Preliminary Safety Analysis of the Gorleben Site: Geological Database – 13300

Jan Richard Weber*, Sabine Mrugalla**, Christian Dresbach*** and Jörg Hammer****
Federal Institute for Geosciences and Natural Resources (BGR)
30655 Hannover, Stilleweg 2, Germany
*jan.weber@bgr.de, **sabine.mrugalla@bgr.de, ***christian.dresbach@bgr.de,
****joerg.hammer@bgr.de

ABSTRACT

The Gorleben salt dome is 4 km wide and nearly 15 km long. It is composed of different salt rock types of the Zechstein (Upper Permian) series and extends to the Zechstein basis in a depth of more than 3 km. In the course of the salt dome formation the salt was moved several kilometers. During the uplift of the salt the initially plane-bedded strata of the Zechstein series were extensively folded. In this process anhydrite as a competent layer was broken to isolated blocks. In the core of the salt dome the Hauptsalz, which is characterized by a particularly high creeping capacity, forms a homogeneous halite body with a volume of several cubic kilometres. The Hauptsalz contains gaseous and liquid hydrocarbons in separated zones of decimeter to meter dimensions. The overall hydrocarbon content is far below 0.01 %. At the flanks the salt dome consists of salt rocks with lower creeping capacities. Brine reservoirs with fluid volumes in the range of liters to hundreds of cubic meters exist in certain regions of this part of the salt dome. The water content of the Hauptsalz is below 0.02 %. Interconnected pores do not exist in the salt rock outside of fluid bearing or fractured areas, i.e. the salt rock is impermeable. The exploration of the Gorleben site as a potential site for a HLW-repository started in 1979 and is still in progress. To date no scientific findings contest the suitability of the site for a safe HLW-repository.

INTRODUCTION

The Gorleben salt dome lies in North Germany around half way between Hamburg and Berlin. In 1979, the German government reached the decision to investigate the Gorleben salt dome to assess its suitability for the construction of a geologic repository for heat generating high level radioactive waste. Investigations were initially concentrated on exploration carried out from the surface until 1986, when work began on sinking the shafts to enable the site to also be investigated underground. The underground workings of the exploration mine were drifted at a depth of 840 m. The results of the investigation work which has continued up to the present day form the basis for the preliminary safety case Gorleben which has been carried out to date.

THE GORLEBEN SALT DOME

The Gorleben salt dome has a horizontal outline approx. 15 km long and 4 km wide at the 840-m depth of the proposed repository. The base of the salt dome lies at a depth of 3,200 m to 3,500 m, whilst top salt lies at a depth of approx. 250 m. The salt dome consists of Zechstein salt sequences, and more specifically contains Staßfurt Series salt sequences in the core of the salt dome and salt sequences from the Leine Series on the margins of the salt dome. There is a difference in the deformation behaviour of these two series: Staßfurt rock salt creeps at a faster rate than Leine rock salt. The shafts and infrastructure facilities of the exploration mine were constructed in the more resilient Leine rock salt whilst the zones explored as potential emplacement areas were cut in the Staßfurt rock salt because waste stored here would be more quickly enclosed by the rock mass due to the higher creep rates of this salt sequence. The salt layers in the transition zone between the Staßfurt and the Leine rock salt series contain potash salts at the top of the Staßfurt Series and the brittle anhydrite beds of the Hauptanhydrit sequence at the base of the Leine Series. This anhydrite unit is broken up into separate blocks. Figures 1 and 2 show a geological cross-section and a simplified plan view of the Gorleben salt dome at 840 m depth, respectively.

The main constituent of the Staßfurt rock salt series is the Hauptsalz which was sedimented with an original thickness of 700 m and more. The remaining beds of the Staßfurt Series only add up to a few metres in thickness. The Hauptsalz consists of around 95 % halite and 5 % anhydrite. The only other constituents in the upper parts of the Hauptsalz sequence are the minerals carnallite which occurs in isolated clusters of up to 1 cm in size and polyhalite.

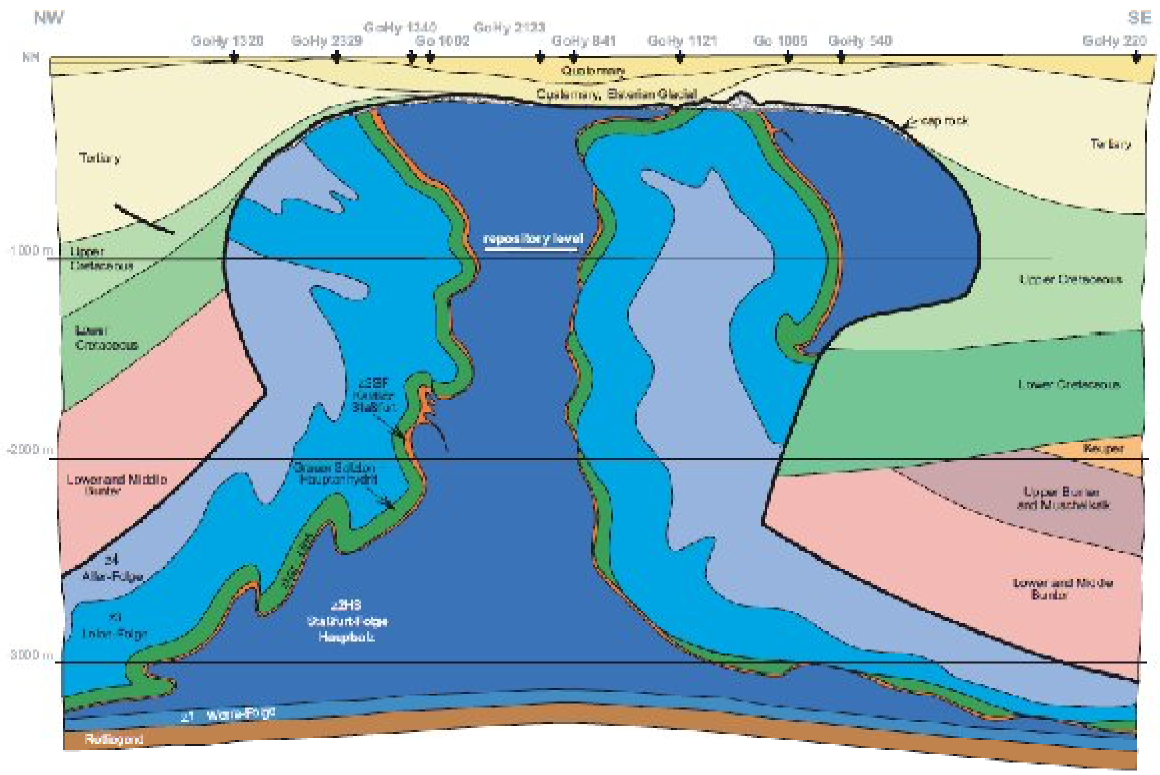

Fig. 1. Simplified NW-SE geological cross-section of the Gorleben salt dome [1].

The top of the salt dome known as salt table is covered by a cap rock with an average thickness of approx. 30 m. The cap rock consists of altered, residual, poorly-soluble constituents left behind after subrosion of the upper part of the salt dome. The cap rock is overlain by a few Cretaceous relicts and by Tertiary and Quaternary sediments. The Quaternary sediments lie directly on top of the cap rock and in places even on the salt in the zone of the Gorleben channel which penetrated approx. 100 m into the salt dome as a result of glacial erosion processes taking place around 400,000 years ago.

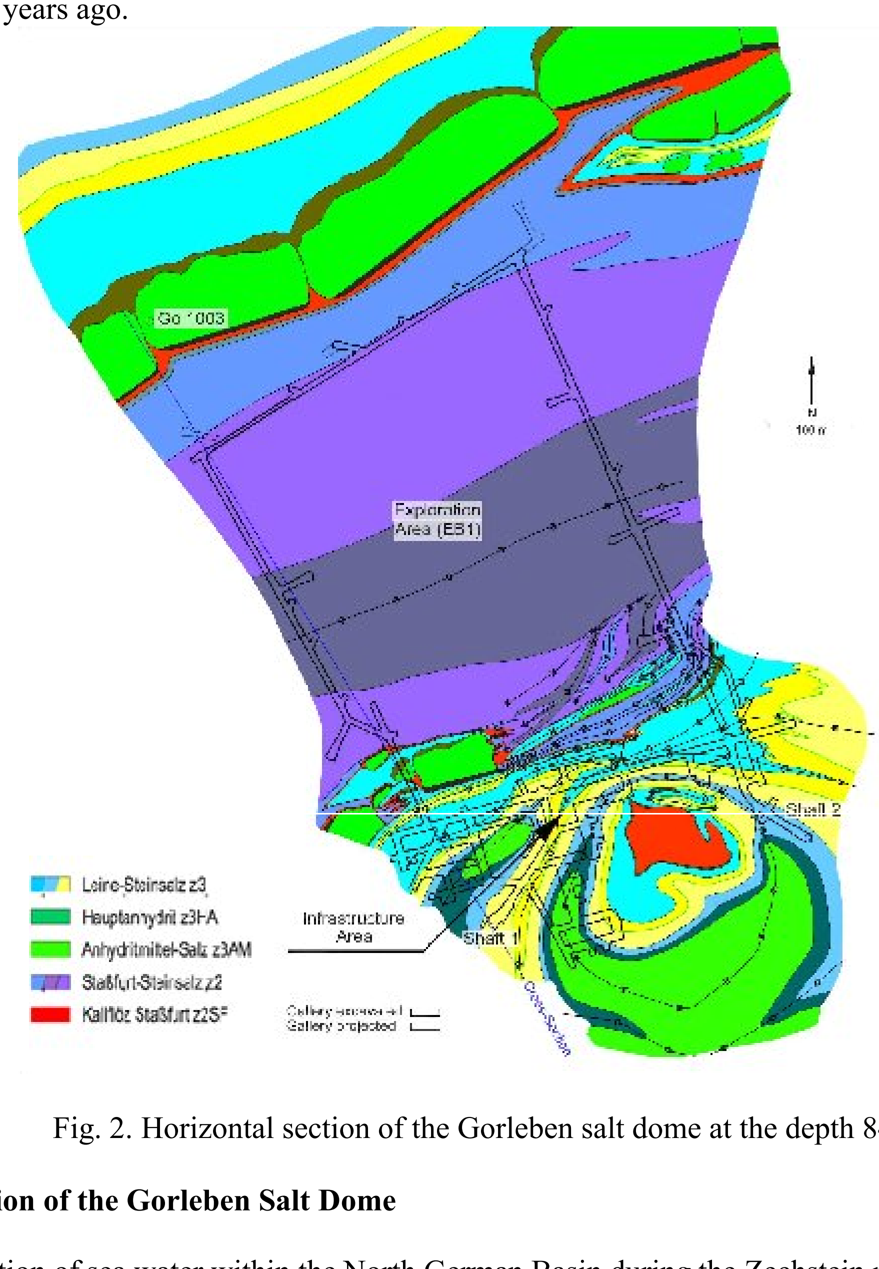

Fig. 2. Horizontal section of the Gorleben salt dome at the depth 840 m.

Formation of the Gorleben Salt Dome

Evaporation of sea water within the North German Basin during the Zechstein period approx. 260 – 250 million years ago led to the deposition of salt. There were several cycles involving the inflow of fresh sea water into the basin, the subsequent isolation of the basin, and evaporation of the sea water to form salt deposits of considerable thickness. The initial thickness of the evaporitic Zechstein beds in the area around the Gorleben salt dome was up to 1,400 m.

In the period that followed, the basin subsided and the salt was overlain by various other sediments. The salt was then pressed upwards to form the salt dome because of the ability of salt to creep, as well as its lower density compared to the overlying sediments.

It is generally assumed that tectonic impulses in the pre-evaporitic sequence could initiate the migration of salt into certain areas, such as into the site of the subsequently formed salt dome, in response to the overburden pressure of the overlying sediments. Because of its elongated shape, an initial tectonic impulse of this kind along a basement fault was also assumed for the Gorleben salt dome. However, seismic surveys carried out specifically to answer this question failed to find any faults beneath the salt dome.

Interpretation of the stratigraphy and structure of the overlying rocks and the surrounding rocks revealed that the changes in salt thickness preceding the formation of the salt dome (development of a salt pillow) already began in the Upper Bunter Sandstone and Muschelkalk periods – in other words, approx. 250 million years ago – and continued into the Dogger up to approx. 170 – 160 million years ago [2]. Approx. 140 million years ago during the Malm, or in the following Lower Cretaceous period, the salt pillow stage ended and the diapir stage began – in other words, the penetrative break-through of the salt through the overlying beds began. The salt dome continued to develop further during the Cretaceous (approx. 140 – 65 million years), leading to the development of salt overhangs during the Upper Cretaceous and the Tertiary. During these developments, when the salt structure reached up as far as the ground surface at times, around half of the original salt volume was subroded, i.e. dissolved. During the diapiric uplift of the salt dome, the salt travelled distances of up to 5 km laterally and 3 km vertically at flow rates of up to 0.14 mm/year. The average diapiric speed of the top of the salt dome was calculated as maximum 0.086 mm/year from the speed of the salt in the catchment area of the salt dome and the largest cross-sectional area of the salt dome in this time. This maximum upward movement took place during the Upper Cretaceous. The upward movement during the last approx. 20 million years took place at an average speed of 0.018 mm/year. Subrosion during the alternating glacial and interglacial periods in the past took place at rates between 0 and 0.4 mm/year or at an average rate over the last 100,000 years of less than 0.1 mm/year [3].

Hydraulic Properties of the Rock Salt

The original sedimentary structure changed considerably during the intensive movement of the salt rocks as diapirism proceeded. This is especially true for the particularly mobile Hauptsalz of the Staßfurt Series which forms the inner core of the salt dome. During the diapiric movement of the salt, the effective stresses repeatedly fractured the rock salt and then healed it again. This caused the Hauptsalz to become homogenised into a mixture in which blocks of primary rock salt crystals, and shredded and scrunched up fragments of anhydrite lines, float in a matrix of recrystallized rock salt.

Original brine trapped in the salt was either squeezed up to the salt table due to diapiric uprise of the salt or squeezed into specific zones, e.g. into the boundary between the Staßfurt Series and

Leine Series, or in the fissured Hauptanhydrit blocks. Dissolution films on grain boundaries were altered by the recrystallization processes to form isolated fluid inclusions. This means that *the rock salt in the Gorleben salt dome outside of fluid accumulations contains no interlinked pore spaces*. Rock salt which has not been affected by mining and is not in the areas where there are accumulations of fluids is therefore impervious to diffusion processes as well as impervious to hydraulic flow processes.

Micro fractures will form around the drifts as a result of the physical excavation process. Drifting therefore gives rise to excavation damaged zones (EDZs) where the barrier effect of the rock salt is diminished. The extent of the mining induced EDZ is typically a function of the depth, the shape of the opening and the time it is unsupported. The growing rate of the EDZ declines in the course of time. Given the depth of the exploration mine of 840 m and the width of the drifts of less than 10 m, the extension of the EDZ around an individual will not exceed a few decimetres. Borehole tests in individual drifts at the exploration level within the Gorleben salt dome only encountered raised permeabilities in the proximal zone around the drifts extending distances of < 30 cm into the rock salt from the walls of the drifts.

Mechanical Properties of Rock Salt

The static moduli of elasticity measured in the rock salt from the Gorleben salt dome are 33 to 36 GPa. The static Poisson's ratios in all of the different types of rock salt lay between 0.25 and 0.32. Brazilian tests carried out to determine the tensile strength of the different rock salt types produced values between 1.5 and 2 MPa. At deformation rates of 1E-5/s, the uniaxial compressive strengths measured for the various rock salt types lay between approx. 20 and 35 MPa. The measured triaxial strength limits are shown in Fig. 3.

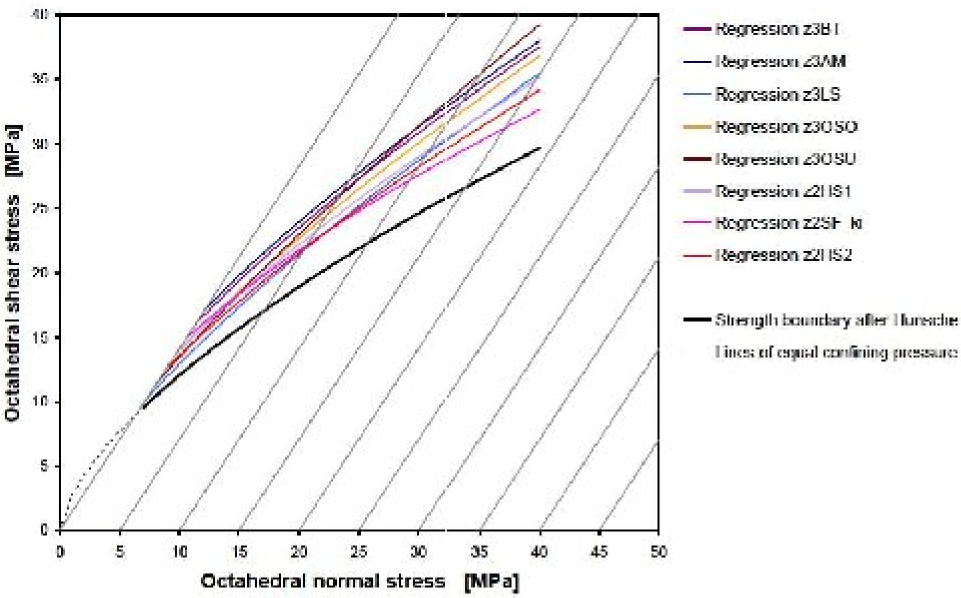

Fig. 3. Failure strengths in Gorleben salt samples.

The measured strengths were lower at higher temperatures. The strengths at around 180 °C were around half of the strengths at room temperature.

Although the deformation of the rock salt associated with stresses exceeding the strength limits can damage the salt, rock salt can creep when the stress conditions remain below certain stress limits. This means that salt can dissipate the mechanical stresses by constant-volume deformation. The salt remains completely undamaged during this constant-volume deformation. There are various creep laws which describe the dependence of creep deformation over time on the stress state. One of these formulations is shown in Equation 1 (= BGRa creep law).

$$\dot{} = \cdot \cdot \exp \frac{}{\cdot} \cdot \frac{}{*} \qquad \text{(Eq.1)}$$

A = 0.18 d^{-1}
Q = 54 kJ/mol
R = 8.314 · 10^{-3} kJ/(mol·K)
n = 5
σ^{*} = 1 MPa (standardisation)
T = temperature in K

The pre-factor V in this equation is a measure of the ability of the rock to creep. Average values of this pre-factor were measured as between 1/32 and 2 for various rock salt types in the Leine Series. The average values for pre-factor V in the Hauptsalz of the Staßfurt Series lay between 1/2 and 2.

Thermal Properties of the Rock Salt

The formation temperature at the depth of the exploration level is approx. 311 K. It is around 5 K above the temperature expected at a depth of 840 m below ground level when using the average continental geothermal gradient.

This is due to the heat flow density which at approx. 115 mW/m² is about twice as high inside the salt dome as in the surrounding rocks. This is caused by the high thermal conductivity of the salt, measured on samples from the Gorleben salt dome at around 5.5 mW/(m K) at 293 K and around 3.5 mW/(m K) at 473 K.

The linear thermal expansion coefficient of rock salt from the Gorleben salt dome varies between 3.5 and 3.9 E-5/K at temperatures between 293 K and 373 K.

The specific thermal capacity was determined to be between 0.85 and 0.90 kJ/(kg K) at temperatures between 293 K and 523 K.

Brine Reservoirs

Brines occur as natural constituents in salt structures. However, they are not randomly distributed but occur in specific stratigraphic horizons. When salt sediments accumulate, large volumes of water are initially present between the still uncompacted grains of salt. As the overburden pressure increases, the water is largely squeezed out and the degree of interconnectedness of pores becomes lower and lower by recrystallization of grain contacts. This reduces the possibilities for the water to be squeezed out into the overlying beds, and fluids therefore collect preferentially in those areas where the load is dissipated to a lesser degree via the fluids – in other words, in more competent rocks. The mobilisation of the formerly more homogenously distributed fluids and their concentration within localised reservoirs is proportional to the amount of rock deformation which takes place: the more intensive the rock deformation, the more thorough the mobilisation and concentration.

In the Gorleben salt dome, the preferential locations for brines are in the Anhydritmittel (anhydrite horizons) of the Anhydritmittelsalz, the Gorleben-Bank, the Hauptanhydrit and its accompanying layers, and the transition zone between the Staßfurt Series and Leine Series.
No accumulations of solutions were encountered in the intensely folded Hauptsalz of the Staßfurt Series.

When solution accumulations were encountered in the Gorleben salt dome, a pressure measurement was first made to verify the isolated nature of the reservoir. Because an isolated solution reservoir is affected by formation pressure which is higher than the hydrostatic pressure of a water column at the same depth, the presence of a pressure which is higher than the hydrostatic pressure confirms that the reservoir is isolated.

The volume of the fluid is then estimated by carrying out a material balance. Because the solutions are accompanied by gas, but the liquid-gas ratio is unknown, considerable uncertainties arose concerning the total compressibility of the fluid in the reservoir. This in turn gives rise to a wide range in the calculated minimum and maximum reservoir volumes. The maximum volume of solution which flowed out of a reservoir was almost 200 m^3, the maximum calculated fluid content of a reservoir was some thousand m^3.

The brines encountered were highly concentrated magnesium-chloride-solutions. These are relicts of the Zechstein Sea, whose bromine, lithium and rubidium content, as well as other constituents, are attributable to metamorphosis within the salt dome, and did not involve any solutions originating outside of the salt dome [4].

In addition to macroscopic solution reservoirs, water can also be present in salt at grain boundaries or in fluid inclusions. Water contents between 0.012 and 0.017 weight per cent were measured in the Hauptsalz of the Gorleben salt dome.

Hydrocarbon Occurrences

In addition to the natural occurrence of solutions, a salt dome can also naturally contain hydrocarbons. Some of the solution reservoirs within the Gorleben salt dome also contained hydrocarbons. And hydrocarbons were encountered in the Hauptsalz without significant accompanying aqueous solutions.

Hydrocarbons occur in the Hauptsalz of the Gorleben salt dome in the form of visible staining of the rock salt in clearly localised zones measuring some decimetres to metres. The hydrocarbon concentrations in the samples of Hauptsalz from the Gorleben salt dome varied between 0.02 and 443 ppm (parts per million) with respect to weight (mg hydrocarbons/kg rock salt), with a median value of 0.3 – 0.4 ppm.

Analysis carried out early on in the investigation of the salt dome determined the molecular composition of the hydrocarbons encountered in the Hauptsalz of the Gorleben salt dome. The interpretation of this composition, and the variations of the carbon isotopes within the hydrocarbons, indicated that the hydrocarbons did not originate in the Hauptsalz but rather in the Staßfurt Carbonate, in other words, in rocks of the Staßfurt Series deposited before the formation of the Hauptsalz. The interpretation assumes that during the intensive movement of the Hauptsalz during the diapiric growth of the salt dome, the hydrocarbons migrated upwards into the temporary fractures which developed in the Hauptsalz and then became trapped and moved to their current positions along with the transported salt. The measured isotope ratios in gaseous hydrocarbons found in the Hauptanhydrit of the Leine Series indicate a partial origin from the Rotliegendes beds underlying the Zechstein sequence. Further investigations are currently being carried out to determine the origin of the hydrocarbons in more detail.

Tectonics

In common with the rest of northern central Europe, the absence of plate tectonic activity means that the Gorleben site is only affected by minor regional stresses. No graben formation or orogenic activity has taken place in North Germany in the last 10 million years. The Alpide orogeny affected North Germany only indirectly. And there is also nothing to indicate that this calm tectonic situation will change at any time in the near future.

Earthquakes are a rare occurrence in North Germany. The tectonic situation can be estimated on the basis of the historic earthquake catalogue which compiles all of the earthquakes documented since 800 BC. The historic earthquake catalogue reveals that the region in which the Gorleben site is located has only been affected by three documented earthquakes over the last 1,000 years. Their MSK intensities (Medvedev-Sponheuer-Karnik scale) lay between 5.5 and 6.5.

Only six tectonic earthquakes with magnitudes > 2.5 have been recorded by instruments in the whole of north Germany since 1995. The upgrading of the seismograph network which took place in 2007 means that all earthquakes with a magnitude of between 2.0 and 2.5 can now also be recorded. Three earthquakes have been registered since 2007. The strongest earthquake occurring since 1995 had a magnitude of 3.4. The earthquake locations are spread throughout North Germany and are not concentrated in a specific zone. The focus depths lay beneath base Zechstein.

An analysis of the faults in the pre-evaporite basement revealed that the faults formed in the Permian approx. 300 – 250 million years ago, and are largely independent of the previously formed Variscan fault pattern. The faults in the pre-evaporite basement have no matching faults above the Zechstein evaporite sequence.

In conclusion, there is no evidence for any major movement along active fault zones near the Gorleben salt dome throughout the geological section.

INVESTIGATION METHODS

Detailed information is available on the stratigraphy of each of the Zechstein beds at the Gorleben site. For instance, analysis has revealed that in the Liniensalz – an approx. 30 m thick rock salt layer in the Leine Series – there are 230 anhydrite layers of which the following pairs of lines: 82 and 83, 139 and 140, 177 and 178, and 199 and 200, lie particularly closely together and can therefore be quickly identified. Moreover, line 110 is a special marker horizon because its characteristic structure enables it to be easily identified. Regular special characteristics have also been determined in other layers. This means that when considered together with other characteristic features such as mineralogical composition or bromide concentration, it is possible to reliably identify the stratigraphic positions of drilled or drifted salt sequences.

During the investigation of the Gorleben salt dome, the Ground Penetrating Radar (GPR) technology was further developed and adapted to the needs of underground exploration by way of special antenna designs. This method has an extremely high spatial resolution capacity. At the measuring frequency of 50 MHz, and the resolutions achieved for the travel times of only a few nanoseconds, GPR enables the distances to reflecting structures to be determined to an accuracy of only a few cm. However, the directions from which the reflections come can only be measured relatively inaccurately – which means that single measurements are associated with considerable variability in the interpreted position of the reflecting source. However, if a structural element can be recorded by GPR from a range of directions, it is possible to reduce the directional uncertainties and even to eliminate these uncertainties completely. The GPR technique has a range of coverage of several hundred metres. This enables the GPR surveys conducted in the investigation drifts to detect the top of the salt lying 600 m above.

Correlating the underground GPR surveying results and the findings from other geophysical logging techniques, such as underground seismic surveys, and combining this information with geological information from drifts and exploration boreholes, gave rise to a very detailed geological model of the salt deposit built up over the course of the underground investigation activities. For example, Figure 4 shows a part of the Gorleben 3D geological model and reveals the Hauptanhydrit blocks floating within the ductile halite and potash salt matrix.

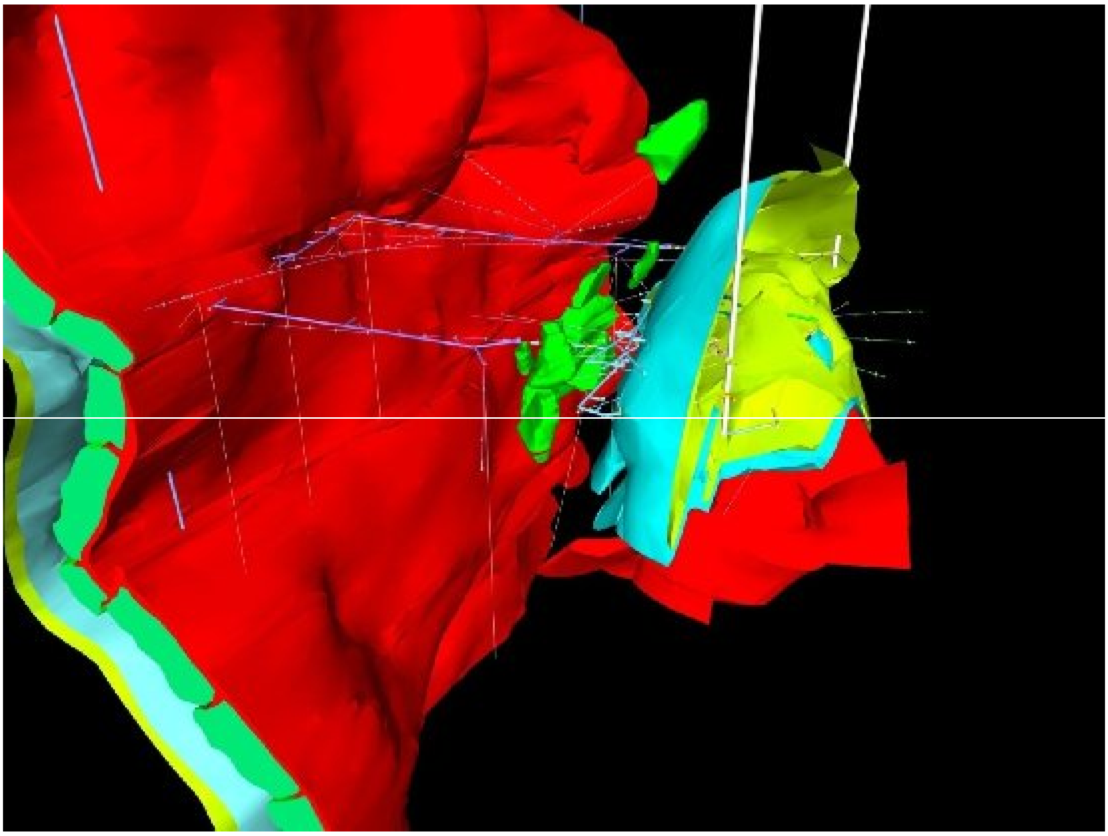

Fig. 4. Detail of the geological 3D model including the shafts and galleries of the exploration mine, carnallite (red), Gorleben-Bank (blue) and Hauptanhydrit blocks (green).

CONCLUSIONS

The investigation of the Gorleben salt dome has revealed no findings which contradict the suitability of the location for the construction of a geologic repository for safe disposal of high level waste.

However, the underground volume which has been investigated so far is not large enough to accommodate all of the waste. This means that the final confirmation of its suitability not only requires the presentation of a safety case but also further underground investigation to determine whether the salt dome is large enough for the emplacement of waste in the Hauptsalz.

The investigation methods are highly developed and fit for this purpose. The properties of the Zechstein stratigraphic sequences have been determined with a great deal of accuracy. Geophysical measurements and geological analysis of samples from drifting or drilling can therefore very precisely determine the position of the sampled salt relative to layer boundaries within the salt body. This enables reliable compliance with the safety pillars between underground workings and certain zones – for instance the potentially brine-bearing Hauptanhydrit blocks – without even having to drill into the zones which should be avoided to maintain the integrity of the salt dome. Detailed exploration of the Gorleben salt dome is therefore possible without damaging the integrity of the geological barriers by drifting or drilling.

The findings revealed by the explorations carried out so far are compiled in four volumes. These volumes can be downloaded from the BGR website (http://www.bgr.bund.de/EN/Themen/Endlagerung/geotechnik_node_en.html). Findings are documented in detail in the BGR archive which contains approx. 800 reports on the exploration of the Gorleben salt dome.

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