Zechstein Salt Structures Evolution in the Northeastern Netherlands

Earth Structure and Dynamics

Internship Report

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Abstract

COVRA is a company that collects and stores radioactive waste in the Netherlands. Since radioactive waste can remain active for a very long time, there needs to be a place to dispose of it until it no longer poses a risk. Geological repositories can be designed and built for this purpose. These repositories are usually clay, salt, or hard rock. In the Netherlands, the Zechtstein salt structures are potential repositories for radioactive waste. Understanding the tectonic evolution and behavior of these salt structures is integral to ensuring it is safe to dispose of radioactive waste. Diapirism and subrosion rates provide a quantitative way of assessing the safety of these salt structures. This study is based on seismic interpretation and is done on four salt structures in the northeastern Netherlands, Zuidwending, Winschoten, Veendam, and Slochteren. Based on the results of this study, the tectonic evolution of the region affected the salt movement. The salt movement can be summarized in three phases. Phase 1 is when salt started moving during the Triassic, caused by the regional extension of the region, followed by phase 2, where salt movement decreased during the Jurassic, and phase 3, where salt movement increased during the Cretaceous caused by the regional compression. The salt budget calculations indicate that the four salt structures in this study are safe for radioactive waste storage for the next one million years.

Contents

1 Introduction

Radioactive waste remains active for a very long time and causes harmful effects on living organisms and the environment, making the safe disposal of such waste crucial. Currently, the most accepted scientific disposal method involves waste disposal in deep geological formations [1]. The slow geological processes can make a stable environment that lasts a very long time deep below the surface, so it is not affected by any events and processes closer to the surface. Multiple barriers, engineered barriers (containers), and natural barriers (host rock and overlaying formations) contain the radioactive waste and isolate it from the biosphere for a long time without the need of future maintenance. (Figure 1). This multi-barrier approach provides isolation of radioactive wastes and containment of the radiation until it has decayed enough that it no longer poses a risk. This approach is already implemented by different countries, such as France by ANDRA (Cigéo - clay)[2], Finland by POSIVA (Onkalo - hard rocks)[3], and the USA (WIPP - rock salt)[4]. The repository in Finland is expected to be operational in a few years [5].

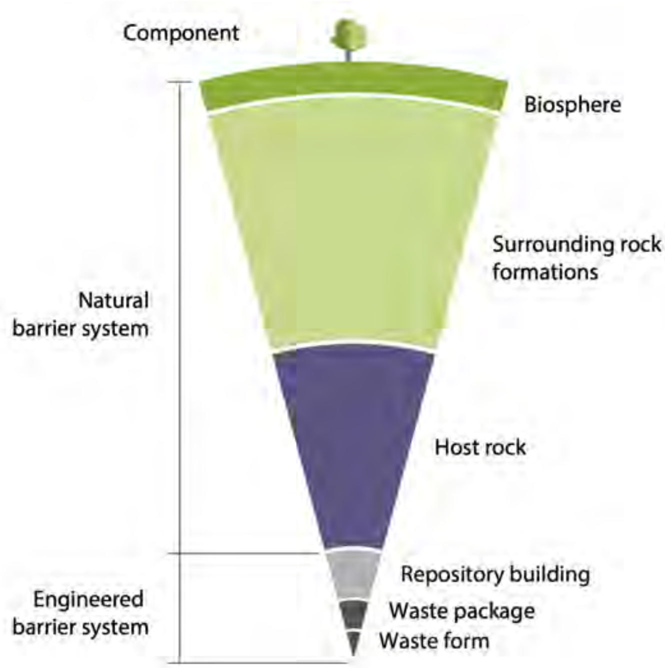

Figure 1: Components of a geological disposal system with two main barrier systems, engineered and natural burial systems [6].

The Netherlands has one nuclear power plant and a nuclear industry that produces nuclear waste that needs to be dealt with. COVRA (Central Organisation for Radioactive Waste) is responsible for all radioactive waste in the Netherlands. It is currently stored above ground in Zeeland for at least one hundred years [6]. There are three types of radioactive waste currently stored at COVRA, Low and intermediate-level radioactive waste (LILW), Technologically enhanced naturally occurring radioactive material (TE-NORM), and high-level waste (HLW), with high-level waste taking thousands of years to become harmless. This requires a more permanent and safe solution for the disposal of radioactive waste, which is deep geological repositories as per the policy in the Netherlands [7]. After the 100 years period, radioactive waste in the Netherlands will be disposed of in a geological disposal facility. Rock salt is currently being considered as a host rock due to its wide availability, impermeability, self-healing, and its ability to form dome and pillow structures providing extra protection [8].

Salt structures should be studied to understand and predict their future evolution and assess the safety of a repository as a disposal facility. Two processes that could lead to releasing radioactive waste are diapirism and subrosion [9]. Diapirism is the rate at which the salt rises upwards. A high diapirism rate could mean a salt rising to the surface and exposing radioactive materials before it is safe. Subrosion, on the other hand, is the dissolution of salt caused by contact with groundwater, reducing the barrier thickness. By studying salt structures and their diapirism and subrosion rates, we can assess how safe it is to dispose of radioactive waste until it is decayed and no longer poses a risk to the environment. This period is usually 1 million years. A study was done on four salt domes in the northeastern Netherlands, the Schoonloo, Hooghalen, Anloo, and Gasselte-Drouwen diapirs [10]. The calculated diapirism and subrosion rates aligned with other diapirs in the South Permian basin. This project looks at four different salt structures in the northeastern Netherlands, north of the area studied by Lauwerier (2021). The four salt structures are, Slochteren, Veendam, Winschoten, and Zuidwending. To perform this assessment, seismic data were interpreted to study the four salt structures. A method based on Zirngast (1996) was used to calculate the diapirism and subrosion rates.

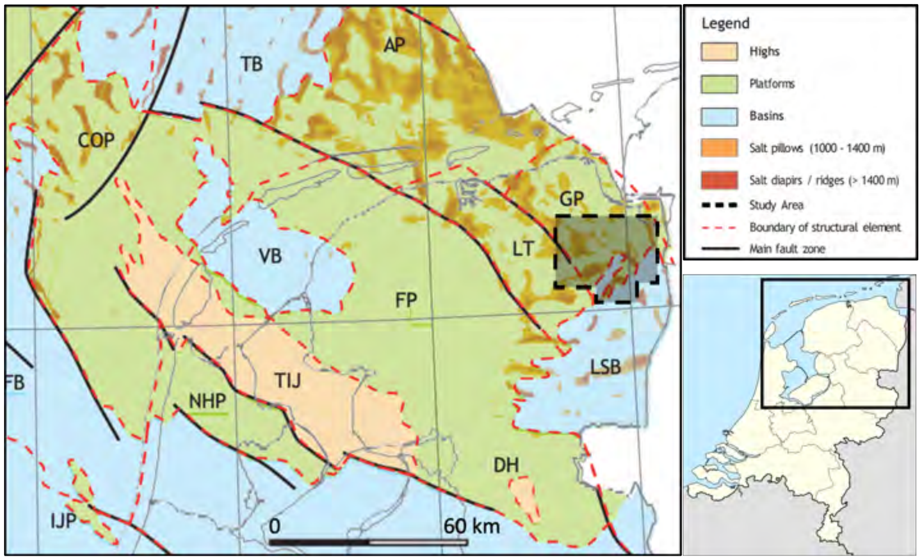

Figure 2: The study area is shown on the North Sea basin, with GP being the Groningen platform [11].

2 Geological Setting

The geology of the Netherlands is diverse and influenced by its geological history, which spans millions of years. The country's geological setting is primarily shaped by processes related to sedimentation and tectonics. Figure 2 shows the study area in the northeastern Netherlands on the Groningen platform. The area has a complex geological history as part of the Lower Permian basin. Figure 3 gives an overview of the tectonic phases in the Netherlands.

2.1 Pre-Permian

Before the Carboniferous period, Pangea started to form from the collision of three continents, Laurentia, Baltica, and Avalonia resulting in the Caledonian orogeny [12]. The Netherlands was located near the triple junction of these three continents, in the Caledonian foreland [12]. The early Carboniferous is marked by the start of the Variscan phase of the Pangea's assembly [12]. The resultant shortening led to the formation of many grabens-oriented NNW-SSE that would be the precursor of the Dutch central graben [12]. At the end of the Carboniferous, late orogenic volcanism was rampant [12]. Magmatism led to the formation of wrench faulting and thermal uplift, which resulted in subsequent erosion [13]. It has been suggested that the wrench faulting system is caused by the Variscan orogenic collapse [13]. These faults reactivated the previous trend of NW-SE faults formed earlier in the Paleozoic [12]. The faults formed in this period hold great significance and imprint all shallower formation deposition.

2.2 Permian

The early Permian period is marked as a period of decreased thermal activity and regional subsidence in the foreland of the Varsican orogeny [12]. The Permian is divided into three groups, the Lower Rotliegend group, the Upper Rotliegend group, and the Zechstein group. The clastic Rotliegend formation is deposited across the E-W trending southern Permian basin or SPB [14]. The SPB received clastic deposits from all directions but mainly from the Variscan Mountains that bordered it from the south and to lesser extents from the London-Brabant Massif, the Mid North Sea, and the Ringkøbing-Fyn highs to the north [12]. Continued subsidence led to the coupling with the establishment of a connection to the Artic Ocean led to the deposition of cyclic thick Zechstein halite and carbonates at the end of the Permian [15]. The Zechstein is composed of a sequence of evaporites (anhydrite, rock salt, and minor amounts of bitter salt), carbonates, and thin claystone layers [11].

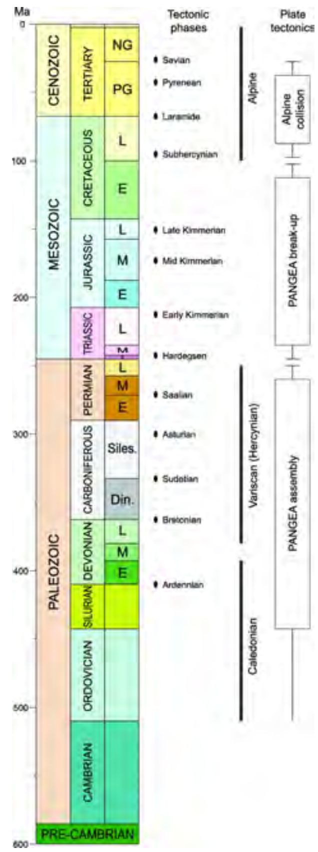

Figure 3: Tectonic phases in the Netherlands and their relation to tectonic events [12].

2.3 Triassic

During this period, Pangea began to break apart, and as such, it is greatly affected by the extensional system settings [11]. This rifting commenced in the Arctic-north Atlantic between Greenland and Scandinavia that continued propagating southward with a segment propagating into the North Sea in the early Triassic [12]. In the middle Triassic, the extension reached the southern part of the North Sea and ceased, rendering it a failed attempt to open the Atlantic [12]. During this time, the formation of salt walls has been observed in connecting to rift-related forms [16]. At the end of the Triassic, rifting increased in the early Kimmerian phase, but it is challenging to decipher due to the effect of diapirism on late Triassic deposition [16]. Triassic deposition, in general, was influenced by thermal subsidence and is divided into two groups, the lower Germanic group and the upper Germanic group. The lower Germanic group consists of sandstone and claystone successions deposited in a lacustrine and fluvial environment. In contrast, the upper Germanic group consists of claystone, evaporites, carbonates, and sandstones deposited in shallow, restricted-marine, and floodplain settings [17].

2.4 Jurassic

During this period, Pangea continued to fragment in a similar level of tectonic activity that has been going on through the Permian-Triassic. Thermal subsidence governed sedimentation in the Jurassic, much like the Triassic, and led to the deposition of majorly marine Altena, Schieland, Scruff, and Niedersachsen groups. The opening of the central Atlantic Ocean in the middle Jurassic led to variability in eustatic levels and sedimentation as a result [12]. The Schieland, Scruff, and Niedersachsen groups deposited at the same time in different basins. During the middle Jurassic, a significant tectonic uplift occurred in the mid-Kimmerian phase, leading to the erosion and the creation of the mid-Kimmerian unconformity in large parts of the North Sea [12]. After the uplifting subsided, the rifting accelerated in the northern part of the North Sea, following a N-S trend that was overprinted in the south by the pre-existing NW-SE trend established in the early Paleozoic [12]. The late Jurassic structural elements remain strongly evident in the subsurface, with upper Jurassic sediments eroded in most of the subsurface except for the Dutch central graben, rim basins, and a thin layer over platforms [11].

2.5 Cretaceous

The Cretaceous is separated from the Jurassic by the late Kimmerian unconformity that represents the last tectonic phase of the breakup of Pangea [12]. Crustal separation was established in this period, and the Atlantic Ocean widened further with the concentration of rifting to the region between the Norwegian and Greenland seas [12] [13]. The landmass that would become the Netherlands drifted northward, away from the equator, and assumed its position in what is now Europe. The Cretaceous sedimentation is governed by both subsidence and the rise of sea level, which led to the deposition of two marine groups, the Rijnland group (lower cretaceous) and the Chalk Group (upper cretaceous) [18]. The Rijland group consists of marine clay formations with sandstone layers [8]. The Chalk group consists mainly of carbonate rocks that were deposited due to subsidence and rising sea level [12]. In the late Cretaceous, the Alpine orogeny (Sub-Hercynian phase) began with the convergence of Eurasia and Africa and led to the shift to compressional stresses that led to episodic inversions [12].

2.6 Tertiary

The Tertiary is divided into three groups, Upper, Middle, and Lower North Sea Groups. The Lower North Sea group sits unconformably on the Chalk group. The North Sea groups consist mainly of siliciclastic sediments. The North Sea group covers the entirety of the Netherlands, but its thickness varies highly due to multiple inversion pulses.

3 Methodology

Diapirism and subrosion rates of salt structures are important factors in understanding its future evolution. The first step to assess the safety of salt structures as geological repositories for radioactive waste is to interpret seismic data of the subsurface. Using this interpretation, we can calculate the salt budget (diapirism and subrosion rates) based on the current locations of salt structures and their source areas.

3.1 Seismic Interpretation

Seismic interpretation is a crucial process that involves analyzing and interpreting seismic data to understand subsurface structures and properties. A project containing data from NLOG (Nederlandse Olie- en Gasportaal) was created by Utrecht University and provided. All seismic interpretation was performed on Petrel software. Two seismic surveys were used for seismic interpretation. The two seismic surveys are Groningen_Lite_NAM_2016-R3136 and 12FH13AC_L3NAM1985G, both are in the depth domain. The wells in the area were quality checked and used as a guide for seismic interpretation. Using both the seismic data and wells in the area, nine horizons were interpreted, continuing the work of Lauwerier (2022) [10]. The nine horizons are, from deepest to shallowest, The Zechstein group (ZE), Lower Germanic group (RB), Upper Germanic group (RN), Altena group (AT), Niedersachsen (SK), Rijnland group (KN), Chalk group (CK), Lower North Sea Group (NL), and Upper North Sea group (NU). Surface and thickness maps were created using the horizons that were interpreted. Figure 4 shows the horizons that were interpreted and their characteristics.

Horizon	Stratigraphic Code	Characteristics	Example
Base Upper North Sea	NU	Strong amplitude Continuous	
Base Lower North Sea	NL	Strong amplitude Continuous	
Base Chalk	CK	Strong amplitude Continuous	
Base Rijnland	KN	Medium amplitude	
Base Niedersachsen	SK	Weak amplitude Discontinuous	
Base Altena	AT	Strong amplitude	
Base Upper Germanic Trias	RN	Weak amplitude Discontinuous	
Base Lower Germanic Trias / Top Zechstein	RB	Strong amplitude when on top of anhydrite	
Base Zechstein	ZE	Strong amplitude Continuous	

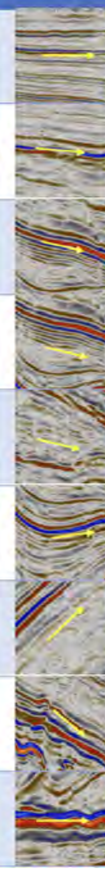

Figure 4: Seismic reflectors and their characteristics.

3.2 Salt Budget

A salt diapir is a type of geological structure formed by the upward movement of salt. It is a specific type of salt tectonics, a process that involves the movement of salt layers due to their buoyancy and plastic behavior under pressure [19]. When salt pillows form, they cause the overburden layers to be thinner and increase the thickness above areas where the salt flowed from (known as withdrawal basins) (5). During the diapirism stage, salt flows from the withdrawal basin into the diapir. The salt flow and accumulation stages can be reconstructed using the thickness variations of sediments in these withdrawal basins. This can be done by comparing the sediment thickness in withdrawal basins to the normal sediment thickness, which was determined from areas that were not affected by salt movement. The DGM-deep model v5.0 [20] was used

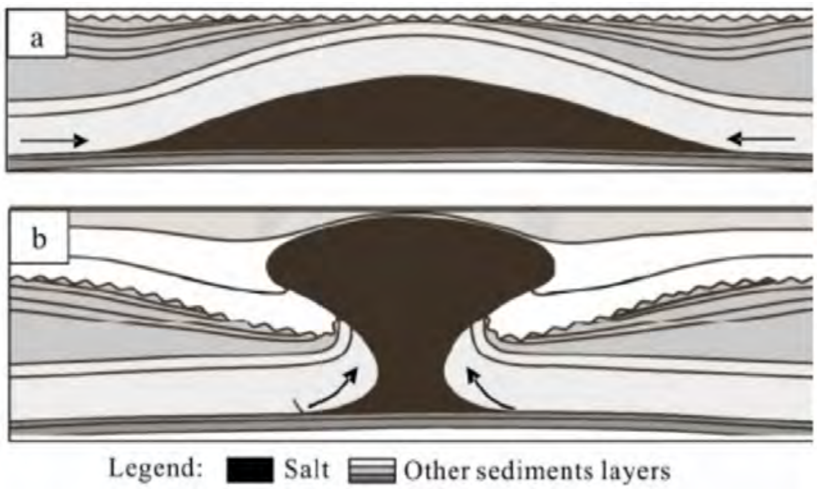

Figure 5: a. Salt pillow. b. Salt diapir [22].

to estimate the normal sediment thickness for each stratigraphic group based on their average thicknesses. The estimated normal sediment thickness is used to calculate the volume of salt that flowed into a diapir from the same withdrawal basin. This method is based on the work of Ziegler (1990) in the Gorleben salt dome area, northwest Germany, by budgeting the salt movements to determine the diapirism and subrosion rates. One advantage this method has over other methods for calculating the salt budget [21] is that it includes the eroded salt in the calculations, making it possible to calculate the total salt budget. For this method to work, three assumptions are made. First, salt always moves upwards. Second, sediment thickness variations are the result of salt movement. Lastly, when two salt domes are close to each other, the source area in between supplies the two salt domes equally.

To calculate the salt budget, the first step is to generate a compilation of surface maps, construct isopach maps (stratigraphic thickness maps), determine the amount of normal sediment thickness, and finally, delineate the salt source area (withdrawal basin). Withdrawal basins are close to salt domes and are caused by the salt flowing into the salt dome (figure 6). The volume of the sediments that filled the withdrawal basin equals the volume of the salt that flowed into the salt dome. To calculate the diapirism and subrosion rates, the following steps are taken:

1. The salt dome area (A_d) and salt source (A_s) are identified per stratigraphic group with salt movement. The salt dome areas are areas where the salt is thicker than the average salt thickness, while the salt source areas are areas where the salt thickness is less than the average salt thickness.

2. The sediment thickness in the withdrawal basin (h_{sw}) and withdrawal basin area (A_s) is used to calculate the sediment volume in the basin.

3. The withdrawn salt volume is calculated by subtracting the normal sediment volume from the sediment volume in the withdrawal basin.

4. The total column height (c_t) can be obtained by dividing the withdrawn salt volume by the dome area (A_d). This includes the subroded salt.

5. The salt column during deposition (c_a) can be obtained by subtracting the thickness above the salt dome (h_sc) from the normal thickness (h_n).

6. The difference between the salt column during deposition (c_a) and the total column height (c_t) is the column of the subroded salt (c_e).

7. The diapirism rate can then be obtained by dividing the column height during deposition (c_a) by a stratigraphic time interval.

8. For the subrosion rate, it can be obtained by dividing the eroded salt thickness (c_e) by a stratigraphic time interval.

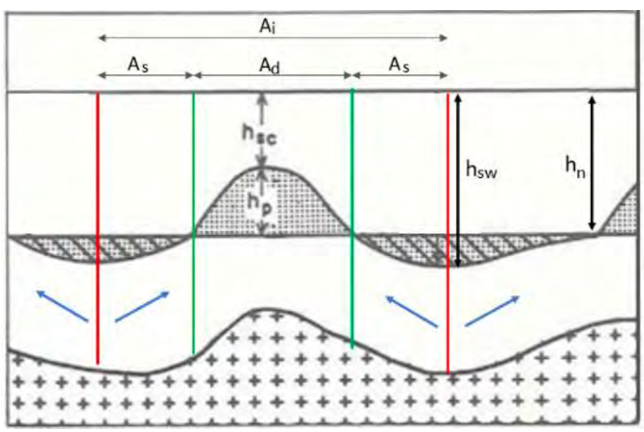

Figure 6: A cross-section showing a salt dome and a withdrawal basin. The salt dome influence area (A_i), salt dome area (A_d), salt source area (A_s), minimum sediment thickness (h_{sc}), maximum sediment thickness (h_{sw}), normal sediment thickness (h_n), and salt dome height (h_p) [10].

4 Results

4.1 Seismic Interpretation

To be able to study the salt domes in the area, information on the subsurface is needed. Subsurface information can be acquired by interpreting seismic data. Formation tops from wells were used to interpret nine formations in the study area. Wells stratigraphic marker data from NLOG follows the stratigraphic nomenclature of the Netherlands [23]. The Zechstein Group thickness is used as salt layer thickness (A.12) since it is mostly salt stratigraphy. Due to the decoupling of the geology caused by the salt, the faults on the base Zechstein do not continue upwards. The Surface maps for the interpreted horizons can be found in the appendix.

4.2 Salt Structures

Figure 7 shows the top of the Zechstein with four yellow lines corresponding to cross-sections of the four salt structures, Zuidwending, Winschoten, Veendam, and Slochteren, that will be discussed in this section. The Zuidwending and Winschoten are salt domes, while the Veendam and Slochteren are salt pillows. For a salt pillow, the salt moves in a lateral direction without piercing the overlaying sediments, while for the salt dome, the salt moves vertically and pierces overlaying sediments [24].

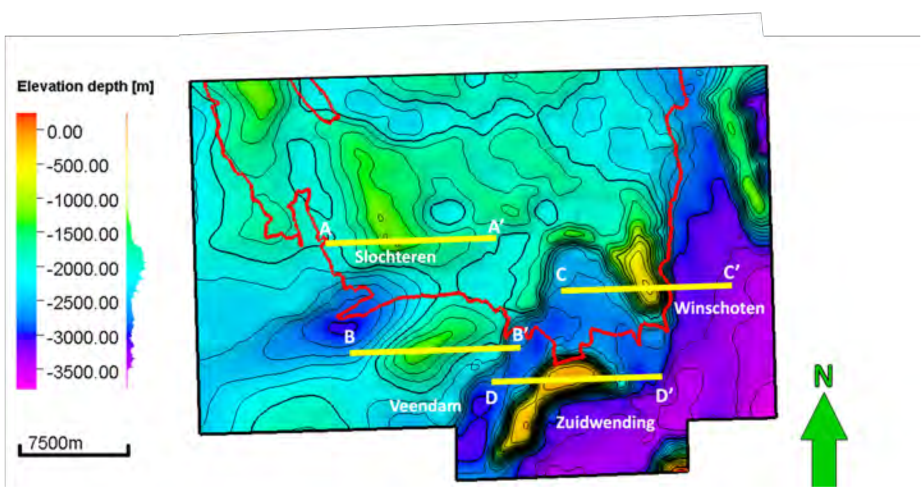

Figure 7: A map of the top of the Zechstein group showing the locations of the cross-sections for the four salt structures.

4.2.1 Zuidwending

Figure 8 shows the Zuidwending salt dome. It is a large salt dome with relatively steep sides. The Zuidwending salt dome reaches a depth of 200m below the surface with a vertical thickness of up to 3000m. The depth of the Zechstein group around the salt dome is approximately 2700m, with the base of the Zechstein group being at 3000m below the surface. The transparent seismic data is an indication of salt. Due to the quality of the seismic data, the boundary of the salt dome is not always clear. The high amplitudes at the top of the salt dome are considered to be a caprock. As the salt moves upwards, it begins to dissolve. Anhydrite is an evaporite that does not dissolve as easily as salt and forms a caprock [25]. Wells ZWZ-A1A and ANV-01 confirm a caprock thickness of at least 50m thick. However, the caprock could be as deep as 850m below the surface. Anhydrite banks also occur within the salt dome, as indicated by the high amplitudes highlighted in figure 8.

The area east of the Zuidwending salt dome lies on the Lower Saxony basin, with one major fault above the salt. This fault activated during the deposition of the Upper Germanic Trias group and could be related to the boundary between the Groningen platform and the Lower Saxony basin. This explains the general deeper Lower and Upper Germanic Trias groups in the eastern area. The Altena group shows little to no thickness variations, while the Niedersachsen group shows no thickness variations on the western side of the salt dome while pinching out on the eastern side. The Rijnland group has a constant thickness across the area. All this indicated that the Zuidwending salt dome experienced no salt movement during the Jurassic and early Cretaceous due to minimal thickness variations. Withdrawal basins can be seen on the Chalk and Lower North Sea groups, indicated by sediment thickening. Salt movement occurred during the late Cretaceous (Chalk group) and Tertiary (North Sea Supergroup), with the movement being higher during the late Cretaceous due to the higher increase in thickness. The Lower and Upper North Sea groups are the only formations present on the top of the salt dome.

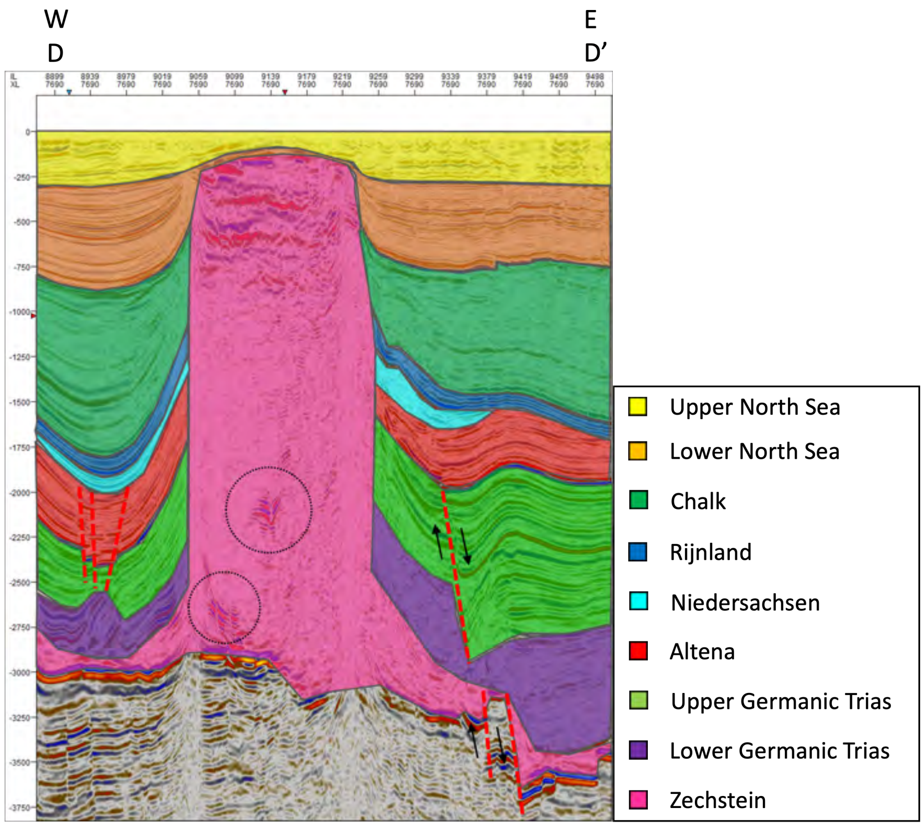

Figure 8: A W-E seismic section showing the Zuidwending salt dome and its surrounding geology with faults indicated by red dotted lines. The circled areas are anhydrite banks.

4.2.2 Winschoten

Figure 9 shows the Winschoten salt dome. It is a large salt dome located east of Groningen. It has a vertical thickness of 2500m and reaches as high as 400m below the surface. Wells going through the salt dome confirms the presence of salt (WSN-01). The upper part of the salt dome contains a 40m thick caprock. Floating anhydrite banks exist at the bottom of the salt dome, as highlighted in figure 9. There are no major faults above the Zechstein group.

The Upper Germanic Trias group shows thickness variations which could indicate salt movement during the Triassic. The Jurassic formations (Altena and Niedersachsen) presence is limited in this area, with Niedersachsen not present at all. The Altena group is pinching out on the western side of the salt dome. This all is an indication that the Jurassic sediments got eroded after deposition. The Rijnland group shows no thickness variations, while the top three formations, Chalk, Lower North Sea, and Upper North Sea, show sediment thickening around the salt dome, with the withdrawal basins seen in the Chalk and Lower North Sea groups. This indicated that the major salt movement started during the late Carboniferous.

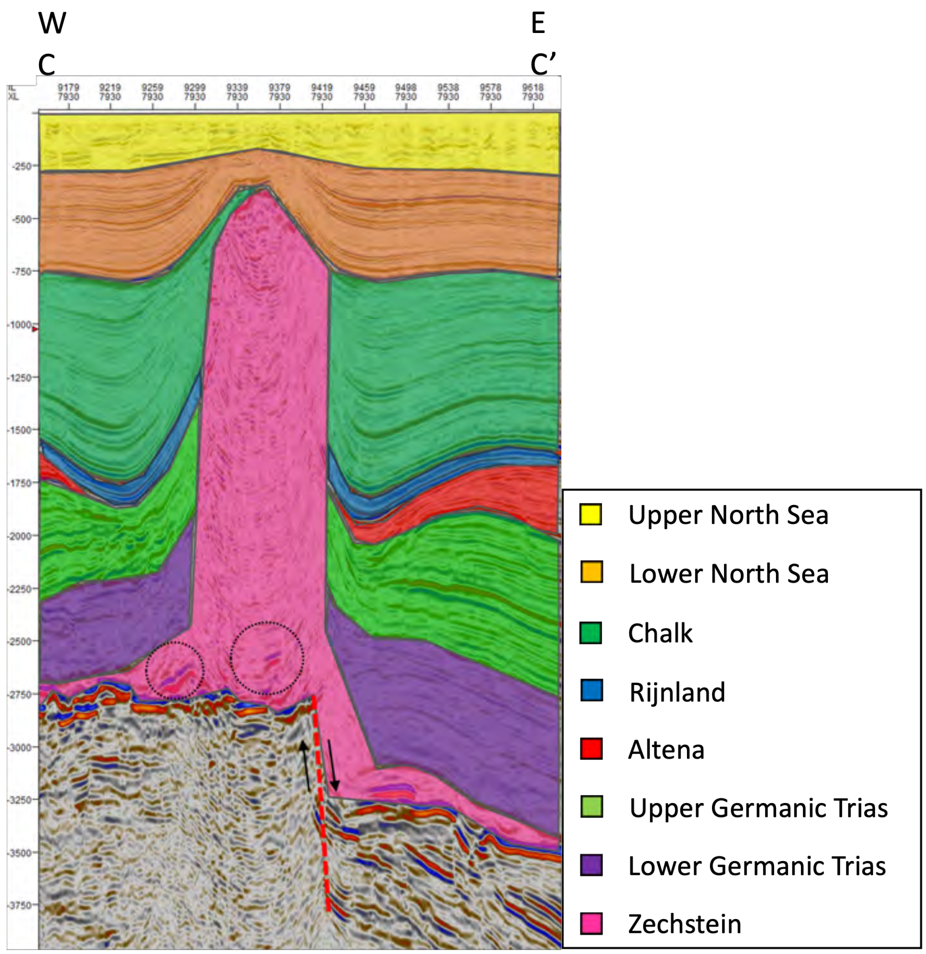

Figure 9: A W-E seismic section showing the Winschoten salt dome and its surrounding geology with faults indicated by red dotted lines. The circled areas are anhydrite banks.

4.2.3 Veendam

Figure 10 shows the Veendam salt pillow located at the southern edge of the Groningen platform. It is a wide salt structure reaching a depth of 1300m below the surface. The transparent seismic data is salt, as confirmed by the wells in the area. The distinct reflector inside the salt are thin layers of anhydrite and carbonate. These thin layers are known as stringers [26]. Stringers are layers of rock fragments that consist of mineral other than halite that behaves differently than the surrounding halite. This difference causes the stringers to have a very high amplitude in the seismic section. The Zechstein group consists of different formations (Z1 to Z5), with the stringers being part of the Zechstein Z3 formation [27] [28]. The average thickness for the stringers is around 50m with a complex folding structure [29].

The Lower Germanic Trias group shows slight thickness variations, which could indicate when the salt initiated movement. The Upper Germanic Trias group has a constant thickness and pinches out on both sides of the salt pillow. The Jurrasic section is missing in most of the area due to it being eroded after deposition, with the Altena group pinching out on the eastern side. The Rijnland group shows no thickness variations indicating a quiet period for salt movement. This quiet period lasted until the late Cretaceous, where thickness variations can be observed in the Chalk group. This period of salt movement continues, and its effect can be seen in the Lower and Upper North Sea groups. Faults can be seen above the Veendam salt pillow, which could be related to the basin inversion during the late Cretaceous, causing the overburden to buckle.

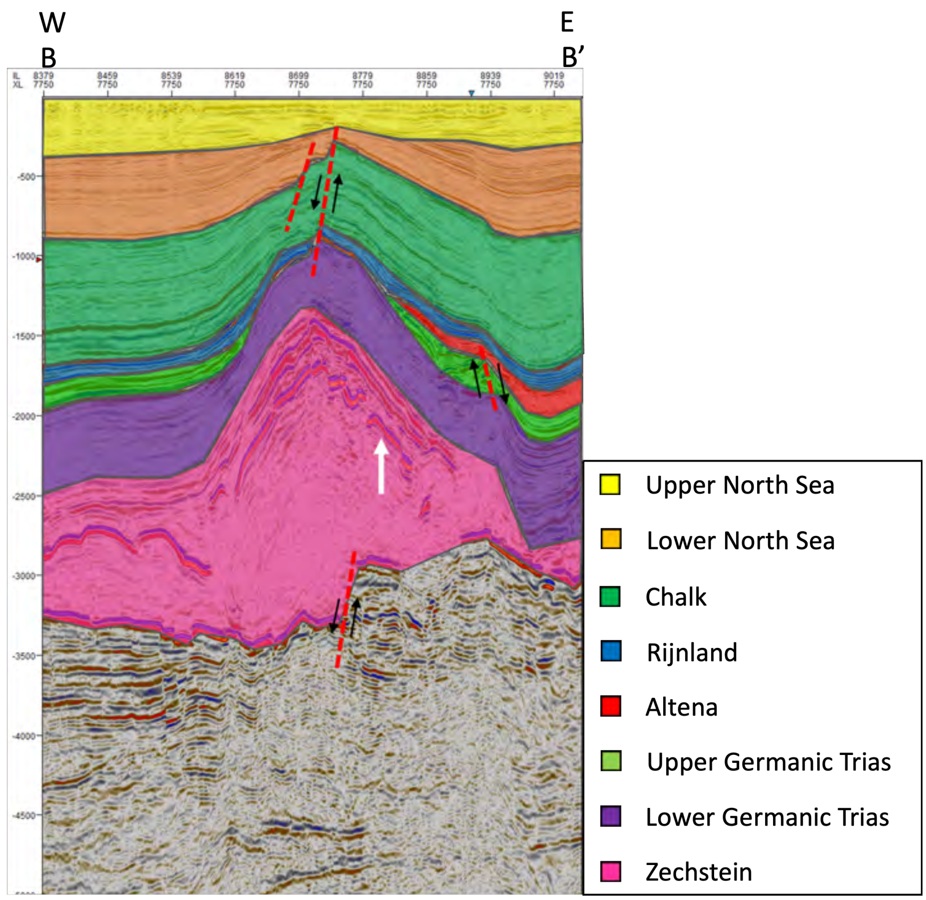

Figure 10: A W-E seismic section showing the Veendam salt pillow and its surrounding geology with faults indicated by red dotted lines. The white arrow indicates the Zechstein Z3 stringers.

4.2.4 Slochteren

Figure 11 shows the Slochteren salt pillow located at the southern part of the Groningen platform. It is a wide salt structure with a depth of 1200m below the surface with a vertical thickness of 1700 in the pillow core. Like the Veendam salt structure, the Zhecstein Z3 stringers are present in this structure, indicated by the high amplitude thin layer inside the transparent salt.

The Lower Germanic Trias varies in thickness across the area, indicating salt movement. The Upper Germanic Trias pinches out in the area east to the east of the salt pillow and is not present on top of the salt pillow. This pinching out could be an indication of the salt pillow's continued rise during the deposition of the Upper Germanic Trias group. The Jurassic section was eroded after deposition as well. For the Cretaceous, the Rijnaland has a constant thickness indicating no salt movement during the early Cretaceous. However, that is not the case for the late Cretaceous, where the chalk group thickening indicates a renewed salt movement. This salt movement continues all the way to the Tertiary but slows down during the deposition of the Lower North Sea group. There is one major fault above the Slochteren salt pillow, which is related to the same late Cretaceous inversion affecting the Veendam salt pillow. The fault was active during the deposition of the Upper North Sea group deposition.

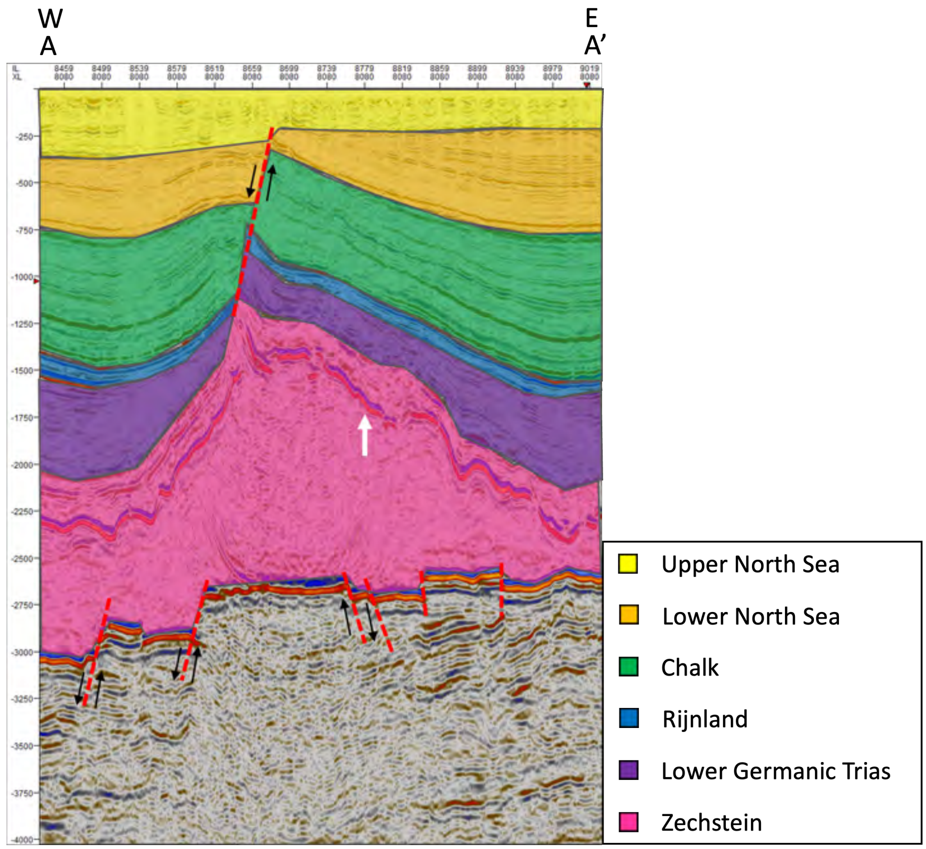

Figure 11: A W-E seismic section showing the Slochteren salt pillow and its surrounding geology with faults indicated by red dotted lines. The white arrow indicates the Zechstein Z3 stringers.

4.3 Salt Budget

The salt budget was calculated for the shallowest three formations, the Chalk, Lower North Sea, and Upper North Sea groups. Salt withdrawal basins, where the salt moved from, were delineated on the thickness map of each of the three stratigraphic groups. The salt withdrawal basins can be identified by sediment thickness variations above the salt structures, with significant variations in thickness being an indication of salt movement. Delineated thickness maps and surface maps used to create the thickness maps can be found in the appendix.

The diapirism and subrosion rates were calculated using the method mentioned in Section 3. Figures 12 and 13 show the diapirism and subrosion rates, respectively. Based on the salt budget results, all four salt structures have similar growth rates during the Lower and Upper North Sea groups deposition. However, during the Chalk group deposition, the Zuidwending and Winschoten salt diapirs grew more than Veendam and Slochteren salt pillows. Similarly, for the subrosion rate, the Zuidwending and Winschoten salt domes share similar rates during the North Sea supergroup deposition, where most of the subrosion happened during the Upper North Sea supergroup deposition. This trend differs for the Veendam and Slochteren salt pillow, where most of the subrosion happened during the Upper North Sea group deposition. The negative subrosion rates for the Chalk group in three of the salt structure means that the subrosion during that period was very low.

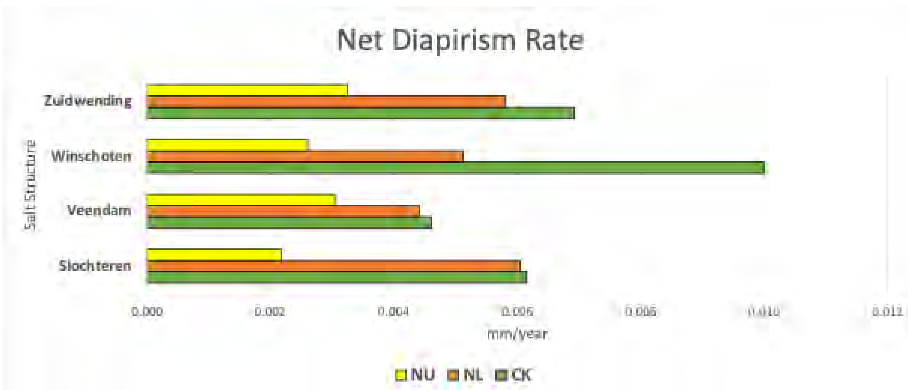

Figure 12: Net diapirism rate for each salt structure during the Chalk group (CK), Lower North Sea (NL), and Upper North Sea (NU) deposition.

Figure 13: Subrosion rate for each salt structure during the Chalk group (CK), Lower North Sea (NL), and Upper North Sea (NU) deposition.

5 Discussion

5.1 Pre-Salt Deposition

Figure 14 shows the base of Zechstein (top of the Rotliegend) with the major faults in the area highlighted with the white dashed lines. These faults are extensional normal faults. The general trends of these faults are approximately NW-SE, NE-SW, and E-W. The E-W striking faults are most likely related to the Variscan Orogeny that started during the early Carboniferous [30]. Post-orogenic tectonism and thermal uplift during the late Carboniferous are associated with the development of the NW-SE and NE-SW conjugate fault system [13] [31]. All these major faults are in close proximity to the salt structures, Slochteren, Veendam, Zuidwending, and Winschoten, which could indicate a relation between salt movement and the basement faults [32].

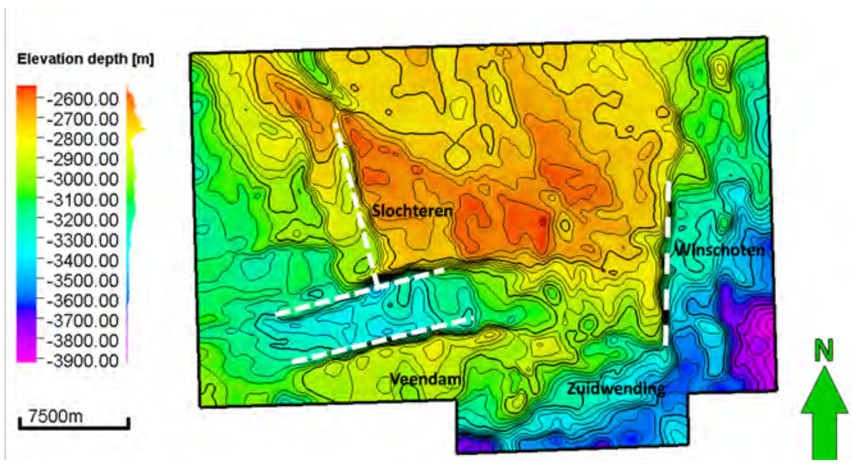

Figure 14: A surface map of the base of Zechstein (top of Rotliegend). The white dashed lines show the major faults in the area.

5.2 Zechstein Salt

Salt deposition occurs in sedimentary basins when evaporation of seawater or brines leaves behind salt minerals. These salt layers are buried under sediments. Over time, the salt layer becomes buried under a significant thickness of sedimentary rock. If the salt layer is later subjected to tectonic forces, it can become deformed and start to flow due to its relatively low viscosity compared to surrounding rocks. Under tectonic stress, the salt layer can form a salt pillow. This is a localized bulge in the overlying sediments caused by the upward movement of the salt. A salt pillow can continue to rise and pierce through the overlying rock layers due to its buoyancy [33]. In this study, Zuidwending and Winschoten are salt domes, while Veendam and Slochteren are salt pillows since the salt did not pierce through the overburden layers.

Anhydrite layers can act as natural barriers to salt formation. They have lower permeability than salt, which can provide an additional layer of isolation for the containment of hazardous or radioactive waste. Both the Zuidwending and Winschoten salt have atick layer of anhydrite caprock. The two salt domes also have anhydrite floaters, which can introduce heterogeneity and variability in the mechanical properties of the salt formation. The Veendam and Slochteren salt pillows have an intra-salt anhydrite layer known as stringers as part of the Zechstein 3 unit. It is necessary to accurately assess the potential impacts of anhydrite stringers and floaters since they can affect the stability of geological repositories [34].

Not all faults in the sub-salt strata propagate to the supra-salt strata as the Zechstein salt decouples the geology below and above it. However, this is not always the case as faults below and above the salt can be soft-linked, as seen east of the Zuidwending salt dome with NE-SW fault.

5.3 Post-Salt Deposition

Based on the seismic interpretation, salt movement can be divided into three main phases. The first phase was during the Triassic extension, a second quiet phase during the Jurassic, and a third phase during the late Cretaceous.

5.3.1 Triassic

The first phase happened during the Triassic after salt deposition, where the post-salt sediments initiated salt movement. This was caused by the reactivation of older faults due to regional east-west extension, which led to Pangea breaking up [35]. The thickness variations in the lower and upper Germanic Trias groups indicate salt movement during this period. The Upper Germanic Trias group is significantly thinner on top of the Veendam salt pillow and eroded on top of the Slochteren salt pillow, indicating a higher salt movement in this area. The increased salt movement is related to the three main faults around the two salt pillows. Other studies done in the Dutch offshore [36] and Groningen platform [37] suggest that salt movement also started during the Triassic.

5.3.2 Jurassic

The second phase lasted from the Jurassic to the early Cretaceous. The availability of the Jurassic is limited in the Groningen platform, with it being completely absent on top of the Veendam and Slochteren salt pillows. Erosion of Jurassic sediments was the result of the mid-Kimmerian strong uplift [13]. Due to no local thickness variations in the present Jurassic sediments, the salt unlikely moved during this period. The Rijnland group has a continuous thickness indicating no salt movement during the early Cretaceous.

5.3.3 Cretaceous and Tertiary

The third and final phase of the salt movement started in the late Cretaceous during the deposition of the Chalk group. The significant Chalk group thickness variations indicate the highest salt movement in the area. The late Cretaceous inversion (Alpine inversion) caused regional compressional tectonics and restarted the salt movement after the quiet phase during the Jurassic and early Cretaceous [38]. The salt movement continued into the Tertiary but at a slower rate since the thickness variations in the North Sea supergroup are not as significant as in the Chalk group. Other studies done on the movement of the Zechstein salt are in line with the finding of this study [37] [36].

5.4 Salt Budget

All four salt structures grew the most during the deposition of the Chalk group, with Zuidwending and Winschoten salt domes growing the most. The subrosion rates are higher during the North Sea Super group than the Chalk group. The subrosion rates calculated for the Chalk group are negative, which means that little to no subrosion happened during that period.

Based on the salt budget results, the Slochteren salt pillow grew by 525m, the Veendam salt pillow grew by 420m, the Winschoten salt dome grew by 780m, and the Zuidwending salt dome grew by 720m during the period of the Chalk and North Sea Supergroup. Figures 15 and 15 compare the salt structures diapirism and subrosion rates obtained with other studies. The method used here is the same as the method used by Lauwerier (2022) for four different nearby salt domes. According to the calculated diapirism and subrosion rates calculated in this research, the four salt structures will not reach the surface in the next million years, and salt will not be completely eroded. This makes the four salt structures, Slochteren, Veendam, Winschoten, and Zuidwending, suitable for radioactive waste storage for the next one million years.

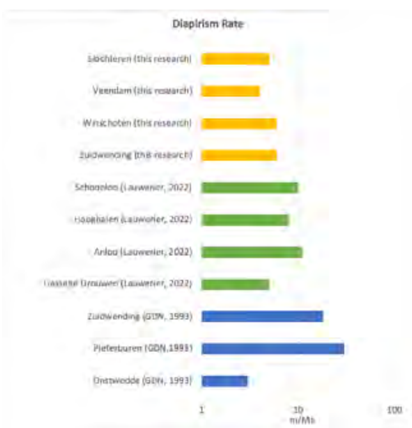

Figure 15: Salt structure growth rates from different studies in the region.

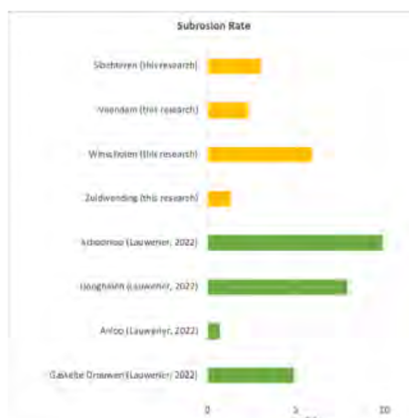

Figure 16: Salt structure subrosion rates from different studies in the region.

6 Conclusion

Salt structures are geologically stable formations that have existed for millions of years. Their geological stability provides a natural barrier to contain radioactive waste. The presence of anhydrite could further improve the quality of the repository. To determine the quality of the salt diapirs, the diapirism and subrosion rates must be calculated. Diapirism rate is important to know if and when the diapir will reach the surface. Subrosion is important because it lowers the quality of the salt barrier. A study of four salt structures has been carried out in the northeastern Netherlands, Slochteren, Veendam, Winschoten, and Zuidwending salt domes, to determine their diapirism and subrosion rates.

As part of the South Permian basin, the study area has a complex geology with different tectonic compression and extension phases. Based on the results of the study, the salt movement was initiated during the Triassic period when the Lower Germanic Trias group was deposited. This phase of the salt movement was caused by faults in the basement activating due to regional extension. During the Jurassic, salt movement decreased during the deposition of the Altena and Niedersachsen Groups. Salt movement increased again during the Cretaceous when the Chalk group deposited. The driving force behind this phase of the salt movement was the compression caused by the Cretaceous inversion. The salt movement continued into the tertiary but at a slower rate during the deposition of the North Sea supergroup.

Based on the salt budget calculation, the fastest salt structure growth was during the deposition of the Chalk group reaching 0.01 mm/yr in the Winschoten salt dome. The movement of the salt started to slow down during the deposition of the Lower North Sea group and to slow down even further during the deposition of the Upper North Sea group. The Zuidwending and Winschoten salt domes experienced the most subrosion during the Lower North Sea group deposition. In contrast, in the Veendam and Slochteren, the highest subrosion rate was during the deposition of the Upper North Sea group, with the highest subrosion rate of 0.11 mm/yr. The salt budget calculations indicate that the four salt structures in this study are safe for radioactive waste storage for the next one million years.

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7 Appendix

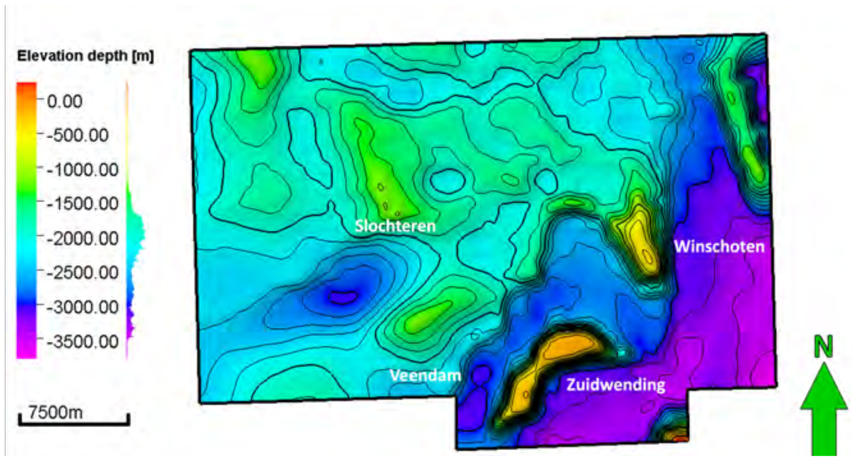

Figure A.1: A surface map showing the top of the Zechstein (ZE). The deeper area in the south east is the Lower Saxony Basin

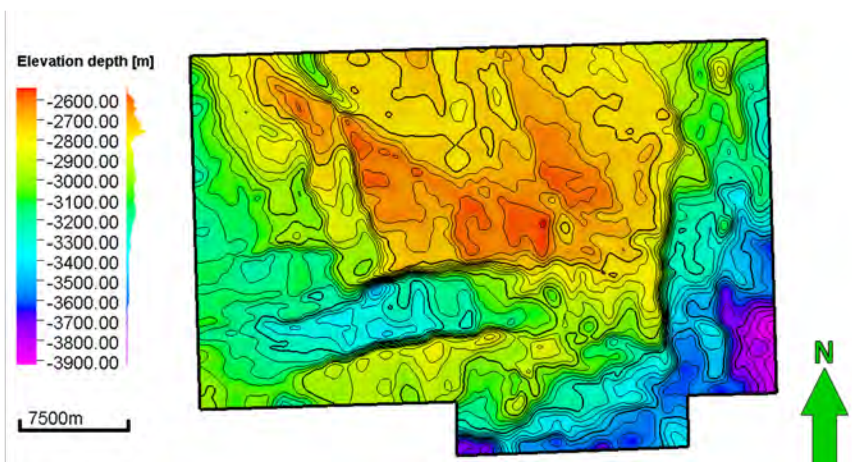

Figure A.2: A surface map showing the faulted base of the Zechstein (ZE).

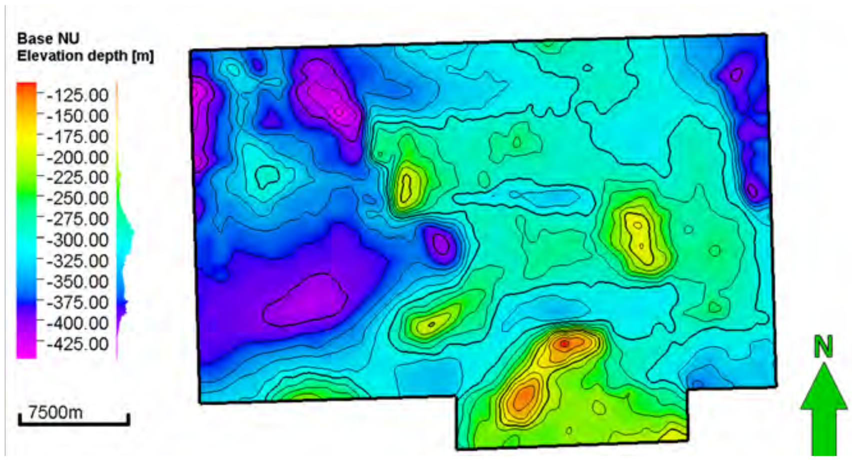

Figure A.3: Base of Upper North Sea (NU) surface map.

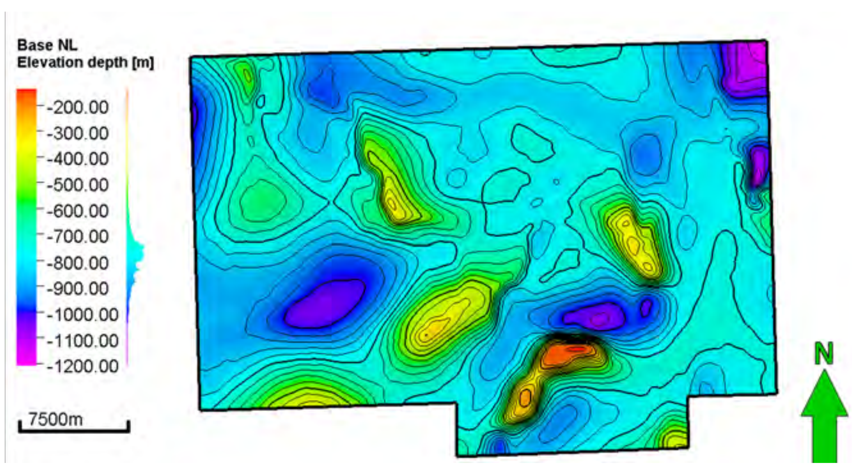

Figure A.4: Base of Lower North Sea (NL) surface map.

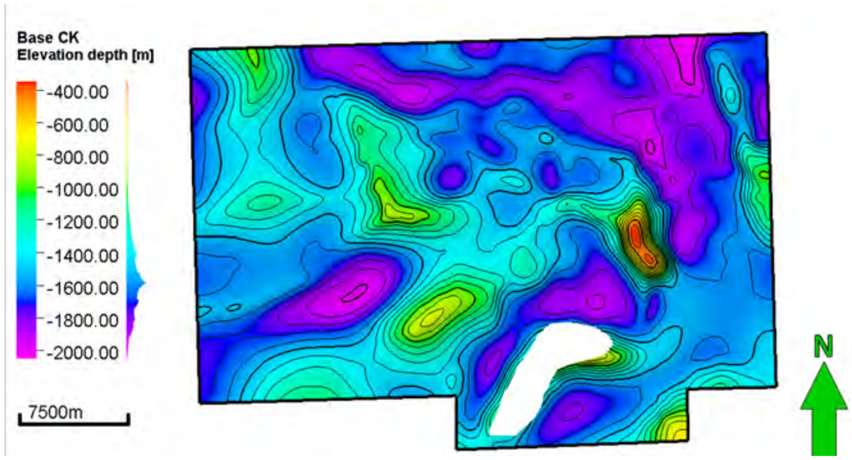

Figure A.5: Base of Chalk (CK) surface map.

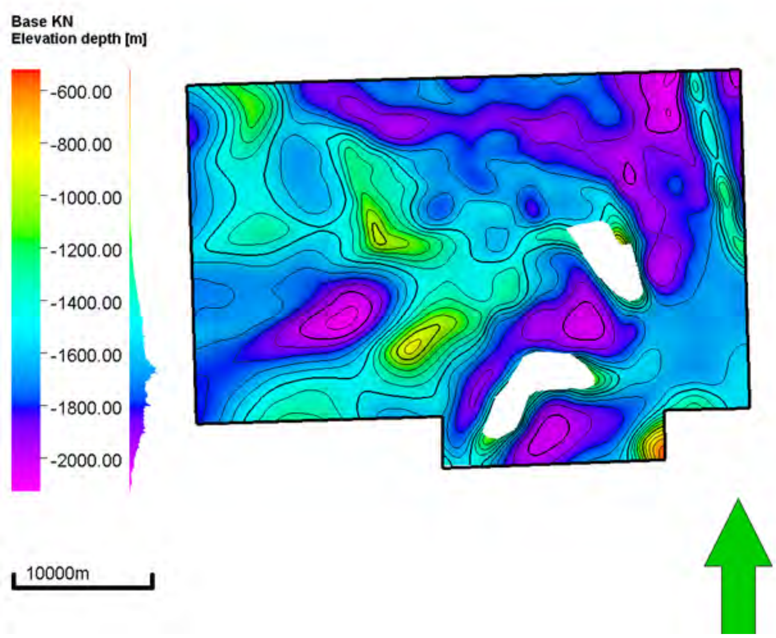

Figure A.6: Base of Rijnland (KN) surface map.

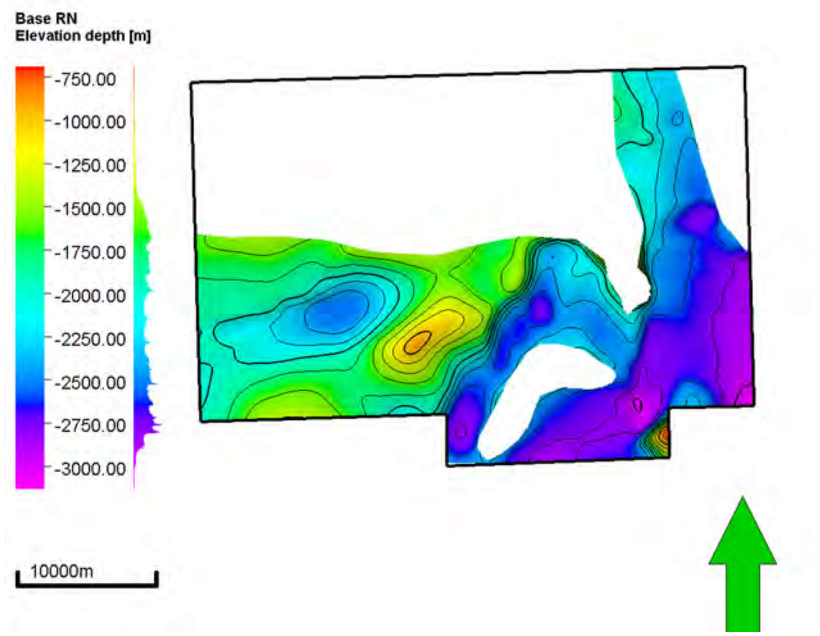

Figure A.7: Base of Upper Germanic Trias (RN) surface map.

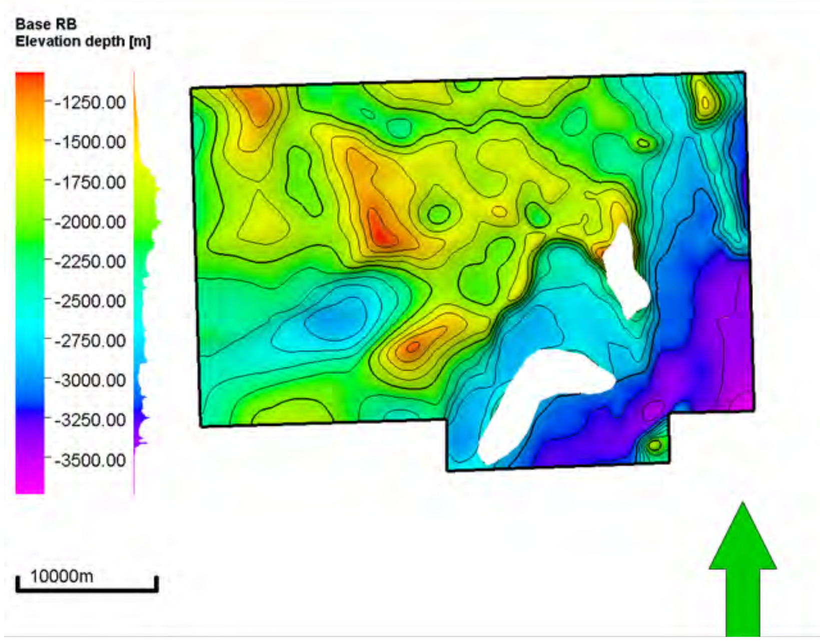

Figure A.8: Base of LowerGermanic Trias (RB) surface map.

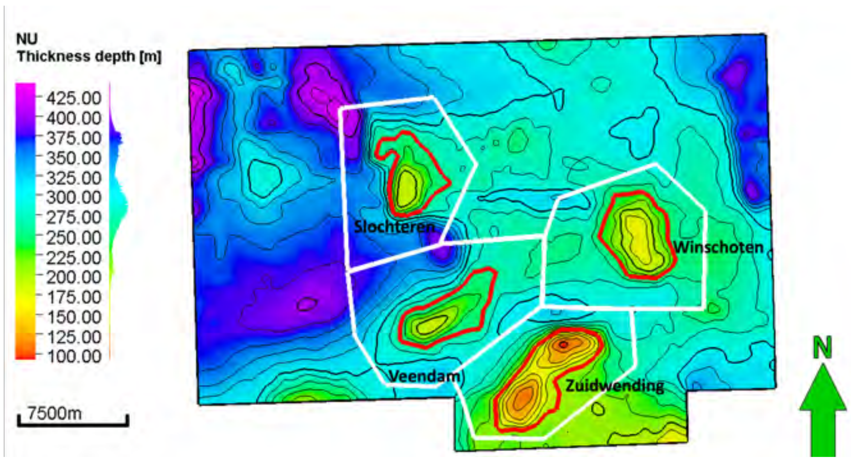

Figure A.9: Upper North Sea group thickness map showing the delineated salt withdrawal basins highlighted in white and the salt structures highlighted in red.

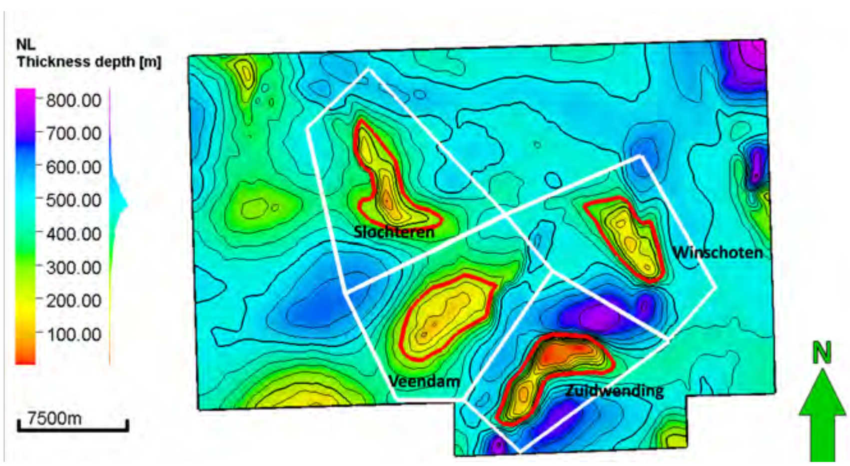

Figure A.10: Lower North Sea group thickness map showing the delineated salt withdrawal basins highlighted in white and the salt structures highlighted in red.

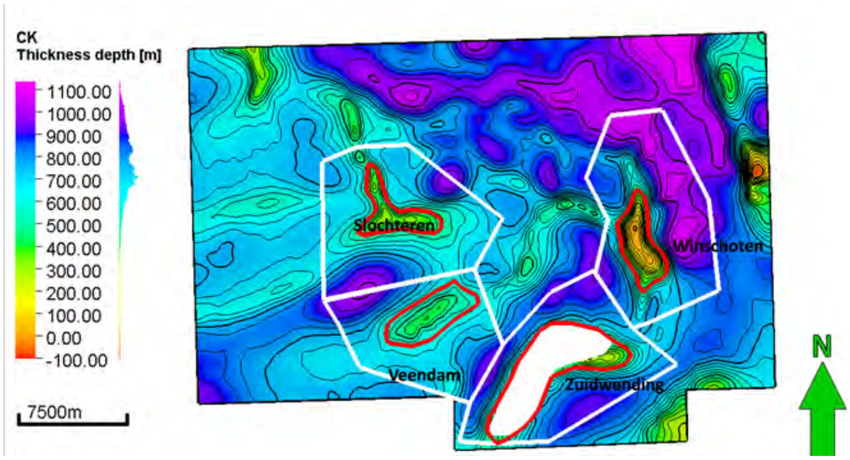

Figure A.11: Chalk group thickness map showing the delineated salt withdrawal basins highlighted in white and the salt structures highlighted in red.

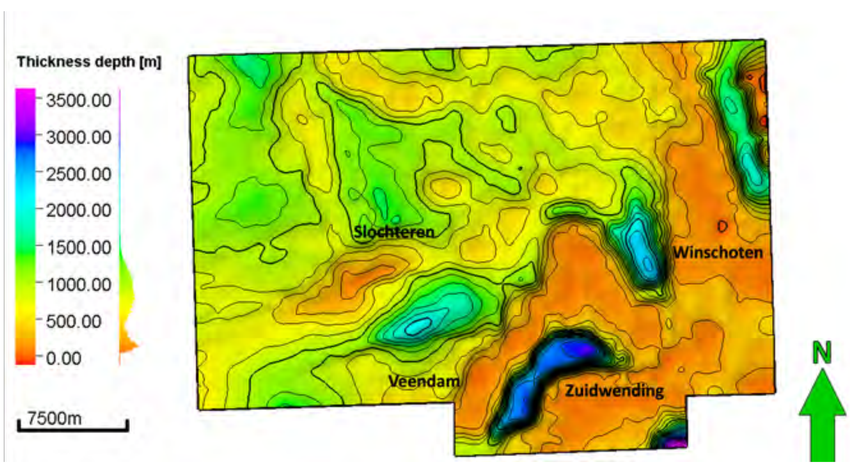

Figure A.12: A thickness map showing the thickness of the Zechstein group.

Salt dome	Formation	Time (Ma)	Withdraw basin area (m^2)	Sediment volume in basin (m^3)	Normal sediment thickness (m)	Normal sediment volume (m^3)	Withdrawn salt volume (m^3)	Salt dome area (m^2)	Column height (m)	Thickness above salt dome (m)	Salt dome during deposition (m)	Erode salt (m)	Diapirism rate (mm/yr)	Erosion rate (mm/yr)	Net Diapirism rate (mm/yr)
	NU	23	6.31E+07	2.06E+10	250	1.58E+10	4.81E+09	1.56E+07	307.82	200	50	257.82	0.013	0.011	0.002
Slochteren	NL	43	8.76E+07	3.86E+10	350	3.07E+10	7.93E+09	1.80E+07	439.30	90	260	179.30	0.010	0.004	0.006
	CK	65	8.04E+07	5.67E+10	700	5.63E+10	4.19E+08	9.99E+06	41.92	300	400	-358.08	0.001	-0.006	0.006
	NU	23	7.80E+07	2.39E+10	250	1.95E+10	4.35E+09	1.76E+07	247.28	180	70	177.28	0.011	0.008	0.003
Veendam	NL	43	7.90E+07	3.32E+10	350	2.77E+10	5.49E+09	2.08E+07	263.64	160	190	73.64	0.006	0.002	0.004
	CK	65	5.39E+07	3.98E+10	700	3.77E+10	2.10E+09	1.41E+07	148.71	400	300	-151.29	0.002	-0.002	0.005
	NU	23	6.78E+07	1.84E+10	250	1.69E+10	1.45E+09	2.09E+07	69.54	190	60	9.54	0.003	0.000	0.003
Winschoten	NL	43	7.47E+07	3.71E+10	350	2.62E+10	1.10E+10	1.55E+07	708.13	130	220	488.13	0.016	0.011	0.005
	CK	65	7.90E+07	6.88E+10	700	5.53E+10	1.35E+10	1.18E+07	1150.77	50	650	500.77	0.018	0.008	0.010
	NU	23	5.16E+07	1.50E+10	250	1.29E+10	2.15E+09	2.46E+07	87.34	175	75	12.34	0.004	0.001	0.003
Zuidwending	NL	43	5.99E+07	3.37E+10	350	2.10E+10	1.27E+10	2.03E+07	625.94	100	250	375.94	0.015	0.009	0.006
	CK	65	5.98E+07	4.73E+10	700	4.19E+10	5.40E+09	3.08E+07	175.26	250	450	-274.74	0.003	-0.004	0.007

Figure A.13: Input data and results of salt budget calculations.