassfurt) and Z3 (Leine) formations. Salt is only exploited from the Z2 where it has a thickness of up to 650 m and occurs at depths of 2200 to 3000 m, which makes it the deepest salt exploited in the world.

Salt pillows are formed by a local thickening of the salt due to horizontal salt flow. In central areas of the Zechstein basin (in the central North Sea, the south of Denmark, and the north of Germany) the cores of the pillows are composed of the Z2 (Stassfurt) salt; in marginal areas (in the east of the Netherlands and the middle of Germany) the Z1 (Werra) salt deformed into thinner and thicker zones, the thicker of which form salt pillows. Extensional faulting commonly affects the beds over the crest of the pillow and are referred as crestal faults. The thickening of salt into a salt pillow is usually accompanied by a series of stacked, large-scale flow folds in the salt, with horizontal axial planes. Interbedded carbonate and anhydrite layers within the pillow are folded and their axial planes are generally parallel to the pillow's roof. Superimposed upon such large-scale folds one commonly finds a series of smaller secondary folds. In the late stage of pillow formation, the direction of salt flow may change from mainly horizontal to more vertical, forming salt diapirs (Lotze, 1957). In the northern and eastern parts of the Netherlands, a series of Zechstein salt pillows is present at relatively shallow depth (500-800 m). These salt pillows were brought close to the surface thanks to a combination of deep erosion and limited burial during the Late Jurassic to Early Cretaceous accompanied by uplift during the Cenozoic. This is in contrast to rift basin areas (e.g. West Netherlands Basin, Broad Fourteens Basin or Dutch Central Graben). Exploration in pillows is a bit more complex compared to that in bedded salt, because the salt layer thickness varies. A good coverage of the pillow by seismic lines is important to interpret the thickness variation. After that, it is possible to interpret trends from well to well. For example, the

Isidorushoeve concession (Fig. 16.1) contains a salt pillow with a maximum thickness of 400 metres in a depth range between 500 and 1100 metres (Fig. 16.5). In areas around the Dutch Central Graben, pillows of upper Permian (Silver Pit Formation, Upper Rotliegend Group, Bouroullec & Ten Veen, 2025, this volume) as well as of Triassic (Röt, Muschelkalk) salts have been identified. The Veendam concession (Fig. 16.1) covers two Zechstein salt pillows. Both contain thick layers of carnallite and bischofite in the Z3 salt (Coelewij et al., 1978). It is the only known occurrence of primary bischofite in western Europe.

In **salt diapirs** the movement of the salt changed from mainly horizontal to mainly vertical, and the salt deforms or even pierces the cover beds. The salt flow results in folds within the diapir with vertical axial planes and horizontal fold axes as well as in curtain folds with vertical fold axes. In the late stage of diapirism these latter folds usually will have deformed the previous generation of folds with horizontal fold axes, but due to the extremely high strains in the diapir, the older deformation phase may be indistinguishable. Along the margins of diapirs, friction between non viscous and viscous rocks can create additional complex fault systems and associated fracture patterns (Jackson et al., 1990). For this reason, wells aiming at targets located below the salt (subsalt) are usually drilled through the diapir itself or at a safe distance from it in order to avoid such structurally complex zones. Sometimes the salt flow and migration may even envelop blocks of the overlying succession (as is observed in e.g. the Gulf of Mexico and West Africa). The salt in a diapir rarely moves at a uniform rate (Kupfer, 1976). Shear zones, known as spines, separate sectors moving at higher speed, from those moving more slowly. The development of salt diapirs normally results in a complicated internal structure, with folds of many different scales and orientations (Richter-Bernburg, 1980). Compressional tectonics during the Late Cretaceous and Cenozoic accelerated the rate of diapirism, or

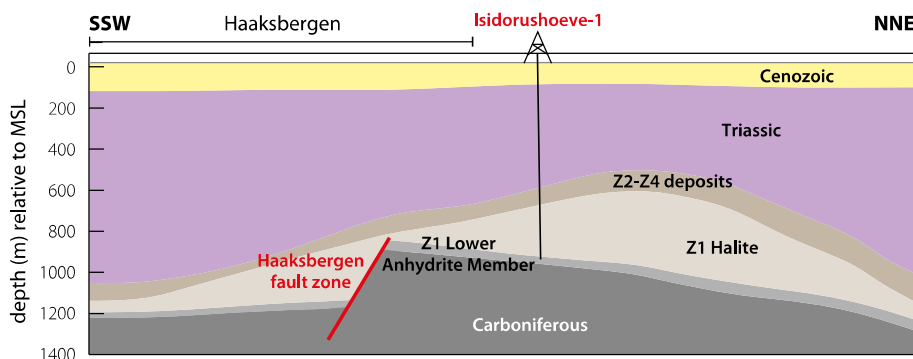


Figure 16.5. Cross-section through the Haaksbergen salt pillow on the Isidorushoeve Concession of Nobian in the northeast of the Netherlands. Location of well Isidorushoeve-1 is indicated. See Fig. 16.1 for location.

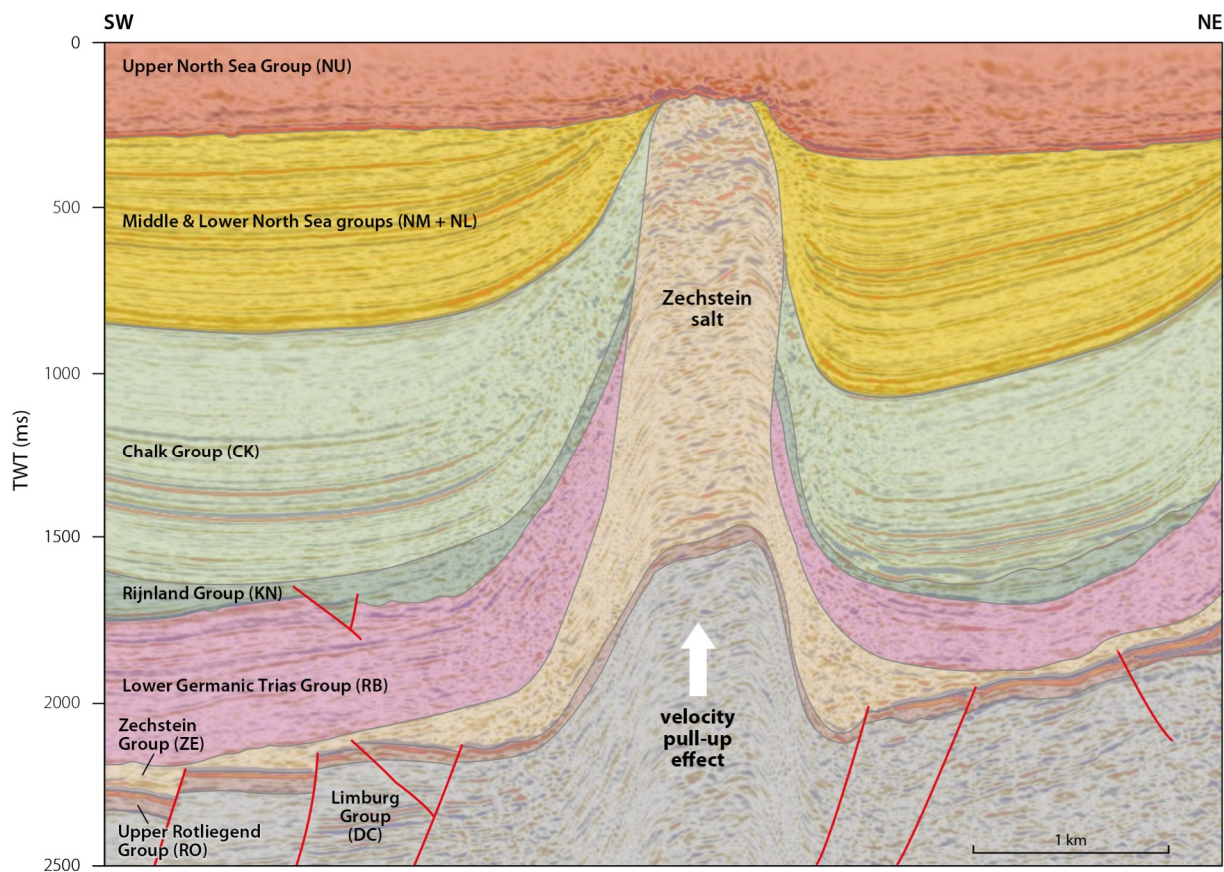


Figure 16.6. Seismic time section of the Zuidwending salt dome in the Adolf van Nassau concession. This dome is the shallowest in the northern Netherlands, reaching to ca. 100 m below the surface. Thickness variations in adjacent sediments result from periods of main salt movement. See inset map in Fig. 16.4 for location of the Zuidwending salt dome.

strongly deformed some of the diapirs. An example of this is shown in Figure 16.6, which displays a seismic cross-section through the Zuidwending salt dome.

The shapes and the internal structures of individual salt bodies are complex; reference is made to descriptions by De Boer (1971), Richter-Bernburg (1972, 1980), Kupfer (1976), Bornemann (1991) and Geluk (1995). Salt diapirs outcropping in the Iranian Dasht-e-Kavir (Jackson et al., 1990) and Zagros Mountains (Kent, 1979) and also in the Spanish Pyrenees (Wagner et al., 1971) present analogues for buried salt structures in the Netherlands (Geluk, 1998, 2000). A generalized simplified model of Zechstein salt diapirs is that the central part of the dome contains mostly Z₂ salt and that the marginal parts are made up of younger salt units. This is shown to be true for structures such as the Winschoten and Zuidwending diapirs (Harsveldt, 1980, 1986). In the Pieterburen diapir, however, the central part is made up of younger salts and the Z₂ salt occurs at the margin (Harsveldt, 1980; RGD, 1995); in Germany this occurs at Gorleben (Bornemann, 1991) and Hanigsen-Wathlingen (Schachl, 1987).

Exploration of salt diapirs is relatively complex compared to exploration of bedded salt or salt pillows. This

is caused by two risks related to cavern development in a salt diapir: 1) the location of the salt dome flank and 2) the presence of non-halite layers within the dome. Caverns should be developed at a safe distance from the salt dome flank (typical values are 150 or 200 metres). However, it is not easy to precisely determine the salt dome flank position due to the (semi-)vertical layering (difficult to interpret on seismic data) and the often heavy folding and faulting in the overburden layers near the salt dome flank. Another risk is the presence of non-halite layers within the dome. Often these are not easy to recognize on seismic data. Due to the complex structure identifying trends from one well to the other may not provide a reliable prediction for the geology of the next well. Ground penetration radar (GPR) within newly drilled boreholes is regularly used within salt wells to improve the reliability of the geological interpretation within the salt diapir.

Several salt domes in the Netherlands reached shallow depth and are close to the surface. The shallowest salt diapir is the Zuidwending diapir, where the top of the caprock (insoluble residue of the salt formed by groundwater dissolution, see below) is at a present-day depth of 100 to 110 m below mean sea level (Fig. 16.6). Other notice-

able shallow diapirs are the Schoonlo (120 m), Pieterburen (190 m), Hooghalen (250 m), Onstwedde (250 m) and Gasselte-Drouwen (350 m) salt diapirs (see insert map in Fig. 16.4 for locations of diapirs). In the western offshore block K9, a salt diapir almost reaches to the seafloor (Giesen & Mesdag, 1995). Some of the Dutch salt diapirs have reached the surface at some point in their geological history, mainly during the Mid/Late Triassic, Late Jurassic or Early Cretaceous, and became subject to later erosion as well as near-surface dissolution of salt by ground or surface water (Bouroullec & Ten Veen, 2025, this volume). As a result, a caprock composed of the insoluble residue of the salt formed (Batsche & Klarr, 1980). This caprock may locally include thick anhydrite floaters and remnant suprasalt sediments such as Jurassic claystones, as dated using palynological analysis in the Dutch offshore G Block (Verreussel et al., 2018). The thickness of the caprock shows considerable variation between salt domes, from 20 m in the Winschoten salt dome to over 100 m in

the Pieterburen salt dome. Also, within a single salt diapir, this thickness may vary strongly in relation to the percentages of insolubles in the subcropping salt succession and their structural style (Balzer, 2000a,b, 2001). In the Adolf van Nassau concession, two salt diapirs are present. The shallow Zuidwending diapir has a typical crescent shape in map view and is interpreted to have been formed by the amalgamation of two individual diapirs that eventually formed a salt wall (Figs 16.6, 16.7).

Production

The techniques applied in solution mining depend upon the geological characteristics of the salt and particularly upon its internal structure. After a general introduction on solution mining, the mining of rock salt and potassium-magnesium salts will be discussed.

In the past, salt was produced from natural brine springs by evaporation. In the coastal areas of the Netherlands, it was produced by the burning of peat wetted by salt water.

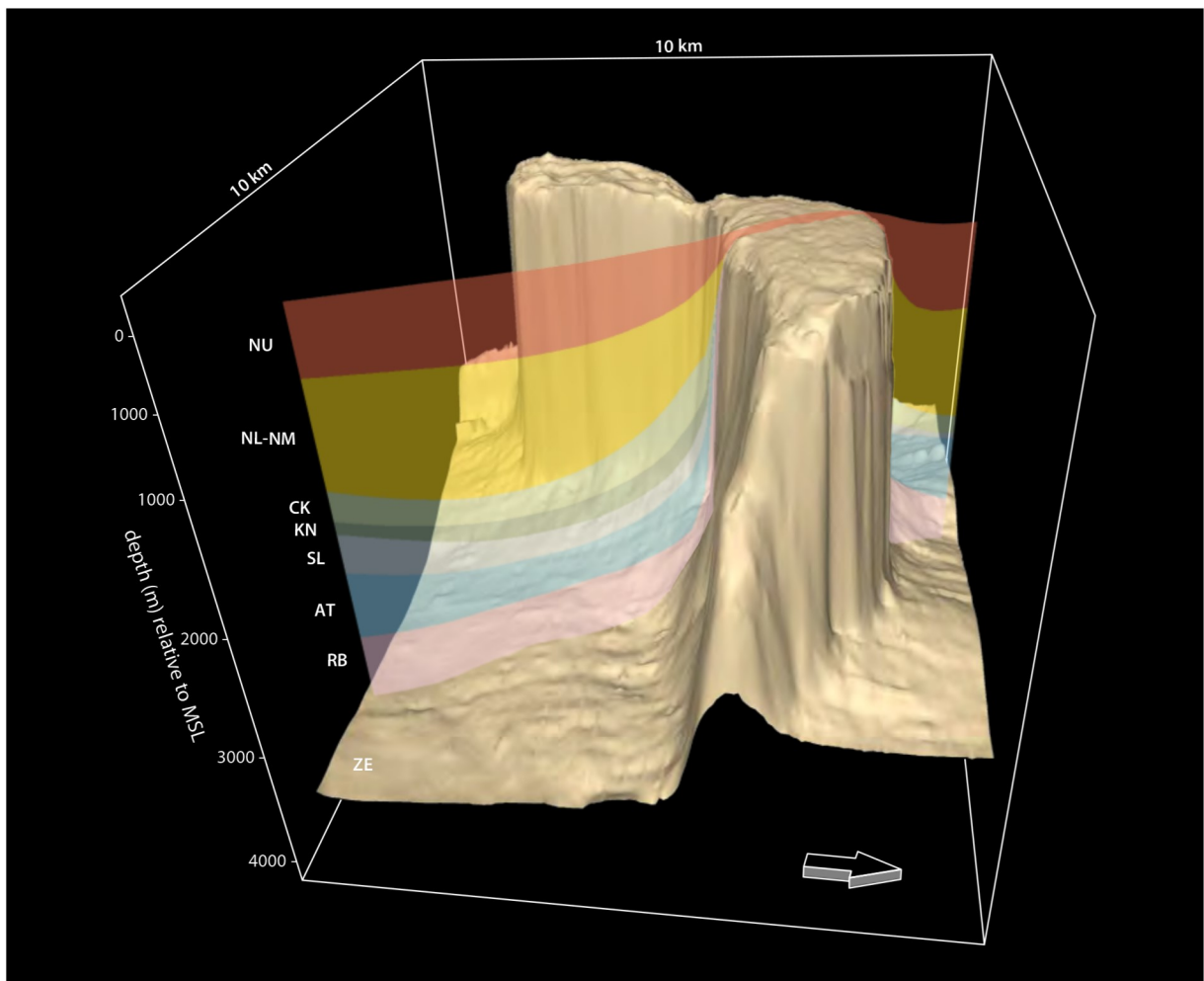


Figure 16.7. 3D geometric model of the Zuidwending salt diapir; viewed obliquely from above. The structure is an amalgamation of two individual domes with a marked difference in strike. The height of the dome is ca. 3 km above the base of the Zechstein salt layer. The salt diapir covers an area of ca. 6 x 6 km. See Fig. 16.4 for location and Fig. 16.6 for explanation of the stratigraphic codes.

The diagram illustrates a wellbore extending through geological layers. The vertical axis on the left indicates depth in meters relative to the surface, ranging from 0 to 1000. The geological layers are color-coded: North Sea Supergroup (yellow, 0-100m), Lower Germanic Trias Group (pink, 100-500m), and Zechstein Group (orange, 500-1000m). The Zechstein Group is further divided into the Z1 (Werra) Formation, which is highlighted with a dashed line at approximately 600m depth. A wellbore is shown extending from the surface down to about 850m. Two callout boxes provide detailed views of the wellbore's interior. The top callout shows the surface area with a 'medium' (red) and a 'cellar' (beige) section, with a 'cement' layer (grey) around the wellbore. The bottom callout shows the wellbore's interior, featuring a 'blanket medium' (red) at the top, 'water' (blue) in the middle, and 'brine' (green) at the bottom, which is contained within a 'sump' (green hatched area).

The diagram illustrates a blanket medium well system. It is divided into two horizontal sections. The top section shows a cross-section of the ground with a 'surface' layer and a 'cellar' layer. A well is drilled into the cellar, lined with 'cement'. At the top of the well, there is a 'blanket medium' (red) and 'water' (blue) entering from the surface. Arrows indicate the flow of water and brine. The bottom section shows a cross-section of the well's interior. The well is filled with 'water' (blue) and 'brine' (green). A 'blanket medium' (red) is shown at the top of the well. Arrows indicate the flow of water and brine. The bottom of the well is labeled 'sump'.

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the injection buoyancy plume. Thus, clogging of tubulars is prevented. In the past, mining started using this direct circulation mode, transitioning to the indirect circulation mode later. Nowadays, the direct circulation mode is hardly used and indirect circulation (top injection) is used from the start.

The final shape of a cavern is controlled by the original thickness and geometry of the salt layer, the depths of the injection and production tubulars, the mode of operation, the water throughput, the specific dissolution rate of each salt layer and the setting depth of the blanket fluid. Cavern development preferentially takes place in an upward vertical direction as fresh water is lighter (1000 kg/m^3) than saturated brine (1200 kg/m^3). In order to allow controlled vertical and lateral development of a cavern, a so-called blanket fluid may be injected (Fig. 16.8). This liquid or gas should not dissolve salt nor mix (too much) with brine, and it should float on brine. Commonly, hydrocarbon-based fluids like oil or LPG are applied ($700\text{--}900 \text{ kg/m}^3$), but compressed air or nitrogen (both in gas phase) can be used as well. Cavern lifetime amounts to tens of years depending on salt layer thickness and mining method. Sequential cavern development, i.e. the leaching of the void by applying subsequent leaching steps, is simulated and subsequently monitored by time-lapse acoustic measurements (sonar). These measurements are acquired using a wireline-mounted probe, which is lowered into the well bore. Comparison with data of former surveys or with results of computer simulations enables the verification of compliance with planned cavern development.

The integrity and long-term stability of a cavern are important issues with respect to potential surface subsidence. Maximum allowable cavern dimensions are determined by finite-element modelling. When the leaching is executed within these given dimensions the cavern wall and roof can be considered stable. The mechanical behaviour of the salt is described by means of a constitutive law, which gives the relation between stress and deformation and which incorporates the visco-plastic, time-dependent, non-linear behaviour of salt. On a scale of weeks to decades, salt behaves like a viscous fluid upon application of an external stress field. The resulting 'creep' is temperature (i.e. depth) dependent and has a large impact on cavern operations. Over time, creep results in a homogeneous stress field around a cavern, which is a prerequisite for the preservation of cavern integrity and long-term stability. Brine production is closely monitored by mass balancing and chemical analysis. In addition, parameters like flow, pressure, temperature, saturation, etc. are recorded continuously to provide information on the actual development of a cavern and on any deviation from default values. Periodically, the surface subsidence is measured to assure compliance with planned cavern development.

Shallow depth salt production (300–600 m),

e.g. Twenthe-Rijn concession

Since production started in 1936, over 550 wells have been drilled and over 100 million tonnes (Mt) of rock salt have been mined. Initially, wells were drilled in the direct vicinity of the evaporation plant, south of the city of Hengelo. The mining method evolved over time; in the past salt was extracted from caverns which each had two or three wells at a spacing of 40 m. Currently caverns are developed from single wells. Cavern development starts at the base of the salt. Once the initial cavern has developed, production is increased and the cavern is further developed, laterally and vertically, into a cylindrical void (Fig. 16.9). The maximum height of a cavern depends on the depth of the salt deposit (more specifically on the distance between the top of the salt and the base of the Cenozoic) and the bulking factor, that is the ratio between loose and consolidated rock material in the overburden in a case of collapse. When the cavern is developed within this maximum height, which generally ranges between 20 and 40 metres, it will not cause a sinkhole even in the unlikely event of a collapse.

Caverns are spaced such that between caverns a safety pillar of proper size is maintained to guarantee cavern integrity and to minimize creep-induced subsidence. Thin dolomitic claystones subdivide the Röt salt into the layers A to D (from base to top) and may hamper cavern development. Salt production takes place from layers A, B and (partially) C. On top of each cavern a safety roof is maintained in salt layer C to ensure cavern integrity and stability and to prevent future surface subsidence. Without a safety roof, as was the case with caverns developed before 1980, mechanical failure of the overlying strata by gravity force may occur. This may result in an upward vertical growth of the cavern, and a resulting surface subsidence of several millimetres per year. Once the collapse zone in the overburden reaches the base of the unconsolidated Cenozoic (at 60 to 100 m depth in the case of the Twenthe-Rijn) and depending on the height of the remaining void, severe subsidence, up to the formation of a sinkhole, may occur. In the Netherlands, this has happened only once, in 1991. On that occasion a collapsing cavern reached the surface and a sinkhole of about 30 metres diameter and 4.5 metres depth was formed. By limiting the height of a cavern, the formation of a sinkhole is prevented, because the material falling from the cavern roof to the cavern bottom occupies a greater volume than the original rock layer. Therefore, a collapsing cavern gradually decreases in height. By using an empirically determined so-called bulking factor Nobian limits the height of the cavern such that the remaining cavern height will be zero when it reaches a pre-defined limit below the base of the unconsolidated layers. This migration process, whereby a collapsing cavern

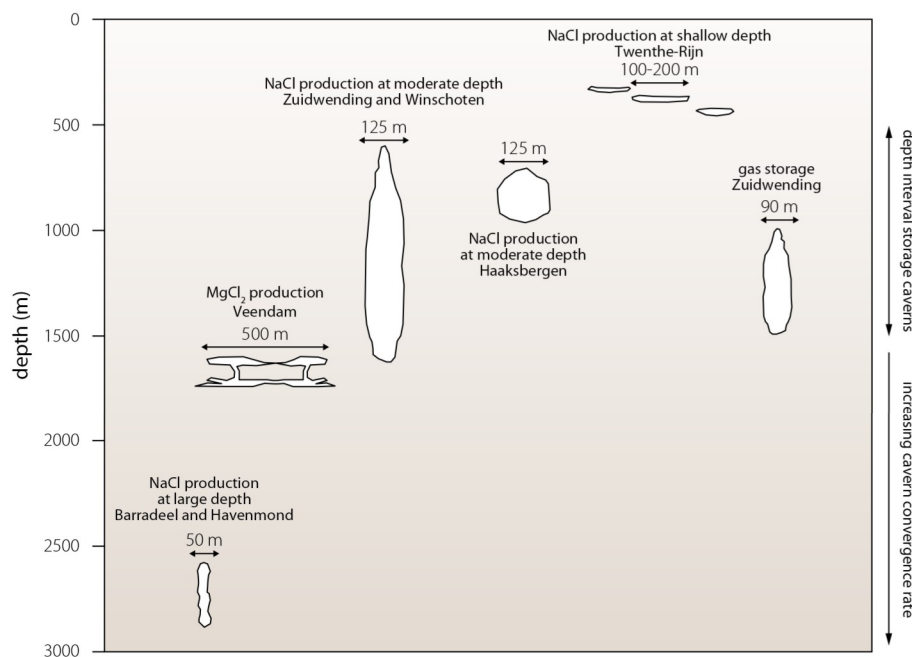


Figure 16.9. Typical cavern geometries, depths and dimensions of salt mining and gas storage concessions in the Netherlands.

gradually migrates upward to the surface, may last 10-20 years. The critical area, i.e. the zone of surface subsidence, is limited to an area that is defined by the 45-degree angle of draw relative to the base of the Cenozoic (Wassmann, 1980, 1983, 1993). When the caverns are developed according to the current safety guidelines, sinkhole formation is prevented and subsidence due to salt creep is limited to a maximum around 1.0 mm/yr, which is in line with natural subsidence rates in large parts of the Netherlands. Therefore, negative surface effects are not expected.

Moderate depth salt production (400-1600 m),

e.g. Adolf van Nassau and Isidorushoeve concessions

Solution mining at moderate depth is carried out from the Zechstein salt using one well per cavern. Presently, production is from 5 wells in the Winschoten salt diapir and from 8 wells in the Zuidwending salt diapir (Figs 16.4, 16.9), from the Zechstein Z2 salt layer. The roofs of the caverns are at depths between 650 and 800 m (Winschoten salt diapir) and 450 and 500 m (Zuidwending salt diapir). The actual heights of the caverns vary between 400 and 700 m (Winschoten salt diapir) and between 400 and 900 m (Zuidwending diapir). The well spacing is approx. 250 m in a line configuration. Cumulative production is over 100 Mt of rock salt since the beginning of the production in the 1950s (Winschoten diapir) and 1960s (Zuidwending diapir) respectively. Surface subsidence due to cavern convergence amounts to 1 to 3 mm/yr. As in the Hengelo brine field, a sphere of influence is defined in this case by a 45-degree angle of draw relative to the deepest point of a cavern. In the coming years the mining company Nobian will develop a new brinefield in the Isidorushoeve concession, near Haaksbergen, to supply brine to the Hengelo salt plant.

The salt to be mined is a Zechstein Z1 salt pillow. Cavern development wells will be drilled with a 300 m spacing. The cavern depth is determined by the depth of the base of the Z1 salt. The permitted cavern height is 125 m, in order to ensure a safe long-term cavern abandonment.

Large depth salt production (1600-3000 m),

e.g. Friesland concessions

The world's deepest solution mine, operated in the Friesland concessions of Barradeel and Havenmond, feeds a vacuum salt factory near the town of Harlingen. Two caverns, 500 m apart, have been in production since 1995 and new caverns at larger distances are under construction. Halite is extracted at 2500-3000 m depth from a 300 m interval in the bedded Z2 salt. Minor faults affect the base and top of the salt. The top 30 m of the Z2 salt is formed by a carnallitic layer. By applying a gasoline or LPG-based blanket fluid the cavern development is kept well below this layer, to avoid carnallite coming in contact with the cavern brine, which would result in contamination of the brine and in loss of the cavern for further production. Subsurface temperatures at cavern depths are as high as 105°C. As a result, the viscosity of the salt is low, giving a high cavern convergence. This effect is greatly increased by the 25-30 MPa pressure difference between the cavern pressure and the far-field lithostatic pressure (60-65 MPa) at a cavern depth of 2500-3000 m. The high temperatures do not influence the solubility of NaCl, but significantly increase its rate of dissolution. Where it takes usually one to two years to create sufficient wall surface in a cavern in

order to saturate the brine to acceptable levels for production, the deep caverns become saturated in a few months, which is a great advantage for salt production. Although the process of solution mining at large depth is similar to that at moderate depth, the behaviour of caverns strongly differs. At moderate depth, most caverns (at near final volume) have a convergence rate that is only 0.05 to 0.1% of the dissolution rate; in the deep caverns, the convergence rate becomes equal to the dissolution rate within a few years. The cavern shapes and sizes are frequently measured with sonar (3D imaging technique). Although their shapes change somewhat with time, their volumes remain almost constant. Hence the term 'squeeze mining' is often used for this type of deep solution mining to reflect the fact that the expected increase in cavern volume by dissolution of salt is completely compensated by the surrounding salt flowing inward at a fast rate, thereby effectively squeezing the cavern.

Solution mining of potassium-magnesium salt, e.g. Veendam concession

Solution mining for potassium and magnesium salts differs greatly from that of rock salt. They are exclusively mined from bedded salt or salt pillows. In diapirs these salts are strongly folded and could be extracted only by conventional dry (room-and-pillar) mining, as is being done in many potassium salt mines in Germany. In the Veendam concession, the magnesium component is the main target of mining, while the potassium component is currently not produced. The mined magnesium salts occur in the Z3 salt. Three evaporation cycles have been recognized in this salt, and the potassium and magnesium salts are separated by layers of halite. The first, lower, cycle contains most of the magnesium salts and all of the bischofite; the second

and third cycles contain only carnallite. The depth ranges from 1300 to 1800 m (Fig. 16.10). The layers are dipping up to about 30 degrees at the mining location. The halite layers occur in all wells with equal thickness and composition, but the magnesium salts are interbedded with thin layers of halite at a centimetre to metre-scale. This interbedding is thought to reflect daily or seasonal variation in the concentration of the depositional brine.

During production the magnesium salts are dissolved preferentially, leaving many less dissolvable overhangs on the cavern walls. Eventually some overhangs will fall into the caverns, occasionally damaging production tubings. Sonar surveys, made in the initial stages of cavern development in the 1980s, showed a very irregular cavern shape, but were largely inconclusive in determining the precise shapes and volumes of the caverns due to many reflections from the rock-salt balconies. Presently, the cavern system has a labyrinthine architecture, comparable to a natural cave system formed by karstification. Non-saturated brines (to bischofite or carnallite) find their way to those parts of a cavern that are the easiest to dissolve and most easily accessible by density flow. The total interconnected areas in the cavern field (called the cavern cluster) have a span of more than two kilometres. Salt dissolution is mainly in the updip direction, since water and brine change-out is driven by density flow.

In 2022 the Veendam pillow had 15 wells, 2 of which are abandoned. Injection and production intermittently take place through the same well or via separate wells. The cavern cluster will be reduced in volume by allowing salt creep (mainly the bischofite) to leave as little cavern brine behind as possible before abandoning the connecting wells. Some 90 cm of maximum ground subsidence is expected in a few decades. This excludes overlapping

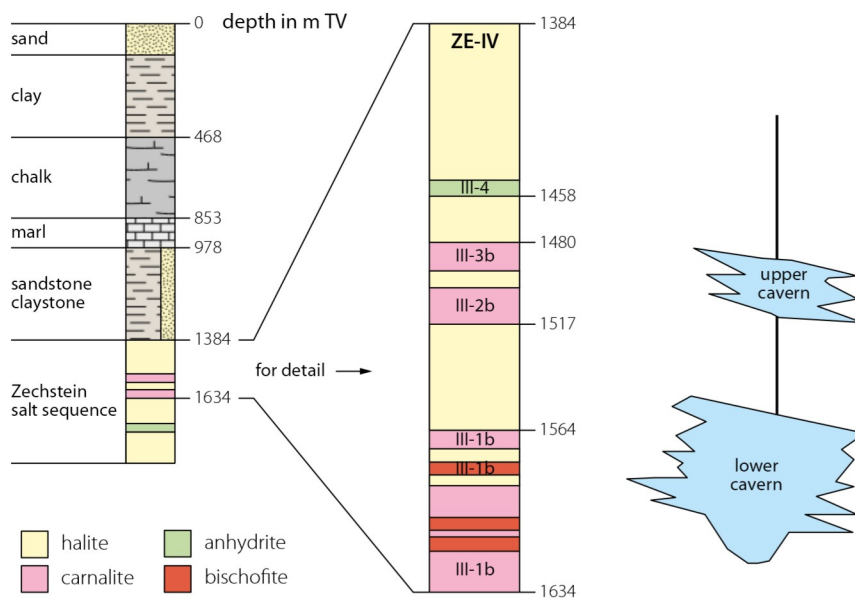


Figure 16.10. Stratigraphy and cavern development in the Veendam concession. Cavern shapes reflect dip and solubility of the salt layers. The upper cavern is no longer solution-mined from the year 2000 onwards. Depths are indicative due to the pillow shape of the salt.

subsidence by gas production from the Groningen and Annerveen gas fields. The (lateral) cavern growth for the same salt-production rate is much larger for bischofite than for halite because: i) the brine, which replaces the dissolved salt contains much more salt ($500 \text{ kg MgCl}_2/\text{m}^3$ versus $300 \text{ kg NaCl}/\text{m}^3$), ii) bischofite contains more water than solids ($850 \text{ kg H}_2\text{O}/\text{m}^3$ and $750 \text{ kg MgCl}_2/\text{m}^3$) whereas rock salt contains $2168 \text{ kg NaCl}/\text{m}^3$ (and no water) and iii) the cumulative thickness of the Mg-salt layers is ca. 40 to 50 m, compared to hundreds of metres in rock salt.

Fresh water is injected 30 to 60 m below a rock salt layer into a cavern filled with fully saturated brine ($1350 \text{ kg}/\text{m}^3$ at bischofite saturation). The buoyancy effects make the water rise in the cavern in a turbulent plume, which causes intense mixing with the existing brine. The brine-water mixture is almost saturated with MgCl_2 when it reaches the rock salt and can only dissolve negligible amounts of NaCl. Hence the rock salt acts as a natural barrier to solution mining. The slightly MgCl_2 -undersaturated brine will flow, usually following the stratification updip, to the highest spot in the cavern, where bischofite or carnallite will be dissolved. Subsequently, the saturated brine will flow down-dip to the deepest point of the cavern, where it can be produced. If the salts were immobile, or if the cavern pressure could be kept at almost lithostatic, the caverns would continue to grow. However, the magnesium salts have a low viscosity and they flow towards the caverns, driven by the weight of the overburden. Since the magnesium salts occur in layers, salt movement occurs mainly in and through these layers. The salts are squeezed towards the caverns, in a similar fashion to tooth paste in a tube. This rate of salt flow is such that the brine volume of the total cavern field remains limited during production: the cavern growth by dissolution is balanced by the cavern convergence.

Suspension and abandonment

Once a cavern has reached its maximum size, depending on practical, permitting or legislative considerations and once no further use is seen for storage of fluid or sequestration of waste material, a cavern usually becomes inactive. If the cavern was used for storage of oil or gas, these get extracted to the maximum possible, and replaced with water or brine from an active solution mining cavern in the vicinity. Sometimes the free-hanging leaching or production tubings are removed during this phase, after which a monitoring phase starts, usually lasting several years or decades.

During the monitoring phase, the cavern can be monitored for pressure build-up and temperature rise (due to heating by the surrounding rocks, especially relevant for the caverns at larger depth, i.e. 1000-3000 m, which were significantly cooled during the production phase). Repeat-

ed sonar measurements can help to prove that a cavern is stable in terms of roof fall in cases where the cavern roof consists of mixed halite-anhydrite-clay interfaces, which sometimes give roof falls due to stress build-up in the non-creeping materials and slow brine migration into clays that can degrade clay and shale strengths. In case of MgCl_2 mining, the sonar measurements cannot be used to measure the labyrinth type of cavern system for volume or extent, as it only sees a central core of the cavern, which adds no information.

The overall objective of cavern abandonment is to make sure that the cavern (or well) does not leak at elevated pressures, for instance caused by a leak path due to bad cementation of the casing. If this is established, the cavern can be closed by abandonment of the well, for example by placing barriers such as cement plugs over the salt roof section. The final abandonment (including more cement plugs to prevent cross flow of overburden fluids in the future) and the removal of the top section to return the well site to its original state (usually farmland) coincides with the full removal of the well site. Once the brine pressure reaches close-to-lithostatic pressures due to salt creep (and a bit of thermal expansion) the cavern is believed to be stable at human timescales. On geological time scale, but also on a scale of centuries, the cavern brine will slowly migrate out of the cavern due to the small excess pressure of brine towards rock stresses at the cavern roof, basically a buoyancy effect caused by the low density of brine with respect to the surrounding salts. When the brine pressures reach lithostatic stress level, it is likely that salt permeability increases, either at a crystal-interface level or by the creation of micro- or macro-fractures.

Which mechanism dominates is still a matter of scientific debate, but most likely it will depend on the pressurization rate, the presence of embedded fracture barriers like anhydrite (not present in domal salt, but usually in bedded salt) and the potential of crystallization in micro-annuli due to cooling of brine when moving upwards. This effect is strong for magnesium brines but almost absent for sodium chloride brine. Especially for higher caverns within halite the cavern field-closure and aftercare is now prepared following a risk-based approach in order to prevent any lagging surface effects on the longer term.

Pressurization tests in (small) sodium chloride test caverns have indicated that leak-off (a stabilization of pressure and continued injection) occurs around lithostatic pressure, but that no macro-scale fracture is created that would cause a massive brine outflow and large pressure drop. Such a macro-scale fracture was seen in 2018 in the Nedmag cavern system for MgCl_2 production where about $100\,000 \text{ m}^3$ of brine leaked off before stopping due to suspension of the fracture at brine levels of about 60 bars less

than original. This cavern system is still in operation and operating normally. Pressure levels will however not be increased anymore until final abandonment.

The general opinion is that all (or most) of the brine will leak from the salt layers (towards some overlying aquifer) in time. The time frame will, however, differ from cavern to cavern and from salt structure to salt structure. Shallow caverns in relatively cold salt will take thousands of years (or more) to leak-off half of the remaining brine, assuming the brine pressure remains close to lithostatic levels. For the deeper (warmer) salt and more creep-prone magnesium salts, the time frame may be centuries. Combined with political and public concerns that subsidence may occur at faster rates, or that fracture processes speed up the process potentially long after the mining operator left the mining site, the present vision on deep and magnesium salt mining is to allow salt creep to occur at a reduced pressure, in order to reduce the cavern volumes to the practical minimum before abandoning the well and cavern. This will create additional subsidence (and associated costs) at an early phase, but at least the consequences are clear and measurable during a phase when the operator is still mining or accountable.

Environmental impacts

The environmental effects of salt mining are largely comparable to the mining effects of oil and gas operations in the Netherlands, in the sense of creating subsidence, noise levels from drilling and production processes, saline wastewater volumes, the requirement for pipelines and cables (usually requiring cooperation from landowners, both private and public) and the (temporal) change of mostly agricultural land use into mining use, hence changing the landscape to a limited extent.

Subsidence

Salt mining leads to subsidence due to the (mainly) viscous flow of salt towards the caverns. The cavern fluid pressure is always lower than the lithostatic stress level to prevent leakage of fluids by permeation or fracturing, but in most it is kept lower for practical reasons. Solution mining for halite usually takes place at the lowest possible injection pressure and is mainly dictated by friction in the injection and production pipelines, including the surface pipelines for production towards the brine tanks. In case of fast flowing salt due to elevated depth and temperature or the presence of magnesium salts, a higher pressure may be preferred by choking the production line. This is at the expense of higher energy costs for injection, but it can reduce the salt creep. The shallow caverns near Hengelo have negligible salt creep rates at halmostatic fluid

pressure. Exceptions are some caverns predating 1950, which were basically overmined, leaving too little salt between the caverns and hence loading the remaining salt (sometimes called pillars from analogy with conventional mining). The overburden load rests on the pillars resulting in creep at measurable rates. Subsidence is a few mm per year at these locations. A few caverns were also overmined at the roof, leaving the clay overburden exposed to the brine, resulting in roof-falls into the caverns. One cavern created a sinkhole at surface. Another cavern caused a local depression (subsidence of about one metre). Around 40 other caverns are earmarked to have the potential to have significant roof falls and creating significant additional subsidence on top of salt-creep induced subsidence. These caverns are monitored regularly. They are being backfilled with sulphates and carbonates from the brine purification plant. The sequence of the caverns selected for backfilling is determined by risk level.

For mining from the salt domes (Zuidwending and Winschoten by Nobian) and the storage of liquids, the pressure in caverns is usually kept close to brine hydrostatic (halmostatic) levels, whereas storage is usually in shallow caverns with limited salt creep. Storage of gasses at Zuidwending and Winschoten (natural gas, nitrogen and most likely also hydrogen and compressed air in the future) is usually performed at pressures that are dictated by demand. In high demand the pressures are low (down to 10-30% of lithostatic), whereas in low demand (or high production), the gas pressure can be as high as 85% of lithostatic (depending on permits, pump and pipeline ratings and safety analyses). The salt creep related cavern convergence mainly takes place during periods of low cavern pressure. Typical cavern convergence rates for the gas storage caverns in Zuidwending (Veendam) are 0.5%-1% per year for caverns with volumes of about 1 million m³. The subsidence at both Zuidwending and Winschoten domal cavern sites amounts to a few mm per year at the well head centre, with a bowl extending to about 2 km radius. The subsidence so far (in 2022) is about 8 cm since start production for salt production and gas storage combined.

The Frisia caverns converge rapidly, so that a maximum volume is reached during solution mining. The caverns are at 2500 m depth and 100°C salt temperature. This makes viscosity low, combined with large difference between lithostatic stress and cavern pressure. The subsidence on land from 5 caverns amounts to some 30 cm, with partially overlapping bowls with a radius of about 4 km each. At present salt extraction is shifted to a cavern below the Wadden Sea. Subsidence will be measured with subsurface anchors and two GPS stations above water (on poles). Only at the sea dike and the harbour site direct measurement is possible (via levelling, InSAR and GPS), but only 5% or less

of the maximum subsidence is expected on some of these locations. The subsidence bowl, although expected to fill itself by natural sand transport, is expected to reach a total of ca. 1 metre in the decades to come (Fig. 16.11).

For the caverns on the Nedmag concession, the bischofite salt causes 80-90% of the cavern convergence, with the bischofite at 70°C, so close to its melting (self-dissolution) point of about 110°C. The caverns are kept under artificial pressure to limit the salt creep and cavern convergence during the active water injection stage in order to maximize the retention time of the brine and maximize the exposure time to bischofite, maximizing the purity of MgCl_2 brine (minimizing levels of SO_4 , K and Na in the brine). In doing so, several of the original 1970-1980s caverns have interconnected to form a single labyrinth type of cavern (Visser, 2018). The subsidence amounts to 1-3 cm per year (depending on the cavern pressure and volume), reached about 60 cm by 2024 and is projected to increase to about 90 cm by 2045 (Fig. 16.12). The radius of the total bowl is about 3 km. New wells are expected to be drilled at a distance of about 2 km from the heart of the existing bowl, so

that the deepest point of the existing bowl is hardly affected by the new mining activities.

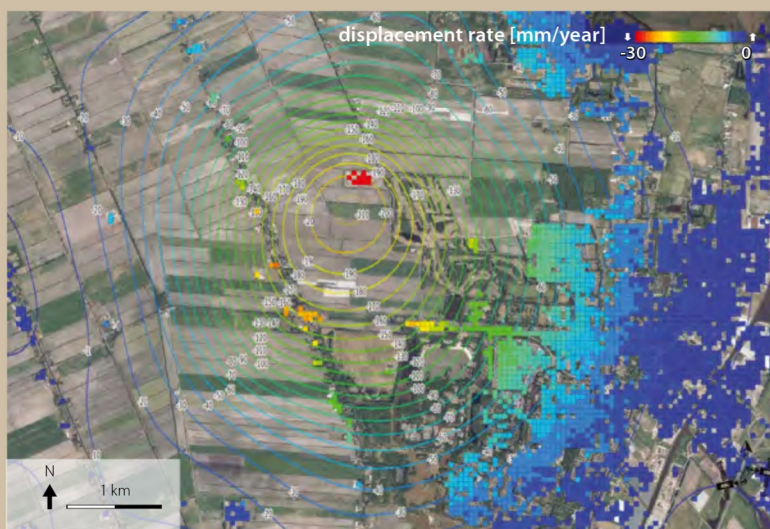
Developments on subsidence (land surface) measuring

Traditionally the subsidence is being measured by bi-annual or even less frequent levelling campaigns, where hundreds of 'solid' points anchored on shallow foundation poles in the land or bolted to well-founded houses or civil structures are manually measured. Advantage of the method is that shallow surface effects, that are influenced by fluctuating water saturation and ground water levels or ploughing of the fields can be discarded. Effect of water extraction from shallow wells will still be visible, however. The downside is that short term effects are not seen and the levelling campaign is expensive (and time consuming, usually taking a month or two).

GPS beacons allow daily measurements from a satellite, the height being compared with other GPS beacons (of other operators or from governmental organizations). The GPS is inaccurate on a daily basis due to fluctuations in the atmosphere, but on a monthly scale can be accurate to within a few mm. The downside is that a GPS station is

Land-surface monitoring from space

InSAR measures the altitude changes of hard surfaces, like roads or roofs. Soft or non-constant reflectors (like farmland) are usually filtered out. Normally, there are sufficient roads or farmhouses to give a reasonable impression of subsidence, such that the resolution in built-up areas (towns) is very good. InSAR is relatively cheap, including the semi-manual interpretation by a specialized company. It can give data on (approximately) a monthly basis and can also give data in retrospect (from about the year 2016 onwards). The downside is that road and roof surfaces react somewhat to groundwater levels and air temperature, so that there is slightly more seasonal fluctuation compared to levelling. If subsidence is several mm per year, this inaccuracy is small over the period of two (or more) years, assuming that the natural compaction of the top 1-10 m of the subsurface is small, like in most places in Groningen and Friesland, where most peat layers have been removed (or have been eroded) in the past centuries.



Example of a contour map of subsidence (concentric coloured lines) based on InSAR data (coloured squares).

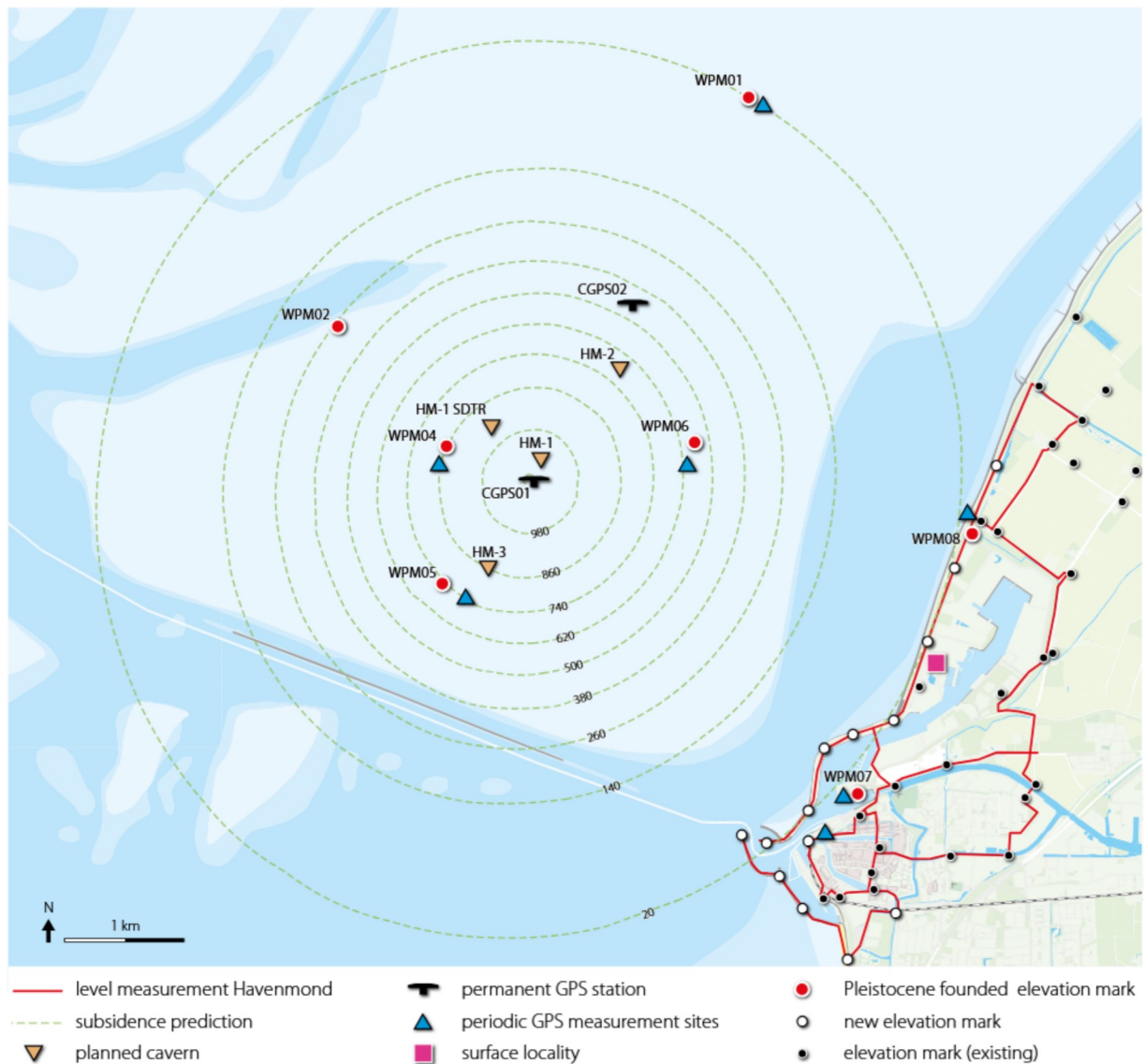


Figure 16.11. Frisia Wadden Sea subsidence bowl prediction (in mm contours) for 2050.

costly and requires electric power and maintenance. Usually, the GPS is placed at a mining site or on a large structure (office building, church, etc).

A relatively new development is the use of InSAR (Interferometric Synthetic Aperture Radar) whereby satellites measure the earth surface altitude (or more accurately it's relative change in altitude in time with respect to a reference point). So far, in salt mining it has not replaced leveling but is seen as complementary.

Damage to infrastructure, farmland or environment due to salt mining subsidence

Mining related subsidence, with the exception of sink-holes, is usually very gradual and it is generally assumed that infrastructure (houses, offices, pipelines, viaducts, roads) are not damaged by the subsidence itself (including bending, tilting and horizontal strain that is associated

with the subsidence; Geurts et al., 2021). Indirect damage may be possible if the groundwater table is not properly or not timely adjusted in cases where tens of centimetres of subsidence are involved. The water table adjustments are usually the prerogative of the Water Boards (and within city limits sometimes the municipality). So far, water tables could be adjusted properly at all of the salt mining locations in the Netherlands.

Earthquake damage by gas extraction from the Groningen gas field has changed the legislation for this specific field, so that damage that could have resulted from earthquakes or (uneven) subsidence is assumed to be related to gas production, unless there is proof of a different cause for the damage. The salt extraction fields of Veendam, Zuidwending and Winschoten overlap with the Groningen gas field (effect zone), but formally do not have the burden of

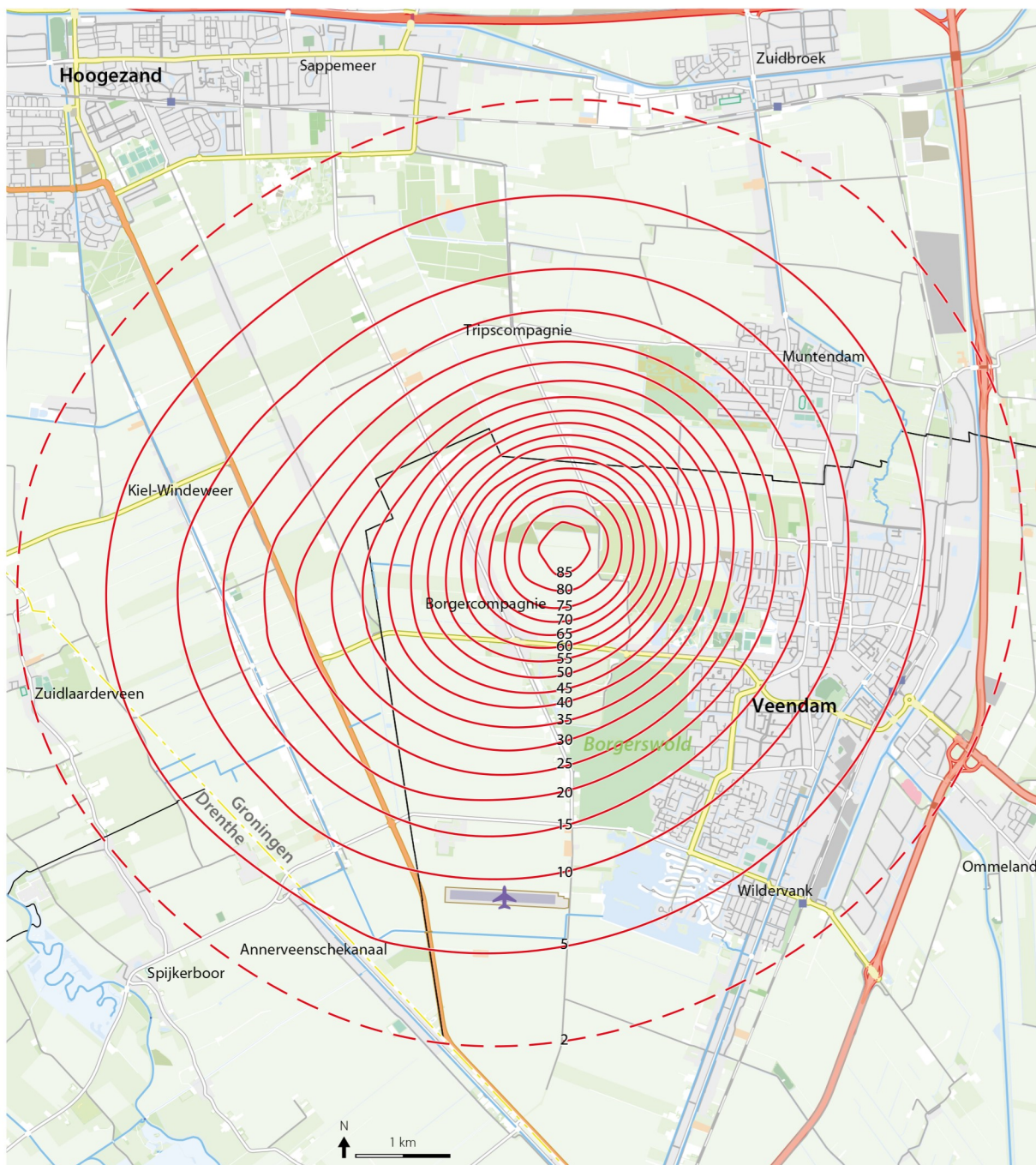


Figure 16.12. Nedmag subsidence bowl in cm, contours as expected in 2050, according to extraction plan 2018.

proof. It is not sure how this will develop in law and legislature in the future, after the closure of the Groningen gas field (2023), and also with respect to the Annerveen gas field (which overlaps with the Veendam and Zuidwending subsidence fields).

For the mine sites close to the Wadden Sea (only Frisia for salt extraction), subsidence (as sea-level rise) may cause a slight increase in salt sea water volumes that seep in (Dutch: *kwel*) and makes agriculture more difficult or less diverse. As of 2021 effects appear not to be severe (at 35 cm maximum subsidence).

Subsidence under the Wadden Sea is much more debated, from what appears to be a political-environmental point of view. Salt extraction was moved here, because of public concerns about subsidence on land, but environmental groups that wish to protect the Wadden Sea (Natura 2000 nature reserve) have objected to any mining at all below the Wadden Sea. Environmental studies have shown that the maximum subsidence itself is not as important as the subsidence bowl volumes per year. The bowl will attract sand from the normal sand and silt flux that moves (starting at the river influx from the Belgian

and Dutch rivers Scheldt, Rhine, Meuse) via the coast northwards, partially via the Wadden Sea. Too much subsidence (from salt and gas extraction) may cause a disruption of the natural sand fluxes, by which the low tide islands in the Wadden Sea may no longer (or to a lesser extent) be available for seals to rest and birds to feed. Although the expected 'sand-hunger' is much less than the sand flux, negative effects cannot be ruled out entirely. Monitoring is hence required for the wild life. Due to the highly fluctuating circumstances in the Wadden Sea (especially after storms with a lot of sand and silt displacement) wildlife populations fluctuate considerably, so that it is not easy to distinguish natural effects from mining effects. Sand suppletion via dredging in deeper North Sea waters and deposition in the Wadden Sea can in principle supplement shortages in sand, when it is believed that (temporarily) too much sand is trapped in subsidence bowls.

Seismicity

In contrast to gas extraction, earthquakes (anything above $M=2.5$) are unknown to the solution mining industry, most likely due to the viscous behaviour of salt and the limited associated shear stresses. Some light tremors (the largest measured $M=1.3$ near the Winschoten salt dome (Fig. 16.4; KNMI, 2022) have occurred around salt extraction areas. Two possible causes have been identified, the

first being movement along existing fault planes above or next to the salt structure, possibly induced by the salt mining. The second cause could be related to collapse of parts of the cavern roof. Given the public concern from mainly the Groningen field earthquakes (mainly those exceeding $M=2$), all the salt mining operators have installed micro-seismic monitors in shallow wells in order to be able to measure and (more precisely) locate smaller tremors. An example is the Zuidwending micro-seismic monitoring network installed by Nobian and EnergyStock to measure and locate micro-seismic activity in the vicinity of the salt mining and gas storage concessions in Zuidwending (see Fig. 16.13). Certainly, for Groningen and Friesland this also allows for a (better) discrimination of the most likely trigger of the earthquakes: salt extraction or gas extraction. No major tremors or earthquakes ($M>2.0$) are known to have been caused by solution mining globally. For the minor tremors, there is far less evidence, as they may not have been noticed at the ground surface, perhaps have not been published in literature or press, or have not been measured beyond noise level by national seismic stations at large distances from the mining operation site.

Environmental footprint

The indirect effect of solution mining is that it requires energy to remove water by evaporation in a vacuum evaporation plant, assuming that solid salt is required for trade

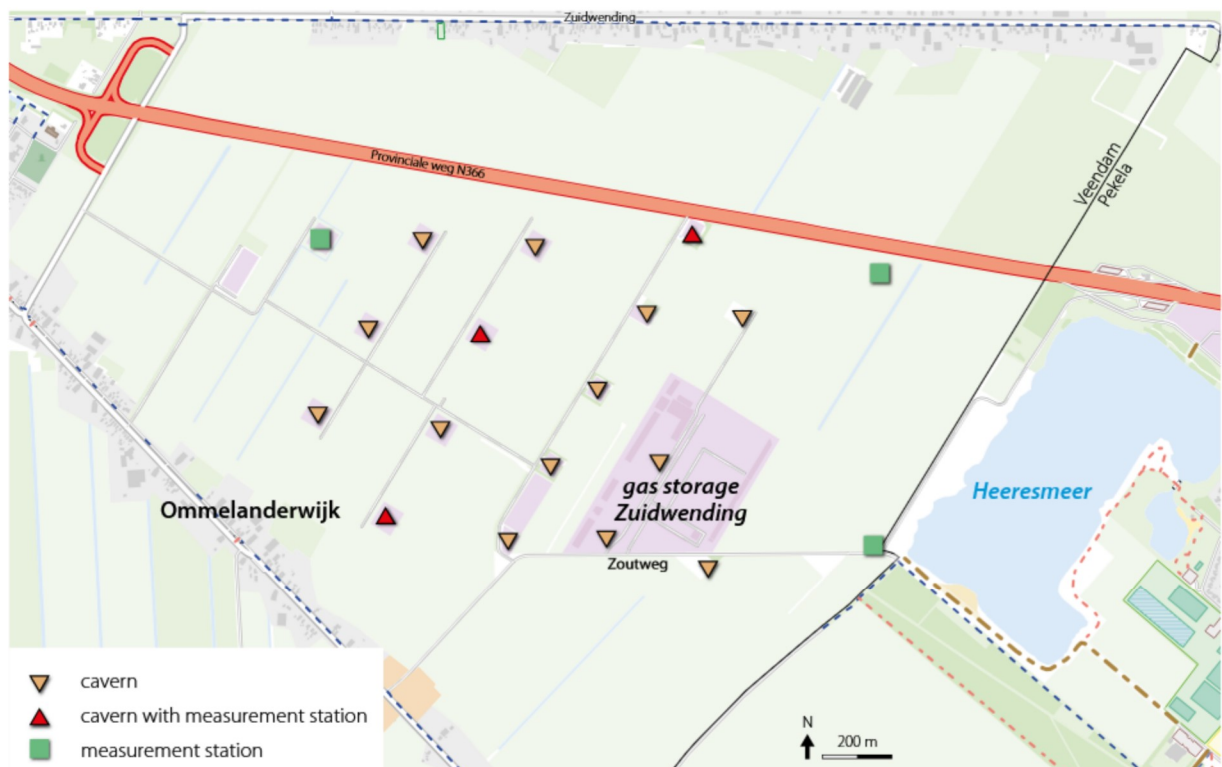


Figure 16.13. Micro-seismic monitoring network to measure and locate small tremors in the vicinity of the salt mining and gas storage concessions in Zuidwending (Nobian, personal communication).

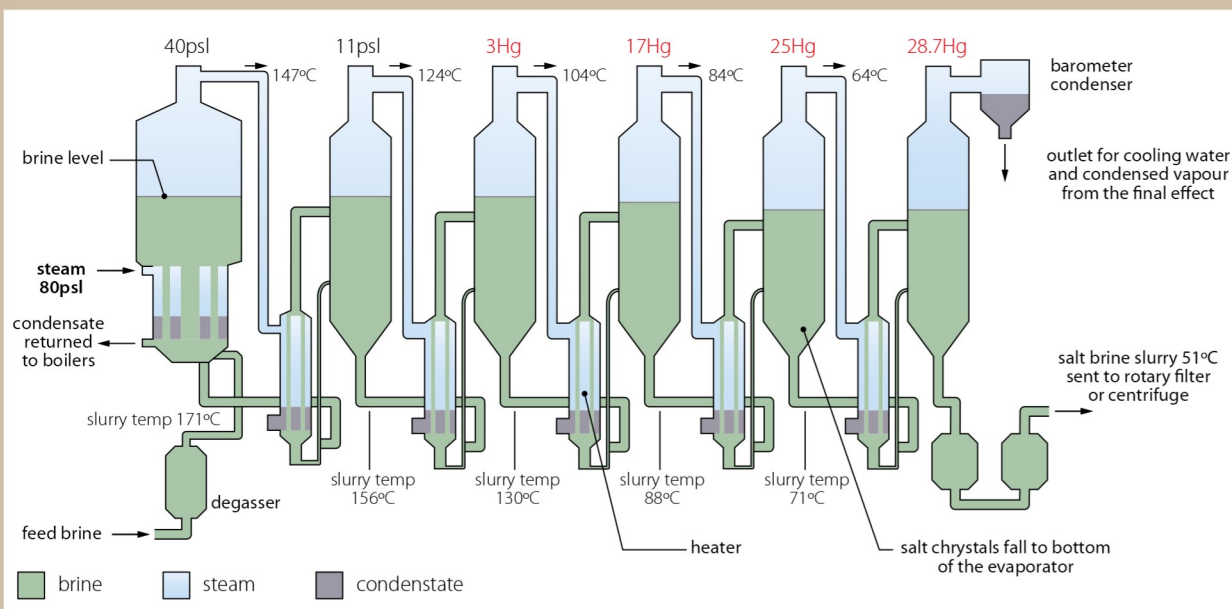
and transport to external clients. As conventional (excavated) salt is less pure, it may require higher purification costs or energy consumption from the client, usually a chemical plant. Which of the two salt mining methods results in a lower CO₂ footprint per ton of salt or final product is unknown at present. Part of brine is sometimes used as brine without having the intermediate step of creating salt, usually in chemical plants that are associated with the mining company, but only if brine transport is possible by pipeline. In that case, brine is mined, purified and consumed by, for example, a soda ash plant. More than 95% of the MgCl₂ brine of Nedmag is processed as brine. Only 5% or less is sold as bischofite salt in the shape of flakes or pellets.

The evaporation cycles of salt use some 90-95% of the inflowing brine to produce commercial salt. Some brine is purged (bled off) due to rising levels of bromine and potassium in the last stage of evaporation, which may off-set quality of salt for some or most of the clients. These brines are allowed to be disposed of in the sea at the Harlingen and Delfzijl salt plants or are being fed into existing caverns again (Hengelo salt plant). Prior to evaporation, the levels of magnesium and sulphates are reduced by precipitation of gypsum and magnesium carbonates. These solids are separated and usually disposed of or reinjected into the cavern system, where they precipitate. The solids are usually too impure and of too little volume to be used commercially.

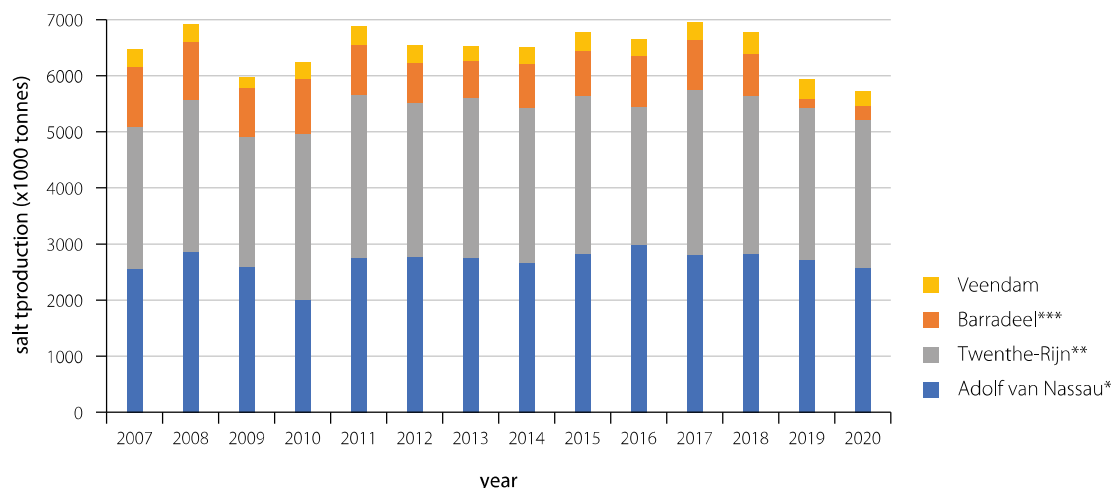
From brine to salt

2

In a vacuum evaporation plant, water is evaporated from the saturated brine in multiple stages to obtain pure solid salt. The evaporation stages are usually four to five repeated cycles in the vacuum evaporation plant, where the vapour of one stage is used to heat the next boiler (stage) that holds a lower vapour pressure. This subsequent boiler has a lower boiling point of the brine, ending at close to vacuum pressure in the last boiler (hence the name vacuum salt). In this process the evaporation energy is therefore reused three to four times. The energy source for evaporation is dry steam from steam boilers. The boilers are heated with gas, but also alternative sources of energy are being used. Frisia Salt is using energy from the neighbouring waste incineration plant (Omrin Harlingen), Nedmag is partly using hydrogen and biogas for its processes, while Nobian is using steam generated by Twence (Hengelo salt plant) and EEW and Eneco (Delfzijl salt plant). Excavated salt from conventional mining contains much more insolubles, like anhydrite, clay and potassium, that cannot be removed to a large percentage (without dissolving and re-crystallization by evaporation). The impurities create additional costs, energy or waste streams with the client chemical plants, for which reasons they usually choose vacuum salt.



Schematic diagram of the multi-stage vacuum evaporation process to extract pure salt from saturated brine. Redrawn after a figure on the website of the Salt Association (UK).



*incl. concession Uitbreiding Adolf van Nassau III

**incl. concessions Uitbreiding Twenthe-Rijn, Twenthe-Rijn Helmerzijde and Twenthe-Rijn Oude Maten

***incl. concessions Barradeel II and Havenmond

Figure 16.14. Salt production figures 2007-2020 (reproduced from MEACP, 2022).

Economic aspects

Approximately 70% of the Dutch NaCl production of 5.46 Mt/yr (2020, see Table 16.1) is used as feedstock for the production of chlorine in the chemical industry, which is indispensable for the manufacturing of PVC, textiles, aluminium, soap and detergents. Other uses of salt include applications in food and beverages, water treatment, licks for livestock, tanneries and road de-icing. Apart from chemical pureness and constant high quality, the cost of transportation is an important issue for most end-users. This is the reason why salt plants usually have direct access to navigable water.

About 0.25-0.30 Mt/yr of $MgCl_2$ is produced, of which the main part is used as brine for the production of high-grade magnesium oxide (MgO) and magnesium hydroxide ($Mg(OH)_2$). The remainder is sold as brine or salt and transported by ship or by road. The magnesium oxide is sold and used for the production of heat-resistant bricks, which in turn are used in iron and cement furnaces. The brine is used in many applications in the cement industry, and in manure treatment, but also as de-dusting and de-icing material. The process of creating MgO with $MgCl_2$ and Dolime (burnt dolomite) $MgCaO_2$, also results in a $CaCl_2$ brine stream that is sold as brine or processed towards solid salt.

Figure 16.14 gives an overview of the salt production (NaCl and $MgCl_2$) in the period 2007-2020, based on figures provided by operators. During this period the salt production has been fairly constant, between 6 and 7 million tons per year. In 2009, 2019 and 2020, the total salt production fell to slightly under 6 million tons. In 2009 and in 2020 this was due to the economic crisis and the Corona

Pandemic respectively, while in 2019, the main reason was that the production from the Barradeel production licenses decreased compared to previous years (MEACP, 2021).

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Digital map data

Spatial data of figures in this chapter for use in geographical information systems can be downloaded here:
<https://doi.org/10.5117/aup.28164287>.

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