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Rock salt, claystone and crystalline rocks as possible host rocks for high-level radioactive waste disposal (Copyright @ BGR).

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International Conference on Geological Barrier Systems, Host Rock Characterization, and Site Selection relevant to Underground Repositories

Abstracts of the **I**nternational **C**onference on **G**eological Barrier Systems,
Host Rock Characterization, and Site Selection relevant to Underground Repositories (ICG 2020),
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Preface and acknowledgements

The "International Conference on Geological Barrier Systems, Host Rock Characterization, and Site Selection relevant to Underground Repositories" covers a wide range of topics directly related to the challenge of locating, constructing, and demonstrating the safety of a repository for heat generating radioactive waste.

The main topics of the two-day conference, taking place at the BGR are thematically divided into the following four sessions:

- geological-mineralogical investigations of the considered rock types,
- site selection criteria and procedure, and the practical realization,
- comparison of different geological repository options,
- and geological and geotechnical barriers.

A particular focus, and to our special pleasure, is the implementation of investigations and considerations, which are performed in different countries. Indeed, the search for a nuclear waste repository is primary a country-specific challenge (e.g. new Site Selection Act – "StandAG" started in 2017 in Germany). However an external perspective is always helpful, either to review – and maybe correct – own opinions, or to confirm the own way and point of view. Therefore, many experts will illustrate their regional research and perspective, with different social, political, cultural and scientific background. Most of them are partners and friends of the BGR for plenty of years, and we are very thankful for the long-lasting collaboration.

We are pleased to record a broad international interest in this conference – it has attracted more than 150 participants from 10 countries from research, economy and international and national institutions in equal propotions. New results from research, site exploration and rock engineering projects have been accumulated in the last years and we are looking forward to an exciting and informative conference with lively discussions.

We are honored to host this symposium together with the German Ministry for Economic Affairs and Energy (BMWi), and the Projekt Management Agency Karlsruhe, Institute for Technology (KIT).

We cordially thank all the authors for their contributions to the conference and their outstanding efforts within the alloted time.

We would like to thank the session chairs for agreeing to participate in the panel discussion.

Special thanks go to the organizing committee and all other colleagues at the BGR for their support in planning and realizing the conference.

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Table of contents

Geological Repository Options

Geological and Geotechnical Barriers

Host Rock Characterization for Geological Repositories

Clayey salts vs. rock salt – geological advantages and disadvantages with respect to repository location

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Upper portions of diapiric salt structures in Poland are composed dominantly of rock salt and clayey salts, which belong to Upper Permian Zechstein evaporite succession, consisting of 4 cycles (Z1–Z4). Rock salt was deposited in all 4 cycles whereas the clayey salts terminated sedimentation in the Z3 and Z4 cycles only. Both rock types are considered as possible targets for waste repository location. This paper presents a review of their petrography and deformational features, both natural and induced by mining, and is mainly focused on comparison of their long-term behaviour. The study is based on analyses of sedimentary and tectonic structures documented in the Kłodawa Salt Structure (KSS) in central Poland and the data were collected in underground salt mine drifts at the depth range between 450 m and 780 m below the ground surface. The meso-scale structure analysis was supplemented with investigation of microstructures in the rocks.

The thickest rock salt domains in the KSS are built of welded Z1 an Z2 rock salts and they contain scattered relics of anhydrite-shale-dolostone-anhydrite beds that originally separated the two depositional units. These domains form a second order diapirs inside the KSS amongst which rocks of Z3 and Z4 evaporite succession are entrapped in synclinorial structures. Since the Z1 and Z2 rock salts were jointly deformed during the KSS evolution, the two rock salts display similar tectonic structures, petrography and microstructures: they are complexly folded and variably sheared, microstructure of halite implies that it has dynamically recrystallized and is typically free of fluid, gas and solid inclusions. There is some admixture of anhydrite in the rock salt, mostly concentrated in anhydrite-rich salt bands. At a micro-scale, anhydrite grains assemble along halite grains. The only relatively porous zones in rock salt correlate with Z1-Z2 rock salt welds, where hydrocarbons and H_2S are also locally entrapped. Thus, the Z1-Z2 complexes are relatively petrographically uniform and do not contain open hydraulic zones that would favour large-distance migration of fluids or gases.

The term clayey salts is referred to lithologically non-uniform rock domains, which are composed of beds varying in petrography and textures. Apart from halite, individual beds may contain between 10% and 90% of clay minerals and minor admixture of other mineral constituents. Main lithological varieties include (1) structureless clayey salts, composed of mixture of halite and clays, and (2) layered clayey salts, built of intercalating halite- and clay-rich layers. These two main types commonly interlayer with thicker beds of rock salt and shales, and, therefore, the clayey salt domains also vary in tectonic deformation. Rock salt rich interlayers are built of dynamically recrystallized halite, whereas clay-rich and shale units underwent brittle deformation and contain several generations of halite and potash veins, fractures and are commonly boudinaged. Also sedimentary structures are preserved in them, including relics of fluid trails in halite. The beds are folded at a large scale and occur in synclinoria. Although the lithological and textural variation is dominantly inherited after the sedimentation stage, the internal structure was also locally strongly modified by shearing during the KSS evolution. Shearing promoted fracture and vein development and led to tectonic disintegration of the more competent clay-rich layers. In places where this process was progressive, clayey salts lost distinct layering and resemble structurless lithological type.

Over 60 years of salt mining also enables the assessment of longer-term behaviour of mining drifts and chambers. Those built in Z1-Z2 complexes show relatively uniform and slow convergence which is evidenced also by direct geodetic measurements carried out over past ~40 years (Marcola-Sadowska et al., 2009). Stability and convergence of drifts built in clayey salts depends on the location in the KSS and lithological type. Structurless and halite-rich domains host stable drifts, unlike the clay-rich domains located in central portion of the KSS, where repetitive reconstruction of the drifts has been required in the past and casing has been applied.

Comparison of the natural features of the rock salt and clayey salts in the KSS shows advantages and disadvantages of both rock types as possible disposal sites. The rock salt domains are relatively uniform in structure and petrographic composition, devoid of open hydraulic zones and low convergence can be expected in the chambers, which altogether shall provide high control on the stability and isolation of a disposal. The main threat to be investigated before the site location is the location and trend of weld zones which are the most porous in the domain and contain relics of anhydrite, dolostone and shale beds. The biggest advantage of the clayey salts is the presence of low strain domains which has not significantly changed over past ~250 Myr. As shown by laboratory tests carried out by Ślizowski et al. (2005), these rocks vary in strength and other physico-chemical properties throughout the KSS which indicates that a detailed laboratory investigations shall be implemented before the decision on a disposal site is made. The biggest disadvantage of the clayey salts is the presence of fractures and veins, documenting that these rock domains have been repetitively hydraulically open in the past, enabling circulation of potash- and halite-saturated fluids. Hence, a detailed structural analysis of vein systems is a must before any decision on further investigations and site location is made. Comparing the effects of natural leaching of clayey salts and rock salt domains at the cap rock level, the residue left after the clayey salts is clay dominated, which provides much better and stable hydraulic isolation against groundwater inflow than the sulphate residue dominating above the rock salt domains.

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Petrographical and mineralogical characteristics of Permian impure rock salt successions from Northern Germany

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The deposition of marine evaporites in the late Permian of the North German Basin (NGB) is contrasted by the deposition of red sediments with a high evaporite content that mark high continental influence on deposition under subaerial conditions or low water depths. These units are now preserved in both diapiric and stratiformal rock salt successions of the NGB.

As an example, drill cores of Rotliegend rock salt and Zechstein series comprising high amounts of siliciclastic rock content, such as the Roter Salzton (z4RT) unit, have been analyzed for their mineralogical, geochemical and petrographical inventory in order to get an overview of the natural variability that is preserved in evaporitic units containing large amounts of argillaceous material.

The samples were studied using a multi-method approach combining microscopic studies with ICP-OES-, XRD-measurements and stable isotope geochemistry.

The macroscopic and microscopic study shows the preservation of sedimentological features in the sediments throughout all the studied sequences. These include desiccation cracks and anhydrite nodules. The detrital fraction of the sediments consists of phyllosilicates, quartz, feldspar and carbonates. While the Rotliegend strata show mineral phases like plagioclase and low phyllosilicate contents as well as dolomite as the main carbonate mineral, the Roter Salzton unit preserves higher amounts of phyllosilicates with lower concentrations of other phases, like K-feldspar and quartz. Carbonate contents are low and comprise exclusively magnesite. Depositional changes in the Roter Salzton unit are tied to the basin position and include thickness variations, changes in dominant evaporite phases as well as slight changes in phyllosilicate mineralogy.

All studied units show sedimentary features of preserved salt flat sedimentation. The Rotliegend rock salt is an example for evaporitic red bed sediments formed in a continental setting, visible in low bromide contents of halite from 3 to 60 µg/g. However, changing $\delta^{34}S$ signatures ranging from 5,8 ‰ to 10,6 ‰ indicate a possible temporary marine influence on the formation of sulfates.

The marine influence on the deposition of the Roter Salzton unit is visible from high contents of bromide from 150 up to 350 $\mu g/g_{Halite}$ and $\delta^{34}S$ signatures of sulfates in the lower range of values from Permian marine evaporites between 8.2 ‰ and 9.4 ‰.

Nevertheless, the fabric in both rock types has been influenced by continentally derived, silica-rich brines represented by authigenic quartz phases and metal concretions present at phase boundaries and in evaporitic phases of the sediment, along with the formation of secondary evaporites in all studied samples. Possible brine sources could be derived externally by contribution from continental groundwater or locally by dissolution processes inside the siliciclastic phase domains of the sediment as indicated by the microstructures.

The differences in occurrence of authigenic minerals and initial sediment structure shows that indicators for processes contributing to rock formation and sedimentation are still preserved in this rock type. The systematic study of differences in the composition of mixed siliciclastic and evaporitic rocks gives an opportunity to discriminate processes that are linked to initial sediment formation from those that could act during possible later tectonic overprint due to diapir formation.

Rheology and permeability of salt rocks: Constraints from thermomechanical experiments

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Evaporitic deposits are heterogenous in composition and rheological behavior. Their viscosity decreases in the following order: dolomite > marl > saliferous clay > anhydrite > kieseritic rocks > halite > sylvite > carnallite > bischofite (Borchert and Muir, 1964, p. 248). The salt rocks of evaporitic deposits include 'rock salt', a term that is commonly used for all rocks composed of mostly halite (Hudec and Jackson, 2007). If competent anhydrite rock layers are enclosed in rock salt, they may be folded or boudinaged (Figs. 1a-d; e.g. Bornemann et al., 2008; Mertineit et al., 2014). On the other hand, single sheets rich in carnallite are incompetent in rock salt matrix and thus may show mullions or inverse folds (Fig. 1b).

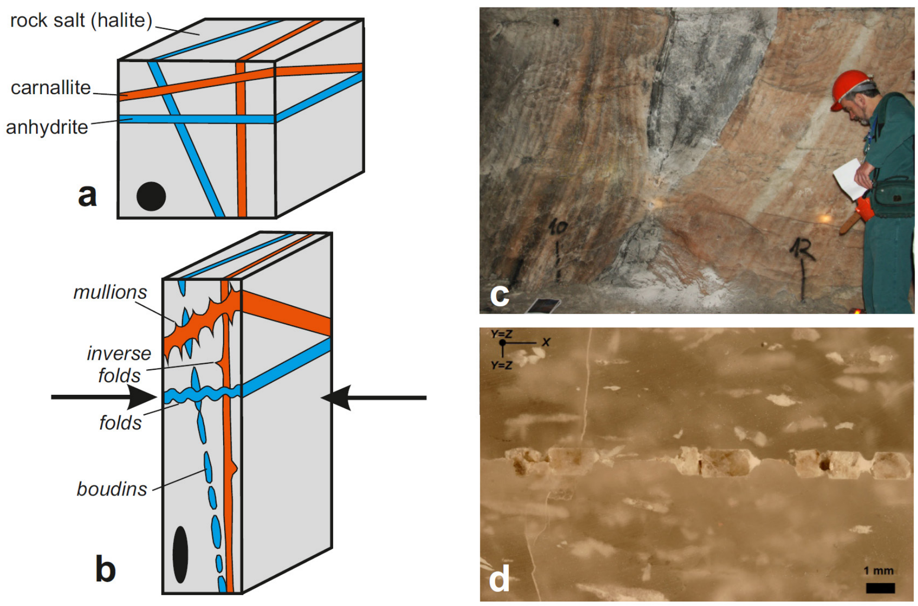

Figure 1: Inhomogeneous deformation of salt rocks. Left-hand side: Schematic drawings showing variously oriented undeformed (a) and deformed (b) sheets in matrix of rock salt. Competent anhydrite sheet is folded or boudinaged, whereas incompetent carnallite sheet shows mullions or inverse folds. Right-hand side: Boudinage of anhydrite sheet in rock-salt matrix from Morsleben mine (c), and from thermomechanical experiments (d) (Zulauf et al., 2009, 2010).

At upper structural levels (T < 200°C) rock salt is deformed by viscous creep and features gradual self-sealing of open pores and fissures (e.g. Schulze, 2007). Most grains in diapiric halite are ca. 1 cm in size and show evidence for dislocation creep in form of subgrains and lobate grain boundaries, the latter resulting from strain-induced grain boundary migration enhanced by grain-boundary fluids (Urai et al., 1986; Thiemeyer et al., 2015). The size of subgrains reflect very low flow stress (< 5 MPa) even at high strain rates (e.g. Urai and Spiers, 2007; Kneuker et al., 2014; Thiemeyer et al., 2016).

The finite strain of diapiric halite is difficult to constrain because of the lack of strain markers. Thermomechanical experiments, carried out under similar low flow stresses (< 5 MPa), suggest that rock salt can be deformed to high finite strain by subgrain formation, although subgrain rotation is rare and restricted to discrete deformation bands (Linckens et al., 2016, 2019). The low flow stress, the presence of fluid inclusions and the high solubility of rock salt suggest that solution-precipitation creep should be a further efficient deformation mechanism (Urai and Spiers, 2007). However, in diapiric rock salt of deep mines, evidence for solution-precipitation creep is largely absent (e.g. Hammer et al., 2015; Thiemeyer et al., 2015). The low porosity (<<0.5%), low permeability (<<10^{-20} m²) and low water content (<0.1 vol%) (Popp et al., 2007), together with the lack of fractures, stylolites and strain caps, prove that diapiric rock salt forms an impermeable closed system, which can be used as host rock for disposal of heat-generating high-level radioactive waste (HLW).

Such closed systems of rock salt, however, can be disturbed by fast near-surface ascent or by the presence of competent sheets. The microfabrics of anhydrite, enclosed in diapiric rock salt, include fractures, undulatory extinction, twins, lobate grain boundaries and stylolites, all of which reflect deformation under brittle-ductile conditions (Bäuerle, 2000; Mertineit et al., 2014). Similar microfabrics have been observed in anhydrite deformed experimentally under similar low flow stress like that recorded from natural halite (<5 MPa, Zulauf et al., 2010). Thus, competent sheets of anhydrite rock can be regarded as fractured rock aquifers, where hydraulically active fractures act as conduits for channel flow and as reservoirs for brines and hydrocarbons (Bornemann et al., 2008; Mertineit et al., 2014).

Based on viscous flow laws for halite and anhydrite (Carter et al., 1993; Müller et al., 1981), the viscosity ratio between both rocks is >20 resulting in striking folds and boudins of anhydrite rock layers (Figs. 1c,d). In cases of subhorizontal anhydrite rock layers, vertical pathways for fluids will not be present even if these layers are folded. On the other hand, in steeply inclined thick anhydrite rock layers, which are common in salt diapirs, fluids can migrate for long distances in vertical direction, disqualifying such rocks as host rocks for HLW. However, given the competent anhydrite rock sheets are deformed into single boudins, which are enclosed and separated by impermeable rock salt (Figs. 1b-d), the vertical fluid pathways will be cut, and the outstanding hydraulic properties of rock salt (with enclosed anhydrite) are still given. Thus, apart from their attitude, the finite strain geometry of competent layers is particularly important and should be taken into account when planning a disposal for HLW in diapiric rock salt.

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Hydrocarbon occurences in evaporites: Methods for trace level quantification and source identification

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In the safety assessment of possible host rocks the transformation of organic matter into gases by the temperature increase is one aspect to be investigated. In contrast to thermally immature shales, which might contain significant amounts of organic matter (up to several weight percent), evaporites usually contain only trace amounts of organic matter. In addition, the thermal maturity of the organic matter might vary considerably between host rocks, on the one hand due to the thermal history of the host rock itself, on the other hand due to possible migration of more mature hydrocarbons into the host rock. Especially in evaporites the information on the amounts and origin of gaseous and volatile hydrocarbons might be crucial in assessing possible migration scenarios and the phase behaviour of the hydrocarbons during heating.

Therefore a set of methods has been developed to extract gaseous, liquid and solid soluble hydrocarbons all from one sample of salt rocks. An important aspect was to minimize the potential losses of volatile components during the drilling operations – and to prevent contamination during drilling and core handling. Losses during core storage were another issue that was considered. By sampling at the drilling site into gas-tight containers filled with degassed water and the addition of an Helium headspace the losses of gaseous compounds were minimized. From the headspace of this container gas samples were retrieved for analyses of amounts of gaseous compounds and for their carbon isotopic composition after dissolution of the soluble salt components of the rock. The container was then connected to an automated extraction/ preconcentration unit to quantify less volatile hydrocarbons in addition to the gaseous compounds analysed before. After this analysis, the container was opened and the aqueous phase was extracted with organic solvents to recover the higher-boiling hydrocarbons. The bulk solvent extracts have been analysed by gas chromatographic methods. Then they were further separated into compound classes and their detailed molecular – and bulk carbon isotopic composition – was determined.

By combining the information from all the steps of the workflow described above an overall quantification of the sum of hydrocarbons from gaseous, volatile, and liquid as well as soluble hydrocarbons was possible for the same sample of evaporitic rocks investigated. In combination with the information from the detailed molecular composition and the compound-specific carbon isotopic composition of the gases an appointment of possible sources for the hydrocarbons – and hence their origin - was possible. This will be elaborated on by the comparison of data from different sites.

Geochemical investigations of brines from the Upper Permian (Zechstein) salt deposits of Northern Germany

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During exploration of salt deposits and salt mine excavations locally, occurring brines are observed. Since these solutions seriously affect the safety of mines (e.g. flooding), they are investigated with highest priority in detail in order to identify their origin, the migration paths, and in particular to exclude ground water infiltration. Brine occurrences in the mines of the Gorleben and Morsleben salt diapir (both Upper Permian "Zechstein" salt deposits of the Southern Permian Basin, Northern Germany) were investigated. During the exploration of the Gorleben site between 1979-2000 and 2010-2012, solution occurrences were documented, which were trapped in various lithologies of different geological strata. At the Morsleben site, one of the solution influxes has been active for more than 100 years.

The solutions were analyzed for their physical and geochemical properties with respect to density, pH as well as main, minor (ICP-OES) and trace components (ICP-MS). Modeling of the mineral saturation of the brines was performed using the software package EQ3/6v7.2 (Wolery, 1992), version c (Siemann & Schramm, 2000, 2002), and the thermodynamic data base hmw (Harvie et al., 1984), modified by Siemann & Schramm (2000, 2002).

In the Gorleben salt mine, a volume of approx. 666 m³ brine were captured between 1980 and 2000, distributed to various influx locations. 389 m³ (58 %) of the whole brine volume were detected in the infrastructure area of the exploration mine, 235 m³ (35 %) in the two shafts, and 42 m³ (6 %) in the deep drillings. At the end of 2015, six influx locations were active. In the Gorleben site, different types of solutions were identified. The majority of the natural geological brine occurrences were observed in the anhydrite-bearing lithologies of the z3HA ("Hauptanhydrit", a max. 80 m thick anhydrite rock layer), the z3OSM ("Gorleben-Bank", a max. 30 cm thick anhydrite rock layer) and the z3AM ("Anhydritmittelsalz", a ca. 30 m thick stratification of impure halite and interbedded anhydrite rocks). Minor occurrences are restricted to the z3BK/BD ("Bank- und Bändersalz") and to the highly deformed boundary between Staßfurt- (z2) and Leine-Formation (z3).

In the Morsleben mine, brine samples of two influx locations are collected and analysed sporadically since 1907, and continuously since 1991 (Schramm, 2015). The total solution volume until the end of 2017 is ca. 3312 m³. At mining claim H, the brine influx started in 1907 and approx. 3082 m³ were captured. Here, the brine enters the mine through the potash seam z2SF (halite dominated, K-Mg-depleted metamorphic overprinted potash seam). Since 1962 approx. 230 m³ brine were collected at mining claim 1a. The brine originates from the z3HA.

All investigated solutions of the Gorleben and Morsleben site interacted with rock salt and are therefore halite saturated. The Gorleben brines vary in the pH values between 2.0 and 6.1. Brines, originating from the z3OSM plot in the stability field of carnallite ± kieserite of the Jänecke diagram. Trace components are enriched, documented by very high Li concentrations with up to 214 µg/g (401 µg/g in fissure fillings) and high Br values (max. 6778 µg/g).

Brines from the z3HA are characterized by relative high Na (max. 1.275 wt-%), K (max. 1.488 wt-%), Ca (1.443 wt-%) and Mg (max. 9.40 wt-%) concentrations and relatively low Br concentrations in a range of 1721 – 3680 µg/g. These brines plot in the stability field of carnallite ± (kieserite and bischofite), or ± sylvite, or ± bischofite, or ± kieserite.

The brines detected in the boundary region between the z2 and z3, are characterized by the fictive component $CaCl_2$ and a very low element ratio of K/Mg (0.005). These brines plot in the field of kieserite or bischofite or carnallite + kieserite.

The brines that are attributed to the z3AM plot in stability field of kieserite. The brines of the z3BK/BD plot in the stability field of carnallite.

The investigated solutions of the Morsleben site vary in their pH values between 3.4 and 5.8 in the brines of solution influx of mining claim H. The composition of the solutions from mining claim H, sampled between 2009 and 2014, show saturation with respect to sylvite and in parts with respect to kainite. The brines from mining claim 1a are carnallite-saturated. The mineral saturation of the brines was verified by EQ3/6 modelling.

Based on their geochemical composition, the Gorleben brines originate from different sources, such as technical solutions and salt structure internal brines (in parts high evaporated or metamorphic). Most of the brine influxes in the Gorleben site can be attributed to the z3OSM (297.36 m^3 brine) and z3HA (249.52 m^3 brine). Solutions originating from the boundary between z2 and z3 yield a volume of 39.95 m^3, 1.594 m^3 from the z3AM and 0.006 m^3 from the z3BK/BD. Therefore the source of 88.34 % (588.37 m^3) of the brines was stratigraphically classified, 11.66 % (77.63 m^3) could not be clearly related to stratigraphic units, or are of technical origin. With the exception of the technical solutions, all captured brines in the Gorleben mine have a salt dome internal origin.

The geochemical signatures of the brines investigated in the Morsleben site have also been assigned to their origin and to the migration path in special. The brines of mining claim H are mainly ground water derived, that can be deduced from their Rb/Br ratio, which plots in the field outside typical marine derived brines according to Mattenklott (1994). In addition, the Li/Mg ratios show that these solutions are diluted in relation to evaporated seawater. On the contrary, the brines captured in mining claim 1a show Rb/Br ratios of typical marine origin. The Li/Mg ratios are comparable to that of evaporating seawater, and are in parts slightly Li-enriched. It is assumed that these brines are highly evaporated relictic Permian seawater, or metamorphic brines of salt structure internal origin (Mertineit & Schramm, 2019).

The geochemical signatures of the brines allow a reliable assignment to their origin, which is necessary for safe and long-term mine maintenance, as well as for planned mine excavations.

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Mineralogical-geochemical characteristics of fracture mineralization in the Upper Permian Staßfurt potash seam (z2SF) and surrounding salt rocks from the Morsleben site, Northern Germany

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Fractures occur locally in the Upper Permian z2 potash seam (Kaliflöz Staßfurt) of the Morsleben salt mine, Northern Germany. The fractures are distributed on all levels in an extremely deformed area at the mining field of Marie shaft. The sampling site is located within a NW-SE trending synclinal structure, which was reverse folded (Behlau & Mingerzahn, 2001). Rock samples were taken between the -195 m and -305 m level. In this area, more than 200 healed fractures were mapped. For long-term safety considerations, the development and healing mechanisms of these fractures were investigated using mineralogical-geochemical and microstructural methods (Grewe et al., 2017).

Mineralogical-geochemical investigations of both, fracture mineralization and surrounding salt rocks, were performed on bulk rock samples using ICP-OES (Inductively Coupled Plasma Optical Emission Spectroscopy) for the main- and trace components, and ICP-MS (Inductively Coupled Plasma Mass Spectrometry) for further trace elements. Isotopic analyses of $\delta^{34}S$ and $\delta^{18}O$ were carried out on sulfate bearing rocks using EA-IRMS ($\delta^{34}S$; Elemental Analyzer Isotope Ratio Mass Spectrometry) and TC/EA-IRMS ($\delta^{18}O$; Thermal Combustion Isotope Ratio-Mass Spectrometry). In-situ $^{87}Sr/^{86}Sr$ isotope ratios on polished sections were obtained via LA-MC-ICP-MS (Laser Ablation Multi Collector Inductively Coupled Plasma Mass Spectrometry). For analytical details, see Grewe et al. (2017) and references therein.

Most fractures extend several centimeter to meter into the surrounding salt rocks and show opening width of only a few millimeters to rarely 15 cm. The dominant strike orientation of the fractures is NE-SW trending, and the dip angles are steep (ca. 70°, dip direction NW and SE, respectively). Minor, flat oriented fractures of different strike directions prevail.

The fractures in rock salt are healed with basically polyhalite, halite and carnallite. In the potash seam, the fractures are filled with kainite, halite and minor amounts of carnallite and polyhalite. In both cases, the mineral content of the fracture mineralization corresponds predominantly to the composition of the surrounding salt rocks.

A strong grain shape fabric of kainite, undulatory extinction, subgrain formation in kainite, and several mineral transformations document subsequent deformation of the filled fractures. Subgrain formation in halite occurred in both, the fracture infill and the surrounding salt rocks.

The $\delta^{34}S$ results display a relatively homogeneous isotopic composition between 8.8 ‰ and 10.6 ‰ ± < 0.3 ‰ (VCDT), which is in good agreement with literature data for Permian rocks from northern Germany (e.g. Kampschulte et al., 1998). The values of surrounding salt rocks and fracture mineralization are similar to each other.

The $\delta^{18}O$ isotopic composition shows more pronounced variations between 9.8 ‰ and 14.8 ‰ ± < 0.5 ‰ (VSMOW), which is in the higher range of published data for Permian rocks (e.g. Claypool et al., 1980). Contrary to the $\delta^{34}S$ data, the $\delta^{18}O$ values of fracture infill are increased by 0.7 to 2.5 ‰ compared to adjacent salt rocks.

The comparatively high values can be explained by high saline solutions during sedimentation, where preferred heavier oxygen is left in the brine, which shifts the ratio to higher values. Further, an increased temperature during subsequent deformation processes (> 83°C, proved by the development of the metamorphic mineral langbeinite) influences fractionation processes of the oxygen isotopes.

The $^{87}Sr/^{86}Sr$ isotopic composition and the Sr content of fracture mineralization and surrounding rocks depend strongly on the mineralogical composition of the rocks. Generally, the Sr content varies between 100 ppm and ca. 9000 ppm.

Fracture mineralization in anhydrite rocks and anhydrite rocks itself, respectively, display a homogenous isotope ratio of 0.7071 - 0.7076 ± 0.001, which are typical values for Permian rocks of the Zechstein basin (e.g. Kampschulte et al., 1998). In the potash seam, more heterogeneous and higher isotope ratios of 0.7091 – 0.7139 ± 0.003 were detected. In rock salt adjacent to potash seams, the isotope ratios of surrounding salt rocks (0.7103 ± 0.002) and fracture fillings (0.7150 ± 0.004) are also increased.

The high strontium isotope ratios may be caused by the formation of ^{87}Sr from in situ ^{87}Rb decay, which shifted the isotope ratio to higher values, or the influence of ^{86}Sr depleted brine. A possible source for ^{87}Rb are potash minerals (Rb content max. 17 ppm/whole rock).

Finally, no indications for postsedimentary changes by groundwater or salt structure external brines are discernible from the obtained data. Comparable results for Gorleben salt rocks ($^{87}Sr/^{86}Sr$ on sulfates) are reported by Schmidt & Mengel (2015), who suggest that the system was closed for at least 5 my.

Further investigations will focus on detailed microstructural and geochemical analyses of the fracture infill and surrounding salt rocks. Age dating of suitable minerals, e.g. polyhalite (Leitner et al., 2013), could help to reconstruct the formation conditions.

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History of the study of physical, mechanical, flow, and solute transfer properties of the Vendian (Kothlin) clay as a medium for the LL RW disposal site

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Lithified clay formations are widespread in the North-West of the Russian platform, in particular, within the St. Petersburg region. They include Kotlin clays (V_2kt) of the Vendian system crossed by blue lower Cambrian clays ($Î_1$ln). Clays underlay or serve foundations for such facilities as the Leningrad NPP as well as existing near-surface RW storage facility (Radon) located in the vicinity of City of Sosnoviy Bor (Fig. 1).

The systematical studies of the Kotlin clays as a potential environment for an underground repository (UR) for the final disposal of LL radioactive waste (RW) began in 2007 with drilling and sampling campaign of four boreholes (up to 180 m in depth, Figs. 1 and 2). Later, additional information from engineering geological survey performed at the neighboring areas became available. Thus, three sites with borehole-clusters related to the Leningrad NPP-2, Radon RW disposal site and mined subway tubes were studied and sampled in detail (Rumynin, 2011; Rumynin & Nikulenkov, 2011). The following rock properties have been investigated: (1) properties affecting the geotechnical conditions of construction and operation of the UR facility; and (2) properties controlling the safety of the UR facility from the point of view of radiation impact on groundwater and the neighboring environment. In order to identify ancient buried valleys additional geophysical soundings were performed.

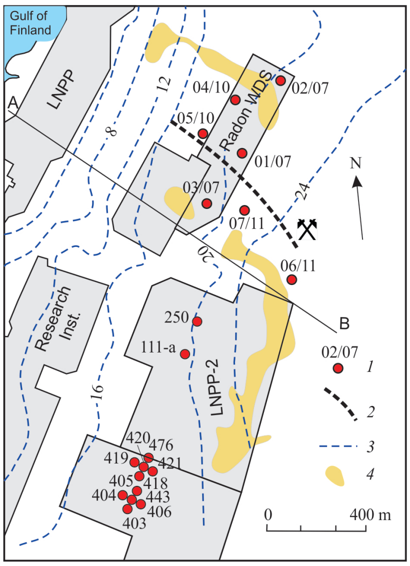

Figure 1: Location of deep engineering-geological wells at the sites of UR and LNPP-2 (1 – well number; 2 – projection of the underground mining on the earth's surface; 3 – potentiometric surface of the groundwater head of the shallow aquifer system; 4 – ancient valley).

Hydrophysical and physical-mechanical properties. Results of core analyses demonstrated the clear tendencies in the spatial distribution of physical and mechanical properties of clay formation. The upper zone (I) of the cross-section (up to depths of 40-50 m) is composed by moist and deconsolidated rocks (Fig. 2). The lower zone (II) is represented by more dense and less moist rocks. Stabilometrical tests demonstrated a clear trend: the hardness of rock increases with depth. Deformation properties of rocks also change with depth. Thus, the increase of the total stress-strain modulus indicates the decrease of the compressibility of rocks at large depths (zone II) compared to near-surface zone (I). The identified spatial variability of parameters allowed the selection of the reasonable depths for the UR.

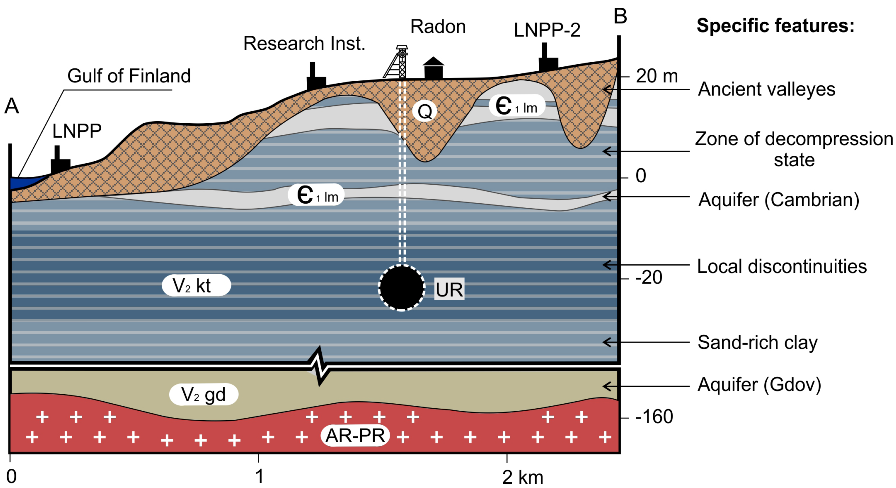

Figure 2: Schematic geologic cross-section along line A–B (Figure 1) and specific features related to the weak-links and limiting factors of the UR engineering.

Flow and solute transport properties of clays. The hydraulic conductivity of Kotlin clays was investigated by using triaxial compression meter WF-50 at monoliths oriented in two perpendicular directions. The interval studies demonstrated that Kotlin clays have fairly low permeability properties. The hydraulic conductivity across the bedding is in the range from 5×10^{-7} to 2×10^{-5} m/d, while the hydraulic conductivity along the bedding is from 4×10^{-6} to 2×10^{-4} m/d. Thus, the studied parameter has strong anisotropy (up to 16), which is explained by fine banding of clay sediments (Rumynin & Nikulenkov, 2011).

Diffusion tests with radionuclides for three experimental configurations (single chamber, two chamber, and 3D tests) provided estimates for diffusion coefficients of Kotlin clays at the proposed location of UR. Obtained values are in good agreement with the results of foreign studies for conditions of similar facilities. Anisotropy in diffusion coefficient of the clays has been confirmed experimentally. The species diffuse up to 2–6 times faster along the strata, than across it, due to fine banding structure of the Kotlin clays. The obtained effective diffusion coefficients, D_e, for various radionuclides were arranged in the order: tritium> Sr-90 > Cs-137 >Co-60. The corresponding values of D_e, are as follows: $3.6\times10^{-10}> 2.3\times10^{-10}>6.6\times10^{-11}>3.0\times10^{-11}$ m²/s.

Clay samples collected from various depths have been used for sorption experiments with Sr-90, Cs-137, Am-241, Pu-239,-240. The obtained ranges for the sorption distribution coefficient K_d differ substantially for various radionuclides (Rumynin & Nikulenkov, 2016). Also, it was clearly seen that K_d values were significantly lower for samples from the lower zone of the cross-section (deeper than 100 m), represented by Vendian sandstone. The sorption is the lowest for Sr-90, and the highest for Am-241 and Pu-239, Pu-240; Cs-137 has intermediate values.

Modeling. The performed studies allowed developing a system of flow, migration and geomechanical models. Simulation of the flow and migration processes in the framework of safety case development has allowed assessing the spatial-time scales of diffusion in the clay in the post-operation period (regular operation of RW), and the map of contamination within the Vendian layer (emergency scenario connected with loss of integrity of rock mass). In both cases, the impact is within the acceptable limits. The emergency (worst case) scenario concerns also with collapse of the underground mine roof resulting in the subsidence of the above massive and surface. Geomechanical modeling of forming the fracture zone due to sharp change in the stress-strain state of the massive shows that the upper boundary of this zone does not reach the aquifers overlain the Kotlin clays (Fig. 2). Thus, the risk of the direct radionuclide release from the UR in the surrounding environment is not high.

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Influence of geological processes on the barrier properties of claystone formations: Insights from microstructural-geochemical investigations

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As part of the BASTION project ("Influence of geological processes on the barrier properties of claystone formations"), BGR carries out investigations focusing on the lithological-petrographic composition, the structural inventory and potential barrier properties of various claystone formations. Our approach is a combination of microstructural-petrographic studies using SEM, nano-CT and "classical" optical microscopy with a set of geochemical and phase analyses, like XRD, XRF and ICP-MS. In addition, the organic (TOC) and inorganic carbon (TIC), total sulphur (TS) as well as the cation exchange capacity (CEC) were determined. The objectives of our studies are (1) to assess and quantify lithological variations of various clay rock formations on multiple scales and (2) to constrain the structure of artificial and tectonic fault zones and the relevant deformation mechanisms (Kneuker et al., 2017).

The work presented here focuses mainly on objective 1. It is based on sample material from the Mont Terri rock laboratory (Opalinus Clay, Switzerland) and on investigations of Lower Cretaceous claystones from the eastern part of the Lower Saxony Basin in Northern Germany. Both rock formations are considered as potential host rocks for radioactive waste disposal (e.g. Jobmann et al., 2017).

The recent excavation work in the Mont Terri rock laboratory gave opportunity to study the upper shaly and upper sandy facies types of Opalinus Clay, including the transition towards the overlying Passwang Formation in samples from new prospection boreholes. The investigations revealed similarities and differences in microstructure and composition between the facies types. The results confirm that samples from the upper shaly facies and a number of samples from the upper sandy facies are closely related to the most homogenous facies type of Opalinus Clay, referred to as lower shaly facies. In contrast, the lower sandy facies, the carbonate-rich sandy facies and the overlying Passwang Formation represent the more heterogeneous endmembers. The distribution and amount of distinct elements and parameters (e.g. SiO_2, Al_2O_3, CaO and CEC) confirm differences in composition, and independently justify the majority of the (micro)structurally based assignment of the samples to a certain facies type. The composition of the "average shale" (Wedephol, 1971) is close to that of the silty-sandy claystones of the upper sandy facies. The new results are consistent with published data and support the classification of the Opalinus Clay at the Mont Terri site into five facies types.

In the investigated drill cores of the Lower Saxony Basin, the Valanginian to Lower Aptian strata are composed of fine grained, dark to medium gray silty claystones, locally with marly or sandy intercalations.

Granulometric data indicate that the amount of the clay size fraction (< 2 µm) ranges from 55 - 65 wt%, and for the silt fraction between 35 - 55 wt%. The sand fraction (> 63 µm) varies from 0 to 5 wt% in the clay rich intervals, but may increase up to 40 wt%, especially in the sandy parts of the Upper Valanginian sediments.

The investigated claystone sequence appears macroscopically monotonous; however, detailed petrographic-microstructural analyses revealed the presence of heterogeneities in form of organic-rich sections (in the Aptain and Lower Barremian), carbonate-rich, phosphoritic and sideritic concretions, and in parts weakly cemented, silty-sandy layers in the Valanginian sediments. Typical for parts of the Hauterivian and Lower Barremian sediments are clay-marl alternations on the scale of 0.5 - 1.0 m, which are well visible as cyclic variations in the geochemical dataset. Further heterogeneities include pyritized horizons, bioturbation and layers rich in biodetritus. The first mineralogical-geochemical and microstructural investigations indicate that the Lower Cretaceous sediments of the Lower Saxony Basin form in part a variegated sequence (see also Thöle et al., 2019).

The similarities and differences in (micro)structure and composition may influence, to a certain degree, the physical and chemical properties of the investigated claystone formations from different locations (e.g. radionuclide retention capacity, swelling capacity, water content, behavior under thermal load, and fracture behavior). This should be taken into account regarding upcoming experiments and investigations for safe radioactive waste disposal.

Acknowledgements:

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Siting of Geological Repositories

DGR siting in Ukraine and features of a promising area

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The purpose of this paper is to give an overview of the state of the deep geological repository (DGR) siting in Ukraine, including boundary conditions, requirements, methodology, and the results obtained.

Currently, 15 WWER reactors are being operated at four Ukrainian NPPs. Four RBMK reactors were operated at the Chernobyl NPP (ChNPP), one of them was destroyed in 1986. The operating units generate approximately $90 \cdot 10^9$ kW·h of electricity (up to 55 %) annually. It is expected that more than 17 000 tHM of SNF and almost 200 000 m^3 of waste (including ILW) will be generated. In the near future, vitrified HLW after the reprocessing of SNF from WWER reactors will arrive in Ukraine from the Russian Federation. The accident at the ChNPP contributed approx. 3.3 million m^3 to the total amount of waste.

Ukrainian legislation (Law, 1995) defines that in the geological disposal facilities HLW and ILW should be disposed. These can be: vitrified high-level radioactive waste, some type of SNF (which will be declared as radioactive waste, e.g. SNF RBMK-1000), as well as - ILW after NPP's decommissioning and ILW of accidental origin. According to Regulation (2008) the site selection phase of the DGR life cycle shall be performed in following four stages: conceptual, regional investigation (including both regional analysis and screening substages), site characterization, site confirmation.

The DGR siting activities were started in Ukraine in 1993. During 1993-1996 the availability of geological formations and regions over the whole Ukraine territory for DGR was assessed. According to the results of this work the promising formations were identified, and the possible areas for repository placement were identified within these formations (Fig.1). Since the late 90s, the main attention was paid to the crystalline formations of the Chernobyl Exclusion Zone (ChEZ). However, these results were not summarized by the operator of the future geological repository in the form of a single comprehensive report and were not agreed by stakeholders.

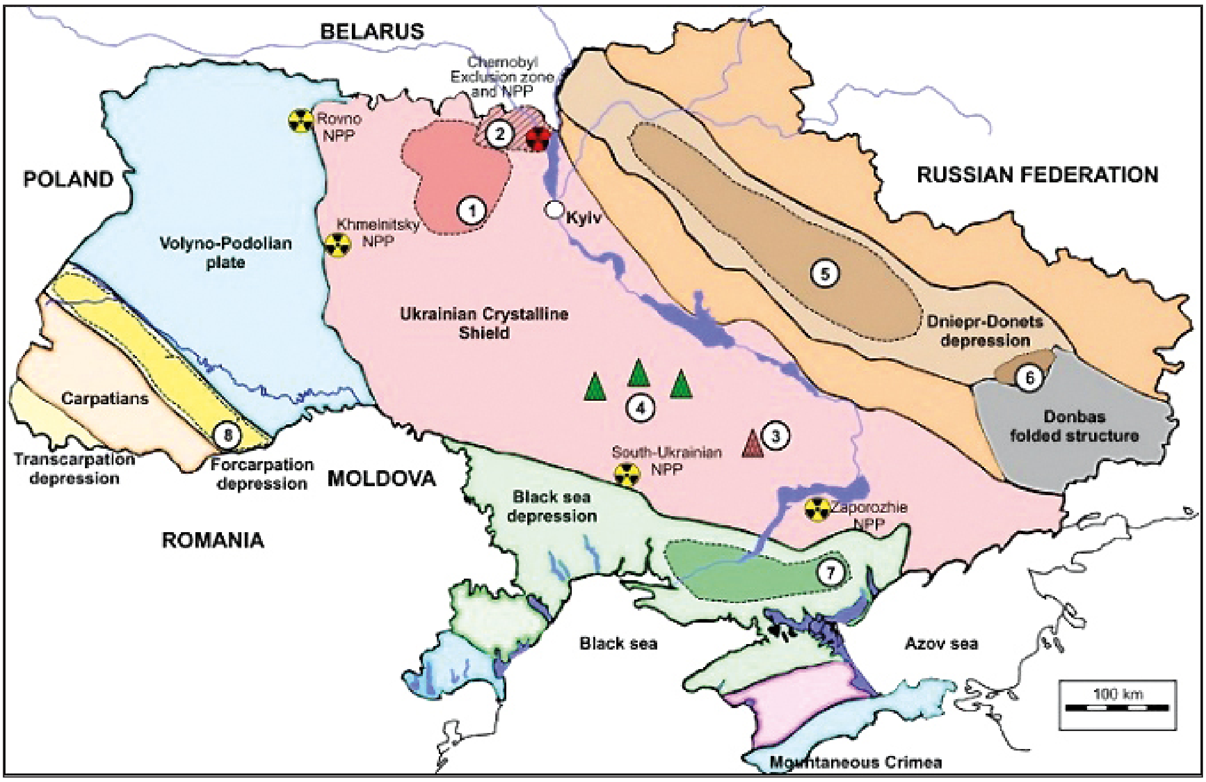

Figure 1: Geological disposal options considered in Ukraine (Shestopalov, 2016): 1. Proterozoic granitoids of Korosten Pluton; 2. Proterozoic granitoids and Archaean gneisses of ChEZ areas; 3. Archaean granitoids of Saksagan Iron mine; 4. Proterozoic crystalline formations of Uranium mines; 5. Salt-domes of the Dnieper-Donets depression; 6. Permian bedded salts of Donbas folded structure ; 7. Paleogene and Neogene clays of Black Sea depression; 8. Potash salts and Neogene clays of Forcarpathian depression

Therefore, the NAS of Ukraine is compiling both the results of a regional analysis of the country's territory (justifying and documenting the choice of a promising region) and the results of initial steps of screening a promising region. These activities are performed at the request of the DGR operator.

During the siting process we proposed to use several sets of screening criteria with specific attributes assigned to them. These sets were applied sequentially and consist of:

- Exclusion criteria (unsuitable geology, seismicity, resources, catastrophic phenomena…),
- Disqualifying criteria (unfavorable factors, existing mines, coastal and boarder areas…),
- Comparison criteria (advantages/disadvantages, transport, risks…),
- Additional criteria (social and political aspects…),
- Local criteria (tectonic, hydrogeology, homogeneity…).

The result of applying the first four groups of criteria served as the rationale for choosing a promising region (regional analysis substage). The application of the last group of criteria allowed us to identify areas in promising regions for investigation at the characterization stage (screening substage).

Regional analysis substage results (see the table) show that the most promising region for DGR creation is the uninhabited ChEZ and the surrounding areas. Crystalline rocks of ChEZ basement can be used as host formation for repository.

Region	Exclusion criteria	Disqualification criteria	Comparison and additional criteria	Result
Ukr.Shield, Korosten pluton	No	No	Yes (less appropriate)	Reserve
Ukr.Shield, Chornobyl EZ	No	No	Yes (more appropriate)	For priority investigation
Volyno-Podolian Plate	No	Yes (border consider.)	---	Disqualification
Dnieper-Donets depression	No	Yes (unfavorable)	---	Disqualification
Donbas, Black See depression	Yes (resources)	---	---	Exclusion
Crimea, Carpathians	Yes (seismicity)	---	---	Exclusion

According to screening substage results (see the Fig. 2) the three most promising areas (Zhovtneva, Veresnia and Novosilky) are identified for the future investigations.

For the first two most promising areas, the typical are hornblend-biotite, rapakivi-like granites dated at 1,75 Ga, for the third one – biotote granites and plagiogranites dated at 2,0 Ga and Archean gneisses. These rocks are covered by Jurassic-Quarternary sediments (clays, marls, aleurites, sandstone, sands) with a thickness between 80 and 350 m.

The geological and surface characteristics of the Ukrainian sites are similar to Scandinavian sites (Forsmark, Olkiluoto). This relates to age, mineralogy, degree of tectonic transformation, hydraulic properties of crystalline rocks, and some ecosystem characteristics. The differences are determined by:

– climatic characteristics,
– presence on the Ukrainian sites of sedimentary cover with several water-bearing horizons,
– groundwater sources and their hydrochemical characteristics,
– scale of the glaciation effects.

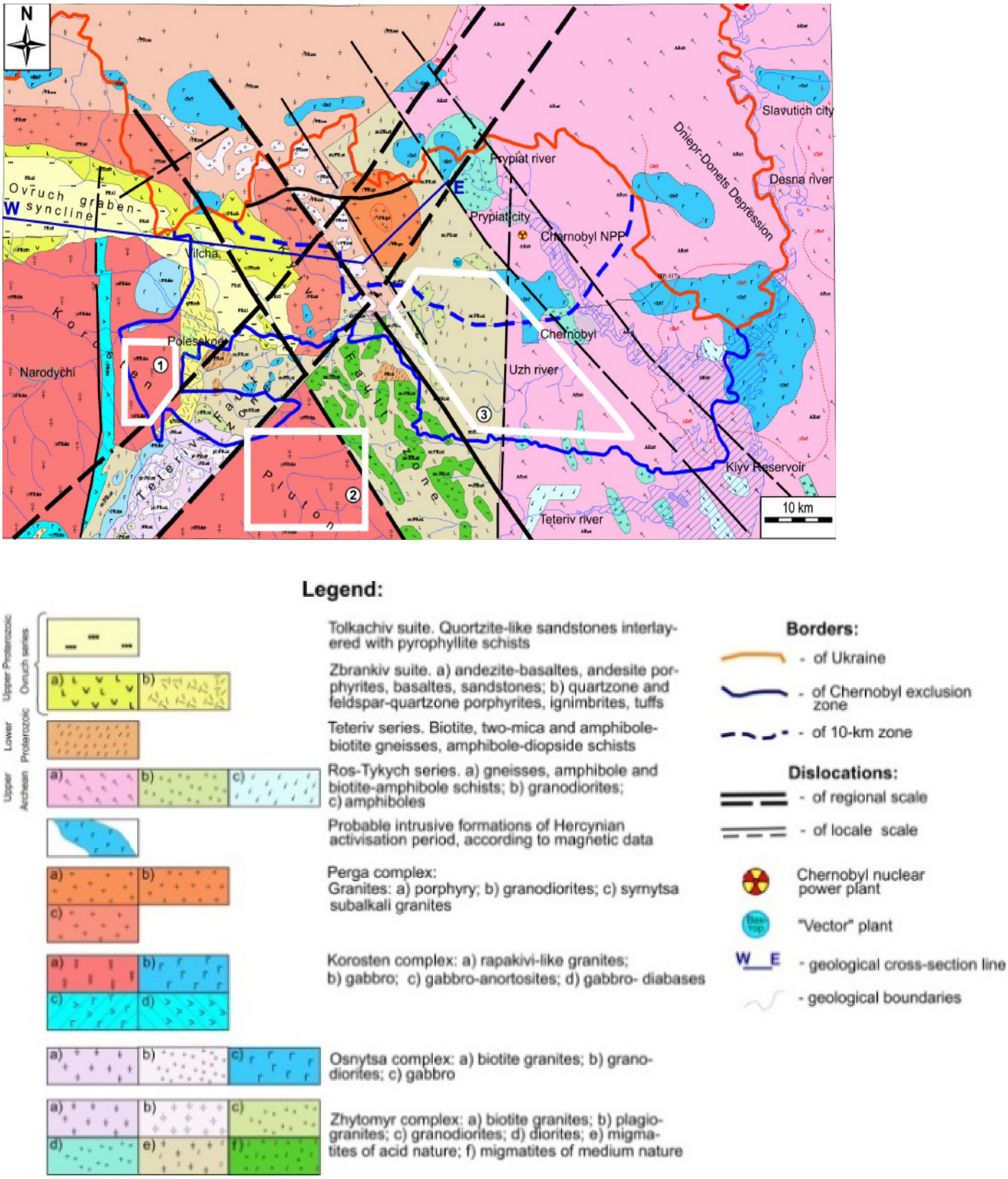

Figure 2: Prospective areas within ChEZ and its vicinity: 1 – Zhovtneva, 2 – Veresnia and 3 – Novosilky (Shestopalov, 2016)

Geological conditions of prospective areas within ChEZ and its vicinity provide a unique degree of protection due to the presence of a sedimentary cover which contains thick clay strata (sorption of radionuclides) and several groundwater horizons (limitation of groundwater flow through the geological repository and dilution of radionuclide concentrations).

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Site selection for the best clay-hosted repository in Switzerland. Approach and results

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The site selection process for the deep geological repositories in Switzerland is in its final phase. All three remaining sites are principally suitable to host repositories for low level waste as well as for high level waste and spent fuel. Using surface-based exploration methods, including 3D-seismics and deep drilholes, Nagra currently collects the necessary data for the site selection.

The comparison of the three sites will again make use of the 13 technical criteria defined in 2008 and used throughout entire selection process. The criteria comprise safety-related aspects including the barrier properties and their long-term stability, as well as the construction suitability of the repository and its access facilities.

Nagras role is to collect a reliable data base, perform an in-depth analysis of the geological situation and the natural and repository evolution at each site. This evaluation will be the basis to select the most suitable site for the two waste categories. If the optimal site for HLW/SF and LLW is identical and the space requirements can be met at that site, a co-disposal facility will be proposed.

All three sites feature a roughly 200 to 250 m thick barrier sequence of claystones and marls. The host rock at the centre of the sequence, the Opalinus Clay, is a homogenous claystone around 100 m thick. It has been deposited under shallow marine conditions with little lateral changes. Overlying and underlying units are less homogenous and lateral facies changes between marls, claystones and limestones are common. Hence the thickness and quality of the geological barrier can be quite different at the three sites.

Currently Nagra is following-up on 3D-seismic surveys performed in the three areas with a deep-drilling campaign. The 3D-seismics have revealed the structural setting of the sites and have already indicated lateral facies changes in the rocks surrounding the Opalinus Clay.

The boreholes have been positioned around the most promising zones of the siting regions and will cross the entire barrier sequence including the bounding aquifers. Some boreholes will also sample the underlying Pre-Mesozoic basement. Total depths of the boreholes will be between 650 and 1350 m depending on the local situation and the explorations aims.

Using mostly continuous wireline coring we will be able to characterize the three sites with respect to lithology and especially barrier relevant parameters such as clay content and porosity. In situ testing is used to determine hydraulic properties and stress conditions. In our contribution we present the findings from the seismic campaign and the first boreholes and give insight into planning of the remainder of the deep-drilling campaign.

The site selection process in Germany: Current status of the geoscientific work

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The Federal Company for Radioactive Waste Disposal mbH (Bundesgesellschaft für Endlagerung mbH, BGE) is a state-owned company established in September 2016 following the 'Act on the Organisational Restructuring in the Field of Radioactive Waste Storage'. The Repository Site Selection Act (StandAG), adopted in 2017, defines the site selection procedure, aiming to ensure the best possible safety for storing high-level radioactive waste in Germany for the duration of one million years.

The site selection procedure is a participatory, learning, transparent and self-questioning process and based on scientific evidence. Participation of the public is envisaged at all times. The procedure consists of three phases. After each phase, the legislator decides about the regions considered in the next step of the site selection process (Fig. 1). Initially, the whole country is taken into account, without exclusion or predetermination of any possible storage site.

The first phase, which starts with the application of a number of exclusion criteria, minimum requirements and geoscientific weighing criteria, aims to identify a set of suitable sub-areas ("Teilgebiete") that will form the basis for the determination of site-regions (Fig. 1).

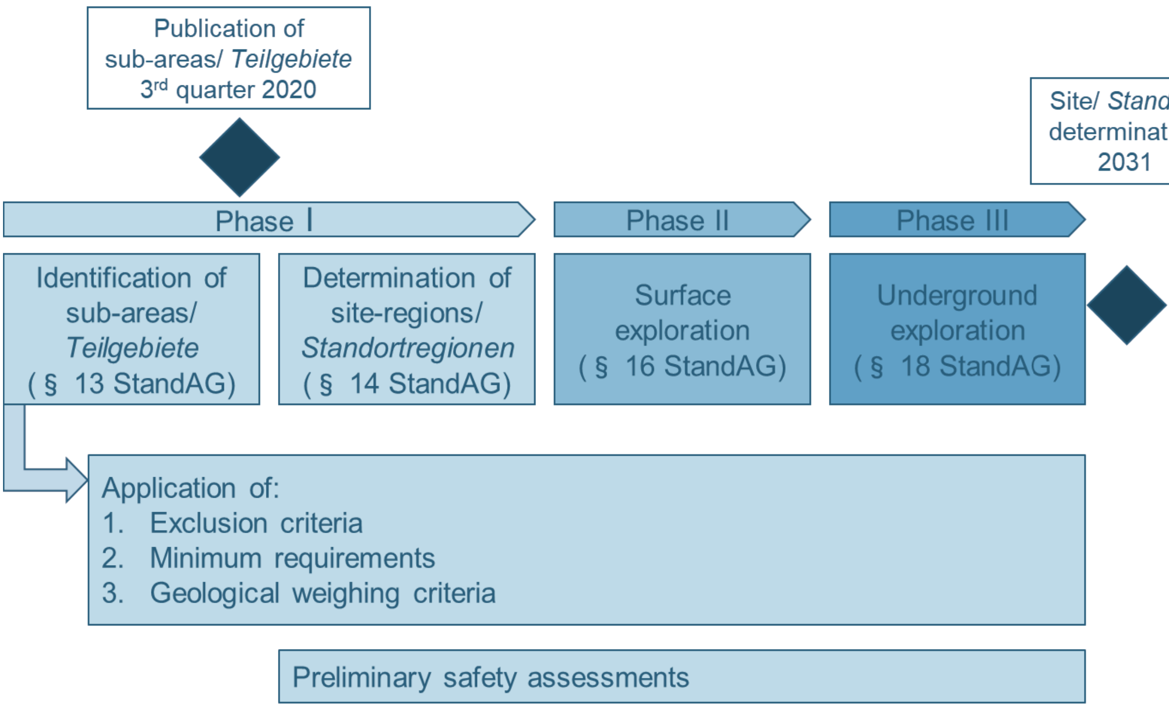

Figure 1: Schematic illustration of the German site selection process.

For this purpose, we started with the specific data requests in August 2017 and, until now, received more than 500 gigabytes of data in more than a hundred different file types. We review, homogenize, and store the data into databases. Data sets are provided by federal and state authorities and, in principle, are grouped in four categories: 1. GIS data, 2. grid maps, 3. 3D-data sets (e.g. geological 3D-models) and 4. other data sets.

Based on the received data, we first apply – if feasible – six legally defined exclusion criteria, e.g. related to fault zones, seismicity, volcanic activity or strong vertical uplift. The exclusion criteria identify regions that are not suitable for radioactive waste disposal and are applied nationwide and independent of the others.

Afterwards, we use the data to identify regions that fulfil five legally defined minimum requirements, e.g. thickness of the containment-providing rock zone, hydraulic conductivity and a suitable area extension. As possible host rocks only rock salt, claystone and crystalline rock are considered. For the application of the minimum requirements, we use stratigraphic 3D-models and bore logs (“Schichtenverzeichnisse”) of boreholes, both provided by the state authorities. With these data sets, host rock horizons are identified within geological and structural context inside 3D-models and based on petrographic bore markers. Three pilot areas for each host rock type (claystone, bedded salt and crystalline rock) and ongoing modelling work of domal salt validated our application method.

Based on geoscientific weighing criteria, we evaluate the remaining regions with respect to their overall geological eligibility. Each of the weighing criteria is assessed on the basis of a specific indicator, e.g. rock permeability. Finally, based on the summarized evaluation (“Aggregation”) of all criteria, a safety-oriented weighing process for each identified region is carried out.

This selection procedure will lead to a set of sub-areas (“Teilgebiete”) to be published in the third quarter of 2020 both as a report and, for fulfilling the aim of transparency, as an interactive web portal, where all used data and sub-areas are presented to the public.

Preliminary safety investigations in the site selection process: Potential, necessities, pitfalls

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By the 2017 German Site Selection Act ("Standortauswahlgesetz"), a stepwise site selection process for a high-level radioactive waste repository is prescribed: In a first step, based on existing data regions for geoscientific investigation from above ground are to be identified. After having investigated these, sites for investigations from underground shall be named. Finally, based on the site investigations a disposal site has to be selected. The process aims at selecting the site offering the "best possible safety for a repository … for a timeframe of one million years" in "rock salt, claystone [or] crystalline rock". By definition, this is the site to be selected "in the course of a comparing procedure" which has to be "participative, science based, transparent, self-scrutinizing and learning" (https://www.gesetze-im-internet.de/standag_2017/BJNR107410017.html, in German, translations by the authors of this abstract). The 2017 amendment of the Site Selection Act is very much based on preceding work of a parliamentary commission (Endlagerkommission 2016).

In order to achieve its goal, the Act stipulates a set of selection criteria which have to be valid throughout the procedure. Some of these criteria, namely the so called screening criteria addressing the general geologic situation and the so-called minimum requirements mostly addressing properties essential for the safe confinement of the waste, have "simply" to be fulfilled by the regions or sites under consideration – in other words: These criteria support decisions about regions or sites to remain in the process or, in contrast, to be screened out.

In contrast, others, the so-called weighing criteria, are meant to support region or site ranking or comparison. For most of these, indicator ranges are given in the Act which fall into categories such as "favourable", "conditionally favourable", "less favourable" or "unfavourable". Furthermore, the Act stipulates that so-called preliminary safety investigations are to be carried out for the regions or sites under consideration. These investigation should assess the performance of the repository system as a whole and are meant to support the comparison of regions or sites. Furthermore, they should inform decisions concerning site investigation and RD&D programmes as well as the derivation of so-called evaluation criteria to be addressed during the site investigations from underground.

Advice about how to carry out these preliminary safety investigations is expected from an ordinance presently under development but it is common understanding that the investigations will carry many important elements of what is commonly referred to as a Safety Case (OECD/NEA 2013), with the degree of detail of course depending on the amount of site and concept specific information available at the respective steps of the site selection (Endlagerkommission 2016, DAEF 2017).

This abstract reports about two PhD projects at TU Clausthal which aim(ed) at juxtaposing the possibilities of acquiring site-specific information at the different siting steps with the needs of the respective preliminary safety investigations. One of these projects addressed repository systems in rock salt, while the other is dealing with crystalline host rocks. Finally, the authors draw some conclusions concerning chances and challenges of the preliminary safety investigations.

The first PhD project addressing steep rock salt formation (salt domes) was finalized in 2016 (Krapf 2016). The project was carried out at the time during which the commission mentioned above developed its report. Therefore, the project was based on criteria development which was to some extent independent of the commission's work. In particular, the author abstained from quantifying criteria; in the PhD thesis the opinion is expressed that quantification should rather be carried out in the course of holistic considerations of the repository system, i. e. safety investigations. For such investigations, uncertainties and safety reserves, investigation and research needs and optimization potential were identified. The work was based on generic considerations utilizing the safety concept for steep salt formations developed in Germany (Fischer-Appelt et al. 2013). As a central element of this thesis a non-invasive determination method for the temperature gradient at every possible site was presented.

In contrast, the PhD project addressing crystalline rocks is still ongoing and therefore based on the stipulations of the Site Selection Act. It had to face the challenge that the Act allows for various options for a safety concept in crystalline rock. The project is addressing just one of these options – a safety concept based on confinement over the whole assessment timeframe in a canister-buffer system as in the Swedish/Finnish KBS-3 concept. It becomes obvious that several of the criteria stipulated by the Site Selection Act are unrelated to such a concept. Basically, site investigation has to address issues going beyond those addressed by the Act but are related to the safety functions central for a KBS-3 type concept. Challenges to be addressed in this project (as well as during site selection) include:

- As explained above, it is possible (and even likely) that the safety concept to be considered for crystalline rock will rely on confinement mainly by technical and geotechnical barriers (as opposed to geologic barriers). The criteria stipulated in the Act, however, account for this option in a rather cursory way (an example being hydraulic and hydrogeochemical conditions in the vicinity of the canister-buffer system). This, and the conceptual difference as such, will be a challenge when comparing sites and systems.
- The only mature concept for this option is KBS-3. It needs, however, adaption due to the different waste inventory and different geologic conditions in Germany. Whether it will be capable of fulfilling the same expectations as systems in salt or claystone concerning confinement and barrier integrity remains to be shown. Also, the ongoing debate on copper corrosion under anaerobic conditions might raise doubts amongst stakeholders and thus jeopardize acceptance.

Concluding from the two projects as well as from general considerations, the authors are of the opinion, that the preliminary safety investigations to come offer chances but also have to address challenges:

– During the commission's work, many concerns had been raised in the scientific community concerning the comparability of conceptually different systems with varying degrees of available information when looking for the site offering the "best possible" safety. However, the 2017 amendment addresses some of these concerns by defining this site as the one resulting from the selection process: The term "possible" in this context means therefore "possible for human beings". Also, the preliminary safety investigations offer a hopefully powerful tool for a holistic comparison.

– However, the Act provides leeway about how to use weighing criteria and safety investigations during comparison. There is need to fill this conceptual gap, complications might arise from the differences between safety concepts in different host rocks as well as from some weaknesses of the criteria set stipulated in the Act.

– In particular, different information levels both about site properties and concepts might complicate siting. E. g., it is conceivable that concept optimization during the process end up with the finding, that the now optimized concept is better suitable for sites which were already screened out at an earlier stage of the process. One can argue that this is a necessary feature of the definition of the process, but would that be accepted?

– Specifically for the preliminary safety investigations, the authors fear (based on experience in the dialogue with interested actors), that the focus of interested laypeople will be on comparing estimated dose values, although their information content about one site being "better" than another will probably be limited.

– Setting the frame: By making the connection of "best possible safety" with the timeframe of one million years, the Act puts much emphasis on the long-term (post closure) phase. However, in the opinion of the authors, "best possible safety" can neither mean indefinite prolongation of storage (which might well be happen if the site identified as offering the best possible long-term safety will not be accepted in the societal process).

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How to identify areas with favorable geological conditions for a repository for high level waste in Germany?

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The German Site Selection Act was adopted in 2013 and revised in 2017. According to this act the site selection shall start from a white map, i.e. the complete German territory shall be considered. The objective is to identify the site with the best possible safety over the period of 1 Mio. years for disposing German high-level radioactive waste. Rock salt, claystone and crystalline rock are to be considered as host rock. The site selection shall be performed in a participatory, science-based, transparent, self-questioning and learning process.

The site selection procedure comprises three phases based on criteria. In the first phase, initially areas in Germany are identified that are not suitable as a repository site and can therefore be excluded by using exclusion criteria and minimum requirements. Subsequently sub-areas in Germany are determined with favorable geological conditions based on “a safety-related weighing of the results for all weighing criteria” in accordance the Site Selection Act. In the second and third phase, the potential sites are narrowed down by again applying the weighing criteria on the basis of results from explorations from above-ground and from underground, respectively. Additionally results of preliminary safety assessments are to be taken into account.

The eleven geoscientific weighing criteria are arranged in three criteria groups, which evaluate a) the achievable quality of containment and the robustness of evidence, b) the preservation of isolation performance, and c) other safety-relevant properties, respectively. For each weighing criterion, properties relevant to assessment as well as associated assessment parameters or indicators are regularised, as well as qualitative characteristics or numerical values for the assessment groups “favorable”, “relatively favorable” and “less favorable”. The Site Selection Act defines some overriding principles to aggregate the results of the individual weighing criteria but no detailed procedures.

Results are presented from a research project which was conducted by GRS, the Federal Institute for Geosciences and Natural Resources (BGR) and BGE TECHNOLOGY. The research project was funded by the German waste management organization BGE (Bundesgesellschaft für Endlagerung). The main objective of the work was to derive recommendations for the safety-related weighing of the results for all weighing criteria.

A prerequisite for a safety-oriented assessment of both the different characteristics and the different geological overall situations is a sufficient understanding of the significance of the individual geoscientific weighing criteria and their assessment parameters for the long-term safety of the repository systems for high-level radioactive waste to be considered. In order to develop such an understanding, nine different repository systems were investigated and the following work was carriedout:

– Development and description of a generic geological model for a possible configuration in Germany for the respective repository system.
– Assessment of the impact of geological and climatic processes on the future development of the repository system.
– Compilation of the main features of a safety concept and a safety demonstration concept.
– Development of a preliminary technical repository concept including the waste packages.
– Description of possible evolutions of the repository system during the demonstration period. For this purpose, a basic case is outlined as a potentially expected development of the repository system without carrying out a comprehensive systematic scenario analysis based on the state of the art in science and technology.
– Numerical analysis of the fundamental thermal, hydraulic and mechanical processes in the repository system caused by the repository over the demonstration period for the base case.
– Assessment of the integrity of the barrier rock for repository systems in which the geological barrier is an essential barrier.
– Qualitative and - where possible - quantitative assessment of the significance of the geoscientific weighing criteria for the assessment of the integrity of the barrier rock.
– Assessment of the radionuclide containment.
– Qualitative and - where possible - quantitative assessment of the significance of the geoscientific weighing criteria for the assessment of the radionuclide containment.

Based on these results, recommendations were derived how to aggregate the results of the eleven weighing criteria in a stepwise manner:

1. For each geoscientific weighing criterion an individual assessment is carried out. To begin with, each assessment-relevant property is evaluated separately, and then the results for the different assessment-relevant properties are combined to an assessment of the criterion.
2. From the individual assessments of the eleven geoscientific weighing criteria, an overall assessment for the siting region or the site, respectively, is derived.
3. For the evaluation of the assessment-relevant properties of the criteria, the same assessment groups are used as on the respective indicator level. Likewise, the same assessment groups are

used for the individual assessments of the criteria as at the level of the properties relevant to the rating

4. The assessment group “unfavorable” is generally not interpreted as an exclusion criterion for the aggregation but is equated with the assessment group “less favorable”.

5. The individual assessments of the criteria are aggregated verbally, and there is no mathematical weighting of the criteria. For some weighing criteria specific procedures are recommended to aggregate the results of the assessment properties.

6. The final assessment for a siting region or site is based on the combination of the assessment results of the criteria in criteria group 1, on the one hand, and the results of the criteria in criteria groups 2 and 3, on the other hand. This distinction is motivated by the fact, that the criteria in criteria group 1 determine the quality of the radionuclide containment by the barrier rock, since they relate directly (as parameters, initial or boundary conditions) or indirectly (as system-defining) to the hydraulic and diffusive resistance of the repository system.

The recommended procedure is compatible with the overriding principles defined by the Site Selection Act for the safety-related weighing of the results for all weighing criteria. For example, the overall assessment is not determined by a single weighing criterion. In addition, this procedure does not apply numerical values for the aggregation of the individual assessments for the criteria and it takes all criteria into account.

Geological Repository Options

The importance of host rock characteristics for the development of repository concepts

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The development of concepts for repositories for radioactive waste is driven by the safety principles containment and isolation. For this purpose, one of the first conceptual activities is the development of a safety concept that describes how safety will be achieved during construction, operation, and closure of a repository both in the short and in the long-term. Based on the national legislation, the data of the national nuclear energy programme, and the description of the geological situation at a selected or anticipated site, repository concept development can begin. Among the following three data bases the latter is the one for which data generation and compilation is the most elaborate and time consuming:

- set of national legislation (e.g. atomic energy act, radiation protection ordinance, safety requirements)
- compilation of the types and amounts of radioactive waste
- Structural-geological characteristics of the geologic formation at the repository site, in particular the host rock

A regulatory framework for radioactive waste management – more or less detailed – does exist in almost every country that produces electricity by nuclear energy. Over time, parallel to the evolution of the waste management programme, these regulations evolve and will become more detailed. Eventually, the legislation provides the legal boundary conditions for the design of a repository; e.g. criteria for site selection or prerequisites for the design (safety requirements (BMU, 2010): e.g. max. temperature underground).

The types and amounts of radioactive waste that have to be safely disposed of directly depend on the duration and volume of the national nuclear energy programme. For countries like Germany, which decided (2011) to phase out of nuclear energy production at a certain point in time (end of 2022), the assessment of the waste data base is very clear. Thus, the second corner stone for repository concept development is fixed and can be described in detail. Despite such fixed boundary conditions, repository concept development leaves lots of freedom in the responsibility of the designers, e.g.:

- packaging of the waste (design, shielding, material selection)
- geometric spacing between the waste packages in the repository mine

- Interim storage time of the waste package prior to the final disposal
- depth below surface of the repository
- choice of emplacement option and respective technology
- access to the underground via shafts or ramps or both
- selection of backfilling concepts and materials
- geotechnical barrier concepts and materials

However, another set of unchangeable, existing data at a site has to be taken into account for the repository concept development: the characteristics of the geologic structures at a site (already selected or anticipated for generic studies). The first challenge in this regard is to identify which of the data out of a huge amount of properties of the geologic structure are of relevance for erecting and operating a repository mine as well as for providing long-term safety. According to (Jobmann et al., 2016), the characteristics of a repository in crystalline rock are for instance: petrophysical properties (bulk density, effective porosity, water content, grain density, etc.), thermo-physical properties (e.g. specific heat capacity (dry and sat), thermal conductivity (dry and sat)), geohydraulic properties (gas and water permeability), geomechanic properties (Young's modulus, Poisson`s ratio, deviatoric stress, axial deformation), petrographic description (alteration and deformation of rock, open pores, and fractures), radionuclide sorption capacity. In case of relevance, all these data have to be gained by core drilling, samples taken from underground, from thin sections or experiments in the laboratory or in situ. One example of thin sections prepared and analysed by BGR (Jobmann et al., 2016) is shown in Fig. 1.

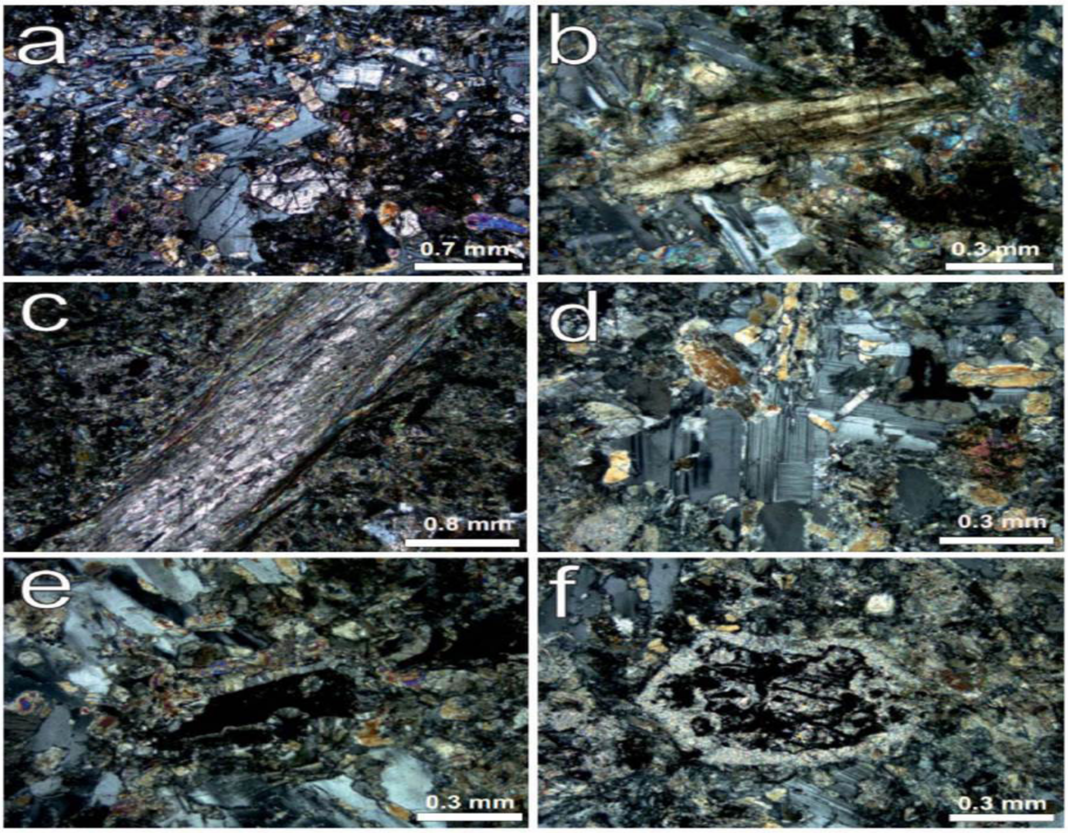

Figure 1: Microphotographs of metadolerite (samples 1319723, 1319724) under crossed polarizers showing e.g. (a) partly altered plagioclase and pyroxene are cut by mineralized tension gashes. (b) bealed fractures are restricted to pyroxene, whereas plagioclase is free from fracturing or(c) mineralized shear fracture filled with actinolite, chlorite and prehnite (at the margins) and with calcite (in the central part). (Jobmann et al., 2016)

The geologic data describing the characteristics of the host rock and of the adjoining rock (e.g. overburden) will be taken into account in the selection of suitable waste packages and consequently in an adjusted emplacement concept. Emplacing waste packages into crystalline rock, which is often fractured and relatively moist, requires waste package material that is resistant in the long term. If a repository is located in a salt formation, the host rock itself will provide the long-term isolation of the waste. Consequently, the requirements for the waste package material are less stringent. The heat conductivities of the various types of rock differ strongly. The decay heat of the emplaced radioactive waste has to be dissipated by the host rock without any negative impact on the mechanical stability and tightness of the entire geologic structure. This simplified consideration of several host rock characteristics, however, shows the importance of precise and comprehensive prognosis and analysis of the host rock properties in order to be able to select a suitable repository concept.

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Design principles and approaches for radioactive waste repositories

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Almost every nation generates radioactive waste. For those nations with a nuclear power program the waste generated is predominately a result of energy production. However, even nations without nuclear power facilities possess radioactive waste generated from other applications of nuclear technology, including industrial uses, research and medical applications. Over the past several decades significant experience in disposal of radioactive waste has been gained. Numerous facilities have been constructed and operated in many Member States and disposal solutions for most waste forms and classes are available or have been developed to an advanced state. Experience gained from these activities has shown that all radioactive waste programmes evolve through the same basic programmatic steps from initiation through to final closure. Based on this experience, the International Atomic Energy Agency (IAEA) has developed a technical publication intended to provide the Member States with an overview of fundamental design principles and best practice approaches to develop repository design solutions.

The development of a repository design has been shown to typically progress and iterate through six major design stages (Fig. 1). Each design stage is marked by an assessment of the overall safety during both the period of repository operations as well as the long-term safety of the site. An initial generic design can be used to assess various strategies for disposal of a specific inventory prior to acquisition of a site. This stage can be used to define the scope of the task and develop the necessary organizational capacities and define future capability needs. Once a decision has been taken, generally at a governmental level, to begin a site selection process it will become necessary to develop a conceptual design or set of conceptual designs. This information together with input from involved stakeholders will be used to facilitate a siting decision. With a site selected the licensing process for the repository can be initiated, and the original conceptual design further developed into a more detailed technical design integrating site-specific data. The goal of this stage is to develop a design that can sufficiently demonstrate the capability of the site to safely isolate and contain waste and thereby support a licensing decision.

Assuming the facility design has met all licensing demonstration requirements and a license is issued to allow construction, the next design stage is initiated. The detailed design translates the licensed design into a constructible facility. The stage is ultimately completed with the commissioning of the repository.

However, the design process does not conclude with the commissioning and operation of the repository. Optimization needs can be expected, and often additional disposal capacities will be required, following a phased disposal approach. At a minimum the design will need to be maintained to ensure that all changes initiated after commissioning are properly planned and documented. A complete understanding of how the repository has developed will be needed at the end of operations to support closure. The design for closure generally begins early in the overall design process because to obtain the license to construct, the licensee must demonstrate that the facility can be safely closed at the end of operations. Often a construction license will require development of demonstration tests to be constructed and studied in parallel to the disposal operations. At closure a specific design for closure will therefore be required that incorporates the knowledge gained throughout the operational phase into a defensible design that ensures the long-term safety of the repository far into the future.

In implementing each of the design stages international experience has shown that certain guiding principles, when followed, best support the successful implementation of the design project within the disposal programme:

- At every level, and at each step, design requirements can be determined that will drive design decisions. These requirements can be defined either at a high level, for example stakeholder defined requirements, or at more articulated lower levels.
- Every repository design by the nature of the long-term requirements placed upon it, must incorporate a multiple, barrier concept that ensures defence in depth in order to provide the level of safety needed over the time frames involved.
- Because of the long time-frames and hazards involved, repositories should be developed, following a robust design approach that makes use of safe, reliable, available, and maintainable technologies.
- Reliance on new technologies should be avoided or minimized and where used, exhaustive testing will be required to demonstrate its reliability.
- The design process is by nature an iterative process, even within a design stage, numerous iterations will be required in order to optimize the design to both the found site conditions as well as changes in understanding of the waste inventory.
- Maintenance of the design’s integrity is essential throughout the iterative process. Documentation of decisions affecting the design and how these are translated into the design must be maintained in order to ensure a transparent and traceable and thereby defensible design.
- A transparent and traceable design demonstrates to stakeholders, including the public, that their concerns and requirements have been met in the repository and that it will accomplish its mission meeting all safety requirements.

– Finally, because a radioactive waste repository deals with nuclear materials which may in turn be subject to international treaty or could otherwise pose a security if misused, the design of a repository must incorporate arrangements for nuclear safeguards (activities and equipment used to verify that nuclear materials are not being diverted to military use) and security (physical protection, personnel security and information technology security).

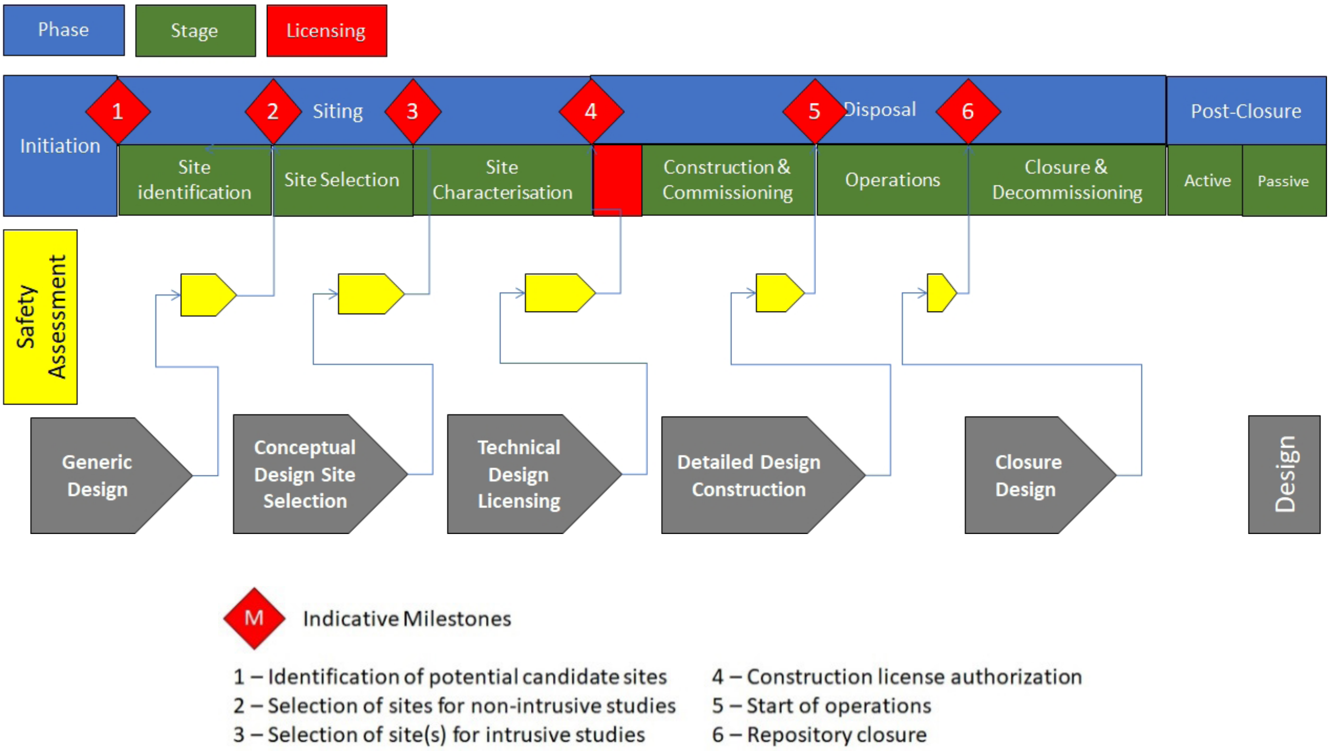

Figure 1: Generic repository programme life cycle and associated design stages aligned with indicative project milestones.

Stages of R&D program development for the underground research facility

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This report presents and refines the main scientific and technical milestones in the development of Russian underground research facility (URF) project during last 5 years.

In 2016, the Russian Federation formally completed the site selection process by issuing a license for the placement of site-specific URF: the Yeniseysky site located in the Krasnoyarsk territory and belonging to the Nizhnekansk granitoid massif was recognized as potentially suitable for disposal of high-level radioactive waste (HRW).

In the same year, the head of the state management body in the field of radioactive waste management (Rosatom state Corporation) approved the "Strategy for the development of RW deep disposal facility" (New documents, 2018), the first three phases of which involve the construction of URF and performing researches necessary to issue the Safety case.

Currently, the first (preparatory) phase of the strategy is being implemented. In accordance with it, in particular:

– construction of surface facilities at the site is going on;
– the developed integrated R&D program is being refined concerning surface pre-excavation investigations, investigations during the excavation, experiments during the operational phase of the URF;
– the developed integrated R&D program is being performed according to surface investigations.

The integrated R&D program is organized so as to make the obtained results provide arguments for safety case and building confidence, most of which are based on predictive numerical modeling. Thus most in-situ and laboratory studies are finally oriented to provide model's parametrization and verification base. The other objective of in-situ investigations is to justify the RW disposal operations (such as, for example, disposal boreholes drilling, optimal according to non-disturbance of the host rock excavation, grouting, RW transportation).

The basic R&D program containing main directions of investigations was created taking into the account different kinds of requirements (comments of regulator, needs of computational models concerning parametrization, etc). It is structured in matrix form: the columns are attributed to components of disposal facility (RW, EBS, geosphere, equipment, biosphere) and lines – activities (monitoring, in-situ investigations, laboratory studies, development of technologies, modelling). Each matrix node gets directions of investigations which are supposed to be performed to study current component by current activity. The same directions can be present in several nodes (for example, hydrogeology and geochemistry refer to both monitoring and in-situ investigations of the geosphere). Directions form tree structures of unique studies (or groups of studies). Separately from matrix structure are activities accompanying the project, among which the key one is development and maintenance of the knowledge base (Svitelman et al., 2018).

The following step in development of R&D program deals with arrangement of the sequence of research, their relationship to each other, as well as links with certain stages of the life cycle of the URF (preparation to excavation, excavation, operation). The closure of site-specific URF is connected with the closure of DDF if nothing goes wrong.

Currently the most intensive activities are devoted to planning the detailed exploration of the site both from the surface (using the boreholes (including deep ones), deployment of the integrated monitoring system, performing laboratory studies, preparations for numeric modeling and structuring project accompanied knowledge base) and during excavation.

The main purpose of investigations during excavation is to replenish a set of knowledge on structure and properties of the host rock as well as water flow in the massif (Gupalo et al., 2019). They include geological documentation of exposures, fracture mapping, rock and water sampling, measurement of water inflow in fractured zones. Investigations can be assigned according to the level of details and to required timing to the following types: (1) regular survey – performed at each sinking cycle; (2) interval survey – performed at special positions within fracture zones detected by advanced drilling; (3) investigations in special rooms equipped on the shaft and technological mine openings. Additionally, one should select positions for rooms where in-situ experiments are to be held.

Currently all investigations planned in URF are under replenishment of their goals, expected results, descriptions of sequences during performance, identifications of required conditions, equipment, time schedules (Abramov et al., 2019).

It was already mentioned above predictive modeling is one of the main tools to obtain long-scale safety estimates and as well it is the main consumer of in-situ and laboratory experiments. Development of a model starts when there is lack of specific data on the specific object for parametrization. Thus, firstly models use data on analogues and from literature. Results of experiments (obtained and treated) allow to calibrate models as well as to verify them.

Yet modeling is useful during design of the experiment: it allows to estimate significance of certain conditions, to optimize positions of sensors and parameters of imitators (Svitelman et al., 2019).

To conclude with, currently the following work is being carried out:

- all types of activities (surveys, long-term monitoring and experimental investigations) required to construct an URF;
- list of in-situ underground experiments – their requirements on positioning and equipment, steps of fulfillment;
- structure of information flows during pre-excavation, excavation and operation phases of URF.

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Geologic disposal options for radioactive waste

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Examination of disposal options for high-level nuclear waste has produced a significant body of scientific research over the past six decades. Each nuclear nation develops its governing principles based on inventory, law, internal geology, and public acceptance. International studies of deep geologic disposal of nuclear waste has led to evaluation of a vast array of geologic disposal options, which provides an opportunity to compare attributes of geologic media for disposal purposes.

Isolation of nuclear waste from the surface environment comprises the principal goal of deep geologic disposal. Concepts have been developed for disposal in a range of rock types including salt, shale, volcanic rock, crystalline rock (granite), and deep boreholes. Not all lithologies possess equal isolation capabilities, but it has been shown that engineered barriers can be devised to overcome geologic shortcomings, if needed. However, great advantage for long-term isolation can be achieved if the geologic setting minimizes dependence on man-made engineered barrier systems.

Suitable host formations for deep geologic repositories would, typically, exhibit favorable characteristics of depth, thickness, and tectonic stability, and geophysical characteristics would limit radionuclide transport. Summarizing these characteristics:

Depth – Geologic isolation is attained by ensuring significant physical separation between the repository and the biosphere, which would provide extensive zones for robust seal systems. Rock strength characteristics would also determine a practical and functional mining depth.

Thickness – Maximal thickness and uniformity of structure are important for operational safety and isolation.

Seismicity – Seismically quiescent regions favor repository design, operations, and long-term performance.

Self-sealing – Lithologies with plastic deformational characteristics reestablish a diffusion-dominated transport system.

Hydrogeology – Low hydraulic conductivity limits possible radionuclide transfer.

Geochemistry – Reducing chemical conditions minimize corrosion, limit radionuclide solubility, and improve sorption.

Geologic disposal studies have consumed many years. In the United States, it is evident that geologic disposal is further away now then when the Nuclear Waste Policy Act was passed and amended in the 1980s. When the nuclear waste imperative is readdressed in the US, policy debates stand to benefit from decades of international studies. National context now emphasizes public outreach and input and will likely require development of a new regulatory framework to judge long-term safety and performance.

Table 1 compares relative attributes for five geologic options. Not all the properties listed have equal impact to waste isolation; however, this type of table is often constructed for general considerations in repository related discussions. Details, characteristics and attributes in Table 1 could be expanded extensively and relative merits will be the subject of continued debate.

Broad option comparisons and attribute summaries garnered from world-wide experience demonstrate with high confidence that a technically adequate repository compliant with national standards can be implemented under a wide range of circumstances.

Table 1. Relative attributes of disposal options

Property	Salt	Shale	Granite	Deep Boreholes	Volcanic
Thermal conductivity	High	Low	Medium	Medium	Medium
Permeability	Practically impermeable	Low	Very low (unfractured) to permeable (fractured)	Very low	High
Strength	Medium	Low to medium	High	High	Variable
Deformation behavior	Visco-plastic (creep)	Plastic to brittle	Brittle	Brittle	Brittle
Stability of cavities	Self-supporting on decade scale	Artificial reinforcement required	High (unfractured) to low (fractured)	Medium at great depth	Artificial reinforcement required
In situ stress	Isotropic	Anisotropic	Anisotropic	Anisotropic	Fractured media
Dissolution	High	Low	Low	Low	Low
Sorption	Low	Very high	Medium to high	Medium to high	Medium to high
Chemical environment	Reducing	Reducing	Reducing	Reducing	Oxidizing
Heat resistance	High	Low	High	High	High
Mining experience	High	Low	High	Low	Low
Available geology	Wide	Wide	Medium	Wide	Low
Geologic stability	High	High	High	High	Low
Engineered barriers	Minimal	Minimal	Needed	Minimal	Maximal

Color Key			
	Favorable	Neutral/Average	Unfavorable

Perspectives on national geologic repository developments

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Over the last several decades, all geologic repository development programs have experienced a challenging existence, with occasional good progress as well as some notable setbacks. Given these individual, and sometimes shared histories, what might the next few decades hold, and what might we share with the next generation of repository scientists and engineers? How will this substantial body of knowledge be preserved and passed on? And what lessons might the next generation of repository developers draw from our collective experience?

This presentation will take a random walk through the international landscape of spent nuclear fuel and high-level waste management, with commentary on the good, the bad, and the ugly of the factors affecting geologic repository development. History and experience can be great teachers, if their lessons are heeded. Every nation's repository development efforts offer a rich mixture of technical, programmatic and sociopolitical insights and lessons. Along with reviewing poignant examples drawn from across the Nordic, North American, Asian and European programs, thought-provoking facts and opinions are offered about what the future might hold regarding geological repository development and options for spent nuclear fuel and high-level waste management.

Retrospect on two decades of German-Russian cooperation in safe management of radioactive materials

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A significant intensification of the German-Russian R&D cooperation regarding radioactive waste disposal has been initiated in May 2001 in Moscow, when the Russian Ministry of Nuclear Energy (Minatom - now State Nuclear Energy Corporation ROSATOM) from the Russian side and the German Federal Ministry of Economics and Technology (BMWi) from the German side defined within the intergovernmental agreement on the peaceful use of nuclear power the main directions for the cooperation between specialists in this new area. Before, this cooperation had been focused mainly on the exchange between Russian and German reactor safety experts.

Under the joint chairmanship of Rosatom and BMWi the main cooperation results have been presented and the main future directives have been updated each two years. Annually German and Russian experts met in several workshops for an intensive scientific exchange and for coordinating the joint efforts in particular regarding safety analysis issues and concept optimization for geological disposal of high-level radioactive waste (HLW). The main German partners of this cooperation were DBE TECHNOLOGY GmbH, the Federal Institute for Geosciences and Natural Resources (BGR) and Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH, as well as universities and institutes in Karlsruhe, Frankfurt am Main and other cities.

At the first stage the work was focused on feasibility investigations regarding I/ILW disposal in permafrost formations at the archipelago Novaya Zemlya. In parallel the range of radioactive waste disposal studies has been extended to the territories of the Nuclear Production Association "Mayak" (Chelyabinsk Region) and of the Mountain-Chemical Combine (State Chemical Complex - SCC, Sheleznogorsk near Krasnoyarsk) and to the Leningrad Region (Sosnovy Bor).

The closest attention in the joint work was given to the long-term safety evaluation of potential radioactive waste disposal sites. In this context, a special role played the progressing project for establishing an underground research laboratory near the SCC with its further possible conversion into a deep radioactive waste disposal facility at the Yeniseisky site of the Nizhnekansky granitoid massif.

Based on Russian primary data German experts implemented in cooperation with their Russian partners several R&D projects financed by BMWi and titled with the following acronyms: ASTER (2003-2007),

WIBASTA (2005-2008), URSEL (2009-2016), SUSE (2016-2020). The project results were published in printed reports either in Russian and German language or in the last years in English.

A wide range of issues was discussed at numerous working meetings, scientific and methodological seminars. From the Russian side, experts from the following organizations took part in their work: State Atomic Energy Agency ROSATOM, NO RAO, NTC YARB, VNIPIPT, VNIPIET, SCC, SCH, PO Mayak, RFYAC-VNIIEF, GNC-NIIAR, NIKIET, Kurchatov Institute, Radium Institute, Atomenergoproekt, Hydrospetsgeology, IBRAE RAS, IGEM RAS, IGE RAS, IFHE RAS, Moscow Engineering Physics Institute, Moscow State University, Tomsk Polytechnic University, etc.

For the German side the joint cooperation provided a unique opportunity for enhancing theoretical investigations by applying them to practical cases and the Russian side benefited from the evaluation of their undertakings and results by international experts.

Conservatively estimated more than 70 joint scientific publications (articles in journals, abstracts in conference proceedings, chapters in monographs, etc.) have been prepared in the past two decades.

Joint study visits to nuclear cycle facilities, for example, to the production area of PAO "PPGHO" in the Transbaikal region, and to German radioactive waste disposal facilities such as, Morsleben, Konrad and to the Gorleben site have been repeatedly conducted.

The positive experience of the past decades clearly demonstrates the need for continuing and developing further the scientific and technical cooperation between Russian and German scientist in solving problems of common interest for both countries in the radioactive waste management area.

Geological and Geotechnical Barriers

Investigation and characterization of geotechnical barrier materials at elevated temperatures

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The Spent Fuel & Waste Science & Technology (SFWST) program under the U.S. Department of Energy Office of Spent Fuel Waste Disposition (SFWD), is focused on research and development activities related to storage, transportation, and disposal of used nuclear fuel and high-level nuclear waste. Within the disposal campaign, various host rock media, which include salt, crystalline, and argillite, are being investigated to advance the understanding and performance of long-term isolation. The ongoing research presented here focuses on characterizing buffer materials proposed for geotechnical barriers within the different media with respect to heat-generating nuclear waste.

Bentonite clay is a primary choice for engineered barrier systems of crystalline and argillite host rock. This is due to its low permeability at saturated states, warranting diffusion as the dominant transport mechanism, and large swelling pressures that promote sealing. In order to predict how well the barrier will function over time at repository relevant temperatures, it is important to understand thermal alteration effects on montmorillonite, better known as smectite, a main constituent of bentonite. One type of thermal alteration is the conversion of smectite to illite, when exposed to elevated temperatures and a sufficient amount of potassium ions, thereby weakening barrier functions. Laboratory studies (Roaldset et al., 1998; Huang et al., 1993; Mosser-Ruck et al., 2001; Velde & Vasseur, 1992; and Inoue, 1983; among others) have tried to reproduce the transformation under a wide variety of conditions. However, the conditions were based on efforts to replicate natural earth processes with commonly found elements, unlike results presented here. To facilitate the conversion of smectite to illite and examine the influence of interlayer cations, illitization experiments on cation exchanged smectite were performed within hydrothermal reaction vessels over one week, two week, and two month timescales. The <2μm fraction of a Na-rich smectite clay was first exchanged with 1M Cs, K, and NH4 salt solutions and further exposed to hydrous pyrolysis using several cation solutions with various solid to liquid ratios at 200°C. Multiple analysis techniques were used to characterize the altered clay and identify extent of conversion, such as XRD, XRF, cation exchange capacity, surface area, and morphology changes by SEM. The pore-water chemistry was also analyzed by ICP-OES to detect any dissolved products and silica content. Results suggest the conversion rate is relatively fast and is dependent on not only the amount of K, but also dissolved silica concentration related to total solid in solution and interlayer cation.

In salt repositories, numerous types of geotechnical barriers have been investigated for decades. Crushed salt backfill is a leading material due to its high potential of developing properties similar to the surrounding host rock. The reconsolidation of crushed salt is dependent on several conditions such as stress, moisture, time, and temperature, which makes long-term performance predictions difficult. To help increase confidence, microscopic investigations were conducted on samples reconsolidated at elevated temperatures (90°C, 175°C, 250°C) to document the deformation mechanisms associated with reconsolidation. Increase of temperature elevates the diffusion rate and dislocation creep mechanisms, thus reducing flow strength and increasing the compaction rates (Ter Heege et al., 2005; Urai et al., 2008). Results show samples exposed to higher temperatures of 250°C experience recrystallization, where 90°C and 175°C samples consisted of mainly mechanical abrasion and minor plastic deformation processes (Mills et al., 2018).

Sealing materials comprised of various types of concrete have also been developed for shafts and drift seals in salt repositories, and thoroughly investigated and monitored from lab-scale to repository-scale. An additional research initiative on seal systems is currently being conducted as part of the brine availability heater test located at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico, USA (Kuhlman et al., 2017). Two types of cement seals, modified salt concrete and Sorel cement, each with embedded strain gauges have been fabricated and installed in a newly drilled horizontal borehole in close proximity to a heated borehole. The strain, temperature, moisture conditions, and brine composition will be monitored throughout the test and cement/salt samples will be collected at the conclusion of the test to observe interactions between salt, brine, and cementitious materials under repository relevant conditions.

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Use of monitoring to obtain data for safety justification

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In 2011 one of key laws for the field of nuclear engineering was enacted – the Federal Law “On the treatment of radioactive waste and on introduction of amendments to certain legislative acts of the Russian Federation” №190-FZ, which postulates mandatory disposal for total volume of already accumulated and arising radioactive waste by establishing an unified national system of radioactive waste management and establishing of a national radioactive waste management operator.

In 2012, by decree of the Government of the Russian Federation, the Federal State Unitary Enterprise “The National Operator for Radioactive Waste Management” (FSUE “NO RWM”) was designated as the National Operator responsible for the disposal of all types of radioactive waste with the main task of creating a system of disposal facilities intended for the final disposal of various classes of radioactive waste.

During the last 8 years FSUE “NO RWM” put a lot of efforts for the decision of accumulated problems, implementation of unified principles, technologies and control system for radioactive waste management (including disposal as its final stage).

According to the legislation of the Russian Federation, radioactive waste of classes 1 and 2 (high level radioactive waste with heat generation, high level radioactive waste and long-lived intermedium radioactive waste) must be disposed into deep geological disposal facilities.

Investigations have been conducted to select a potentially suitable location for disposal of radioactive waste into deep geological formations since the end of the 1990s. Finally, Nizhnekansky massif (Krasnoyarsk region, 6 km from Zheleznogorsk) was preselected for the construction of deep geological disposal facility.

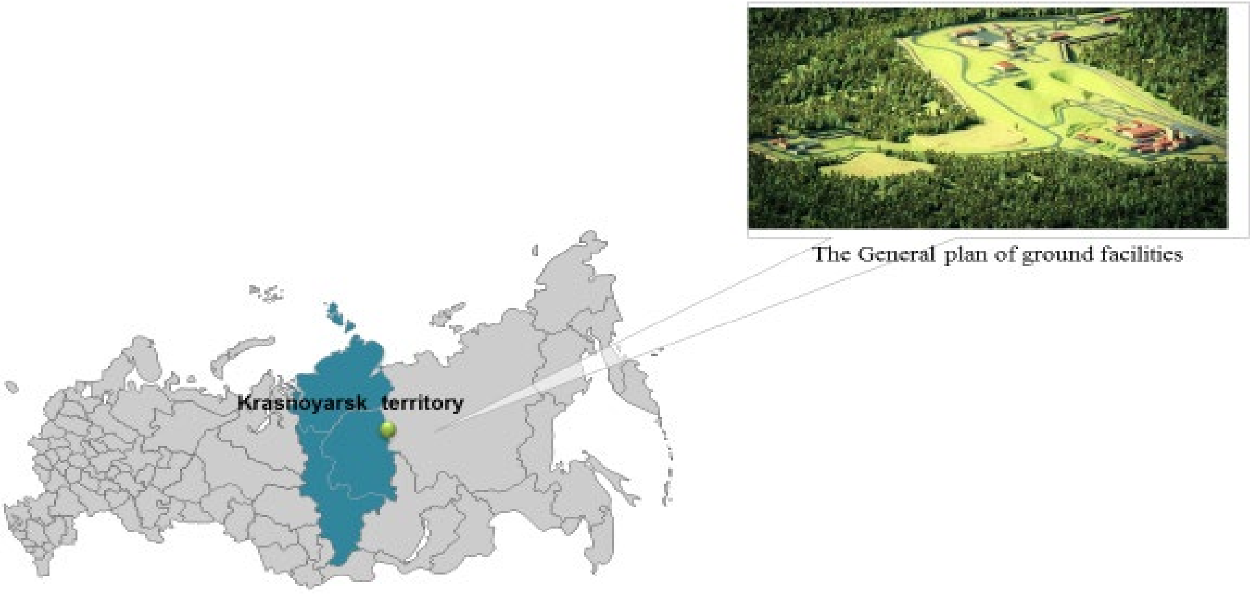

Figure 1: Location of the site.

The Nizhnekansky massif is composed of Archean gneisses and dikes of Proterozoic dolerites.

For detailed site investigations, obtaining site specific data for design development and optimization, justification of technical possibility of design implementation including carrying out a technological cycle of disposal activity, and also for performance of final safety assessment and development of a safety case, the construction of an Underground Research Laboratory (URL) is envisaged.

An important part of research at the stage of systematic site characterization is developing of a monitoring network and monitoring programme.

To date the programs for investigation of the different natural features, events and processes is developed.

The results of water balance studies and results of seismic monitoring are presented in the presentation.

Long-term integrity of the geological barrier salt as a criterion for site selection for a repository of heat-generating radioactive waste

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As a multi-phased comparative process, Germany has started a new site selection procedure to identify a site for a geological repository for high-level radioactive waste. Potentially suitable host rocks are salt, claystone and granite. Finally, only one site will be selected guaranteeing the highest possible level of safety over a period of one million years.

The geological barriers are the main feature of the safety concept. With respect to the site selection process the geomechanics have not only to prove that the mechanical and hydraulic integrity of the geologic barriers are preserved under all given geogen and anthropogen conditions in the long term but also that qualitative differences between sites may exist. From this follows the necessity for (1) a comprehensive understanding of the relevant processes affecting the barrier integrity of salt and (2) a generally accepted scientific approach to demonstrate geological barrier integrity, appropriate to the specific site conditions.

Primarily, the nature, composition and properties of the rocks at the repository sites determine how well these natural barriers protect the environment from radiation. On the basis of natural analogues and from long-lasting practical experiences of gas storage in salt caverns it can be concluded that undisturbed salt formations (bedded and domal salt) are impermeable.

The emplacement of heat-generating high radioactive waste gives rise to temperature changes in the rock mass which itself causes stress and deformation changes, and can diminish the integrity of the geological barrier. Thus, the question arises whether thermo-hydro-mechanical induced stresses, which occur over time as a result of the forecast behaviour of the geologic repository system, could violate the integrity of the barrier during the specified verification period.

The impact of the heat generating radioactive waste on the long-term barrier integrity of the bedded salt is usually analysed numerically based on computer simulations. A potential loss of salt barrier integrity can occur due to the following three main processes:

– mechanical damage due to transgression of the dilatancy boundary which acts mainly in the excavated damage zone (EDZ) – Near field (dm up to several metres)

– convergence and thermo-mechanical induced stress re-distribution. These processes depend on the size of the underground excavations and the impact of temperature induced stresses due to the thermal rock expansion accompanied with extensive up-lift development – Far field (decametre up to several hundred meters)

– fluid pressure driven creation of hydraulical pathways along discontinuities in the micro- and macro-scale in the rock salt (grain boundaries, bedding planes) at fluid pressures > minimal principal stress, i.e. s_{min} – Far field

To evaluate the long-term integrity of the salt barrier, two safety criteria, the dilatancy criterion and the fluid pressure criterion, have to be considered (BMU 2010):

– Dilatancy criterion: The integrity of the rock salt barrier is guaranteed if rock stresses do not exceed the dilatancy boundary. If the deviatoric stress exceeds this boundary, microcracks will form and will cause progressive damage and permeability of the rock salt.

– Fluid pressure criterion: The integrity of the barrier is guaranteed if the hydrostatic pressure of an assumed column of brine extending from the ground surface to depth of the considered location of the salt body contour (e.g. top of the salt formation) does not exceed the minimum principal stress at that point.

Using this approach, in the last decade comprehensive analysis of THM-processes on the barrier integrity related to disposal of heat-generating radioactive waste were performed by IfG and BGR on domal salt (site study Gorleben – VSG, Kock et. al., 2012) and bedded salt (generic study – KOSINA, BGR, 2018). IfG used for THM-coupled 2D modeling the DEM programs UDEC & 3DEC and BGR for the TM-coupled 3D modeling the FEM program JIFE.

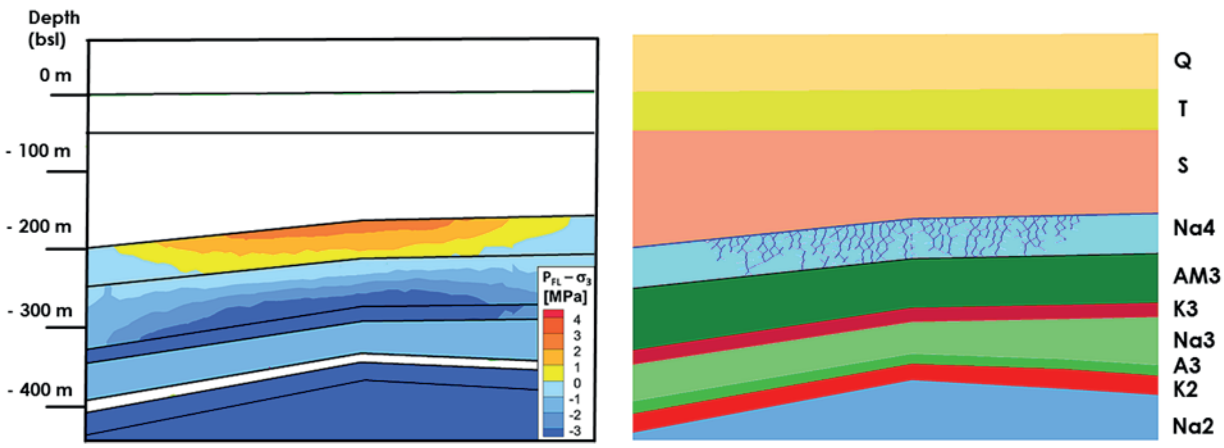

Figure 1: Case study KOSINA - bedded salt; Comparison of violation area of the minimum principle stress criterion (left) and the area, where pressure-driven percolation occured in the coupled thermo-hydro-mechanical calculations (right, dark blue structure) for vertical borehole disposal in a salt pillow structure.

Neglecting the impact of the repository concept, e.g. vertical borehole- or drift-disposal, in both cases, i.e. modeling of the bedded salt and the salt dome, the results of the numerical calculations show the effect of thermal expansion. As a result of the deformation, the horizontal stresses at the top of the salt barrier were reduced and the fluid pressure criterion was locally violated, as shown for the bedded salt in an up to <60 meter thick zone (Fig.1). According to the reduction of horizontal stress, the pressure-driven fluid percolation in the THM-coupled modeling acts in a vertically aligned direction with a penetration depth similar to the violation depth of the minimum principle stress criterion analysed in the continuum mechanical analyses. However, this effect of criteria violation is only associated with the thermal pulse occurring in the first few 1000 years and will diminish with time due to salt creep.

As main result, for both geological situations, at any time no continuous migration paths were found between the top of the salt barrier and the emplacement areas but geological/structural differences are obvious. Regarding the reliability of the outcome, the integrity analysis of the geological barrier by different numerical approaches, model dimensions and constitutive models has yielded comparable results, which substantiates their predictive capabilities.

In summary, appropriate state-of-the-art approaches for integrity analysis of the barrier salt are available but improvements of models and sufficient site specific information are required for a reduction of uncertainties regarding the final site selection.

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3D-Modelling of a generic site for disposal of high-level nuclear waste in claystone in Germany: From geology to THM analysis

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For the safety assessment of deep geological disposal of radioactive waste predictive modelling of coupled thermo-hydro-mechanical (THM) processes on a large scale is essential. Therefore, the whole geological system needs to be characterized and modelled geometrically as well as numerically. This workflow was developed and exemplary applied within the ANSICHT project (Jobmann et al., 2017). In this project, the idea was to use two generic geological models showing typical claystone geology and adjoining rocks situations in northern and southern Germany. According to the Safety Requirements (BMU, 2010), the safety demonstration is carried out for a period of one million years.

A sound basis for a system analysis is a 3D geological site model. For this generic geological models were built up in 3D with defined model units. The model units represent relatively homogenous formations which can regionally be well characterized. The data basis like position, depth, bedding or lithologic properties for the units were mainly derived from the exploration industry on oil, gas, salt and other natural resources. For every model unit representative values were collected. Because the available data for German clay rocks is insufficient, assumptions derived from comparable geological units had to be taken into account. These assumptions are based on the findings from international site investigation programs, for example in the context of repository projects in Switzerland and in France. The parameter collection includes mineralogical and geochemical, petrographic, mechanic, thermic and hydraulic parameters.

In the following, we will focus on the generic model representing a typical geological situation in the North German Basin where potential host rock formations are bedded in a suitable depth under 600 m (Reinhold et al., 2013). The reference region is structured in a crystalline basement, a cover of sedimentary rock of the cenozoic platform and quarternary sediments. The 3D model contains 14 units from the basis Zechstein until the Quaternary. The size of the model is 70 km^2. The Barremian and Hauterivian formation in the Lower Cretaceous represent the host rock formations. They consist of claystones and clayey marl and subordinate micritic lime marl. The hydrogeologic conditions contain a surficial groundwater reservoir of low salinity in unconsolidated quaternary sediments and several deeper aquifers with high salinity water in the Rhätsandstein, Aalensandstein and Hilssandstein (Reinhold et al., 2013).

The generic geological site model, discretised with the software OpenGeo (Hammer et al., 2012), has to be converted into a 3D mesh for numerical investigations. This transformation has been done in two steps. Firstly, the triangulation of the geological site model was checked for consistency and, if needed, slightly modified with help of the BGR software GINA (Kunz, 2015). In a second step, the model was remeshed to satisfy the requirements of the numerical modelling on mesh quality and refinement. The free software GMSH (gmsh.info) was applied to triangulate the surfaces of the geological units and the repository and the free software TetGen (wias-berlin.de/software/tetgen) to mesh the volumes with irregular tetrahedral elements.

The coupled THM behaviour was investigated with the OpenSource Finite Element software OpenGeoSys (https://www.opengeosys.org/) using the created mesh. The model setup is based on one reference scenario. Concerning the geometry and material properties some simplifications for numerical reasons have been done. The model considers THM coupling with Darcy Flow and linear elasticity, neglecting chemistry and gas production. The heat producing waste is modelled as an averaged volume source. The results of the numerical model give a good impression of the temporal development of temperature, pore water pressure and mechanical stresses in the domain and improve the understanding of the total system. An exemplary result is shown in Fig. 1. In order to evaluate the integrity of the geological barrier various criteria, derived from the German safety requirements (BMU, 2010), were investigated. For the fluid pressure criterion, all principal effective stresses must be in the range of compression. For the dilatancy criterion the Mohr-Coulomb criterion is used. The temperature can be evaluated directly from the numerical results. The advection criterion is analysed by evaluating flow paths over 1 million years.

This contribution will focus on the model setup, from geology to numerical analyses, and will give some insights in the interpretation of the numerical results.

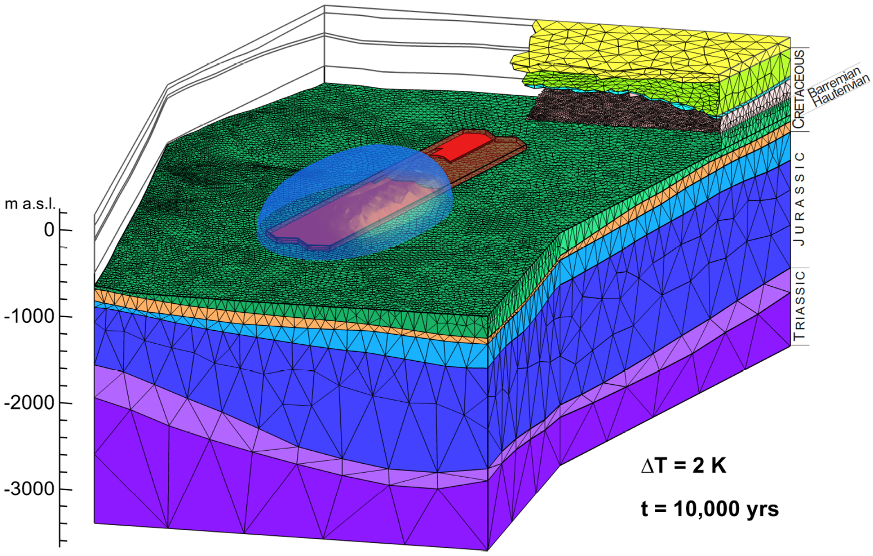

Figure 1: Generic 3D-model of a typical situation in the North German Basin; an isothermal surface of 2 K temperature increase is shown at the repository

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Obituary for Dr. habil. Jörg Hammer

*G. Enste **

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Ladies and Gentlemen,

Dear colleagues,

Dear members of Jörg Hammer's family,

"A career is the backbone of life." This quote from the German philosopher Friedrich Nietzsche applies to few people as well as it does Dr. habil. Jörg Hammer. This scientist, who was highly respected by everyone, was torn abruptly from his productive life exactly one year ago today (birthday 27.02) – at the age of only 61. His sudden death affected us all considerably. I am certain that everyone here in the hall today misses him sincerely.

He stood out not only through his technical expertise as a mining geologist, geochemist and petrologist, but also as someone with a very high degree of integrity. I want to use the opportunity provided by this conference to commemorate his life.

He was born in the small town of Angermünde and grew up in Schwedt on the Oder river. His perceived second home however was the largest country on earth: Russia. This is the country to which he moved after completing his training as a maintenance mechanic in a petrochemical collective, and after matriculation.

He went to the Mining Institute in Leningrad, today's Saint Petersburg, where he studied mining, engineering and geology from 1977 to 1982. And with great success! He gained an award for his degree dissertation on the material-structural investigations of the sulphidic ores of the submarine-hydrothermal chalcopyrite deposit in Gai in the southern Urals.

Back in Germany, the freshly graduated mining geologist worked as an assistant at the Mineralogical Institute of the Bergakademie Freiberg – again with a great deal of success! He was awarded a PhD in 1986 with "summa cum laude" for his thesis on "The geochemistry of selected elements and their binding relationships in the Kupferschiefer of the Sangerhäuser Mulde".

Immediately after gaining his PhD, he moved to the Institute of Geosciences at the University of Greifswald. He was awarded a habilitation scholarship from the Deutsche Forschungsgemeinschaft (DFG) and gained his teaching qualification in 1995 at the TU Bergakademie Freiberg in the field of "geochemistry and petrology".

From 1996 to 2002, he was employed by the state geological survey Mecklenburg-Vorpommern to manage a research project on remediating one of the most serious contaminated sites in the new federal German states – the Schönberg hazardous waste landfill. The comprehensive geoscientific investigations that he carried out there are published in the “Manual on the exploration of the geology beneath landfills and contaminated sites – Quaternary sediments as geological barriers”. These investigations established the scientific basis for the remediation of the landfill.

Having gained this expertise, it was then only a small step to the next major scientific challenge: characterising the host rocks for the final disposal of radioactive waste. Jörg Hammer worked at the Federal Institute for Geosciences and Natural Resources in Hannover from 2002, initially as a scientific employee, and from 2008 onwards, as a head of the unit “Geological and Geotechnical Exploration”. And as a totally dedicated scientist, he made an outstanding contribution to improving our understanding of the barrier properties of all of the host rocks being investigated in Germany: rock salt, claystone and crystalline rocks.

A particular focus of his work was the mineralogical-geochemical and structural investigation of host rocks. He also helped to develop the broad range of methods used for the geological characterisation and assessment of geologic repository formations.

The untiring and committed nature of his work is exemplified by more than 100 publications in peer-reviewed journals, numerous research reports and technical presentations.

In carrying out his work, he maintained close contacts with research institutes. He performed many of his comprehensive structural-geological and mineralogical-geochemical investigations in close co-operation with German universities, such as the University of Frankfurt and the University of Münster. This benefited both sides: BGR profited from external expertise which it did not have to maintain in-house; and the masters and PhD students involved in the research work enjoyed intensive support and assistance from Jörg Hammer in carrying out their research. He even succeeded in convincing some of them to join BGR on a permanent basis.

This is all nothing new to all of you who knew him and respected him. But our colleague Jörg Hammer was not only in demand and appreciated as a reliable, committed and outstanding scientist, but also as a principled and authentic human being. “He was honest and upfront,” is how one of the members of his team describes him. With Jörg Hammer, one always knew where one stood.

Another impression from his team: “One could convince him in discussions on the basis of facts and data, even if he was of a different opinion.” I think this demonstrates his scientific competence very impressively.

He was also always interested in the people involved in the projects: “He always had an open ear for us, whether professionally or privately,” said one employee to me. “We had a great deal of faith in him. He always took an interest in us as people.”

And that was not all: “Helping young scientists was also very important for him.” He therefore did all he could to improve the qualifications of each and every member of his team.

Here as well, his commitment went well beyond the needs of the people working in his team and the BGR. In addition to his research activities, he also lectured for many years in the fields of petrography, mineralogy and geochemistry, at universities including the TU Bergakademie Freiberg and the University of Greifswald. And shortly before his death, he accepted a lectureship for engineering geology at the Institute for Geology at the Leibniz University Hannover.

Jörg Hammer also stood out for his major commitment over many years to the German-Russian co-operation in repository safety research activities, which was almost certainly inspired by his deep love of Russia. The German Ministry for Economic Affairs and Energy (BMWi) had appointed Jörg Hammer on 1st July 2018 as the scientific co-ordinator for the scientific-technical co-operation with the Russian Ministry for Atomic Energy, the national operator for nuclear disposal, as well as Russian research institutions involved in nuclear disposal.

But then fate struck without warning. His serious illness allowed him no time to complete either his life’s work or his life in the way he would have wished. It is now up to his pupils to continue his life’s work as best as possible.

His outstanding expertise, his excellent and comprehensive technical know-how, as well as his sincerity and scientific thoroughness, his exemplary commitment, and his profound sense of responsibility, will be very much missed by us all.

With Jörg Hammer’s death, we have lost an unusually competent and committed scientist and teacher, a caring colleague, and a sincere friend.

We will always hold him in the highest regard and honour his memory.

Dr. habil Jörg Hammer †

Bundesministerium für Wirtschaft und Energie

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