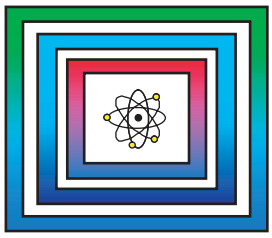
Bundesanstalt für Geowissenschaften und Rohstoffe

Nuclear Waste Disposal in Germany

Investigation and evaluation of regions with potentially suitable host rock formations for a geologic nuclear repository



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1 Introduction

BGR was engaged in 2003 by the Federal Ministry of Economics and Technology (BMWi) to elaborate a study on the distribution of argillaceous rocks as potential host rocks for a nuclear repository for high-level radioactive waste in Germany.

In 1994/1995, BGR had already published one catalogue on salt formations in Germany, and one on crystalline rock formations in Germany, whose findings are still largely up-to-date and valid:

- Final disposal of strongly heat-generating radioactive waste in deep geological formations in Germany – investigation and evaluation of regions in non-salt formations
- Final disposal of strongly heat-generating radioactive waste in deep geological formations in Germany – investigation and evaluation of salt formations.

The more recent investigations into argillaceous rocks, which complement the previous studies, made use of the internationally recognised exclusion and evaluation criteria elaborated by BGR for salt and crystalline host rocks. These were supplemented by the host-rock independent exclusion criteria and minimum requirements formulated in 2002 by the Committee on a Site Selection Procedure for Repository Sites (AkEnd). In addition, BGR also incorporated other evaluation criteria considered geoscientifically important for the selection of the regions.

Presentations on the interim results of the study were made in January 2005 at the “Comparison of salt and argillaceous nuclear repository concepts” workshop (GEIST). The knowledge base on argillaceous rock formations in Germany has since been developed further.

This report summarises the research results on regions in Germany with salt, crystalline rock and argillaceous rock formations potentially suitable as host rocks for a nuclear repository. Preparation incorporated all of the available data from maps, archives and boreholes. No in situ investigations were conducted.

2 Significance of geology for nuclear repositories

The German disposal concept envisages the concentration and isolation of radioactive waste in deep underground geological formations. The safe long-term sealing off of the waste in a repository, and its isolation from the biosphere, are guaranteed by a multi-barrier system consisting of geological and engineered barriers. The geology of the host rock is a crucial factor in this concept.

One of the primary preconditions to be met by a suitable repository site is a favourable overall geological setting, with a suitable geological barrier, because this plays the most crucial role in accordance with the German repository concept. Its effectiveness is to be enhanced by engineered and geotechnical components specially adapted to the geology to form a total barrier system.

3 Properties of potentially suitable host rocks

The international repository concepts primarily look at salt, argillaceous rocks and crystalline rocks to form the geological barriers (Table 1). This report therefore discusses the repository relevant properties of salt, crystalline rocks and argillaceous rocks potentially suitable for hosting a geologic repository in Germany.

Rock salt

Many decades of research work and several hundred years of experience in mining salt in Germany have built up an extensive knowledge base on all of the repository relevant properties of salt and salt formations. Under natural disposal conditions, rock salt is practically impermeable to gases and liquids, has very high heat conductivity, and has visco-plastic properties which cause underground cavities to seal up. These favourable properties make rock salt highly suitable as a host rock, in particular for heat-generating high-level radioactive waste.

Table 1: Repository relevant properties of potential host rocks

Property	*Rock salt*	*Clay/claystone*	*Crystalline rock (e.g. granite)*
heat conductivity	high	low	medium
permeability	practically impermeable	very low to low	very low (unfractured) to permeable (fractured)
strength	medium	low to medium	high
deformation behaviour	visco-plastic (creep)	plastic to brittle	brittle
stability of cavities	self-supporting	artificial reinforcement required	high (unfractured) to low (strongly fractured)
in situ stresses	lithostatically isotropic	anisotropic	anisotropic
dissolution behaviour	high	very low	very low
sorption behaviour	very low	very high	medium to high
heat resistance	high	low	high

favourable property unfavourable property average

Argillaceous rocks

Argillaceous rocks exhibit a wide range of types: from plastic clays, with transitional types, to strongly consolidated and partially fractured claystones. The range of types can be associated with considerable differences in deformation behaviour, temperature sensitivity and rock strength. The known properties of argillaceous rocks which are favourable for hosting repositories are in particular the very low permeability and high sorption capacity. Argillaceous rock formations have proven their long-term effectiveness as geological barriers where they form tight seals, e.g. above hydrocarbon reservoirs.

The concept for nuclear repositories in deep geological formations generally assumes that the formation will exhibit adequate strength for the construction and maintenance of underground drifts. The stability of drifts in argillaceous rocks can only be guaranteed by additional reinforcement and supporting measures. Such measures are particularly complex and expensive in unconsolidated clays. For these reasons, only consolidated argillaceous rocks are considered in this evaluation. Research relevant for repositories, as well as mineralogical, geochemical and geotechnical investigations of argillaceous rocks are currently being conducted in international rock laboratories.

Crystalline rocks

Crystalline rocks (granite and metamorphic rocks) are specially characterised by their high strength and cavity stability, as well as their low heat sensitivity. Their very low dissolution properties are also favourable for repositories. Whilst the permeability of crystalline rocks is usually very low when the rocks are in an unfractured state, they have very much higher to very high permeabilities if they are fractured. In such cases, the escape-proof isolation of the waste can only be guaranteed by also incorporating engineered barriers (containers, bentonite backfill).

4 Nuclear repository concepts in different host rocks

The nuclear repository concepts for rock salt, argillaceous rocks and crystalline rocks differ because of the differences in their rock properties. The nuclear repository concept for rock salt is based on the complete isolation of the waste because of rock salt's impermeability and its ability to creep (Table 1). In general, there is very much more site-specific knowledge on rock salt deposits in Germany compared to deposits of argillaceous rocks and crystalline rocks. Comprehensive knowledge is available on the properties of salt, and investigations can fall back on tried-and-tested exploration methods and techniques (Table 2).

Unlike rock salt, less information is available on argillaceous rock formations, to some extent because of the smaller amount of mining experience. Nuclear repository concepts based on argillaceous rocks as the host formation must ensure that the heat generated by the waste does not cause the formation temperature to exceed a maximum of 100 °C because of the possible changes this may cause to the physical properties of clay minerals, in particular as a result of mineral alteration (the maximum temperature for rock salt by comparison is 200 °C). This temperature restriction means that longer temporary storage times must be taken into consideration, plus a new repository concept with larger areal extension, and a new container concept. Strengthening measures (shotcrete, anchoring and possibly even special construction measures) are necessary in argillaceous rock to protect the underground cavities – this in turn means that consideration must also be given to potential gas generation and associated changes in the chemical environment (Table 2).

Table 2: Main criteria for repository concepts in different host rocks.

Components	*Rock salt*	*Clay/claystone*	*Crystalline rock*
maximum emplacement depth	approx. 900 m	approx. 500 m	500 - 1200 m
storage technique*	drifts and deep boreholes	drifts and/or short boreholes	boreholes or drifts
design temperature	max. 200 °C	max. 100 °C	max. 100 °C (bentonite backfill)
backfill*	crushed salt	bentonite	bentonite
temporary storage period (fuel rods and HAW coquilles)	min. 15 years	min. 30 - 40 years	min. 30 - 40 years
drift reinforcement	not necessary	necessary and potentially very complicated	necessary in strongly fractured zones
container concept	established	new development required for Germany	new development required for Germany
mining experience	very large (salt mines)	almost none	large (ore mining)

favourable property unfavourable property average

* adapted to each type of host rock

All crystalline rock occurrences in Germany are known and geologically mapped. Previous mining experience and the results of geological investigations indicate that it is unlikely that Germany has zones of homogenous and unfractured crystalline rocks large enough for the construction of a nuclear repository mine.

5 Minimum requirements and criteria for repository sites

Because of the crucial significance of geological barriers in geologic repositories for radioactive waste in deep geological formations, priority must be given to geoscientific criteria in the site selection process. The identification of regions was therefore conducted at the first step by applying the following internationally recognised geoscientific and host rock independent exclusion criteria and minimum requirements compiled in 2002 by the Committee on a Site Selection Procedure for Repository Sites (AkEnd):

- Seismic activity: In the repository area, the seismic activities to be expected must not exceed Earthquake Zone 1 according to DIN 4149.
- Volcanic activity: In the repository area, there must neither be any quaternary nor any expected future volcanism..
- The thickness of the isolating rock zone must be at least 100 m and must consist of rock types to which a field hydraulic conductivity of less than 10^{-10} m per second can be assigned.
- The depth of the top of the required isolating rock zone must be at least 300 m.
- The repository mine must lie no deeper than 1,500 m.
- The isolating rock zone must have an areal extension that permits the realisation of a repository (minimum 10 km² in clay stone).
- There must be no findings or data which give rise to doubts whether the geoscientific minimum requirements regarding field hydraulic conductivity, thickness and extent of the isolating rock zone can be fulfilled over a period of time in the order of magnitude of one million years.

When these minimum requirements and criteria are applied, the identification of host rock regions for geologic repositories for radioactive waste in Germany is restricted to salt formations and argillaceous rock formations because they are the only ones which adequately fulfil the requirements for low permeability. Because of their high permeability in fractured zones in Germany, crystalline rocks are deemed unsuitable.

In the second evaluation step, the following criteria are also considered in the selection process because they are considered to be of crucial geoscientific importance for rock salt and argillaceous rocks. Their application led to the exclusion of additional regions:

- The 1995 BGR study defined a minimum thickness of 500 m for rock salt deposits in salt domes (300 m roof sequence, plus 100 m for the underground workings in the mine, plus 100 m underneath the mine). BGR is of the opinion that these criteria are still valid today.
- The 1995 study stipulated a salt roof of at least 300 m above the repository zone in salt domes. The cover rock overlying the top of the salt dome should be at least 200 m thick and consist of horizons impermeable to water.
- The 1995 BGR study assumed that the minimum area required for a nuclear repository in a salt dome should be 9 km^2 for the repository itself. This takes into consideration an outer protective shell with thicknesses of at least 200 m, plus a safety margin of at least 20 % so that adequate reserve areas are available, and to ensure that the safety margins are not jeopardised by unexpected intercalations of anhydrite, potash seams, etc. The 3 km^2 area postulated by AkEnd 2002 is therefore considered to be inadequate.
- Another exclusion criterion included for rock salt was the stipulation that the salt body is not affected by any other mining or drilling.
- Argillaceous rock formations buried to depths below 1000 m are expected to be affected by very difficult rock mechanical conditions, giving rise to very high costs for the excavation and operation of a repository.

Another difficulty in the use of argillaceous rocks at depths > 1000 m is associated with the relatively low heat conductivity of these rocks and the higher temperatures prevailing at such depths. This will lead to considerable technical problems if waste generating large amounts of heat is emplaced. One of the criteria for argillaceous rock formations included in the evaluation was therefore the restriction to depths between 300 and 1000 m below ground level.

6 Host rock formations in Germany

Rock salt

Rock salt formations are known to exist in North and South Germany. They are present in the form of salt domes as well as bedded sequences (stratiform) and occur in different stratigraphic units (Table 3). Figure 1 shows a typical cross-section through a salt dome. The stratiform rock salt deposits have a similar structure to argillaceous rock formations. This is shown in diagrammatic form in Figure 2.

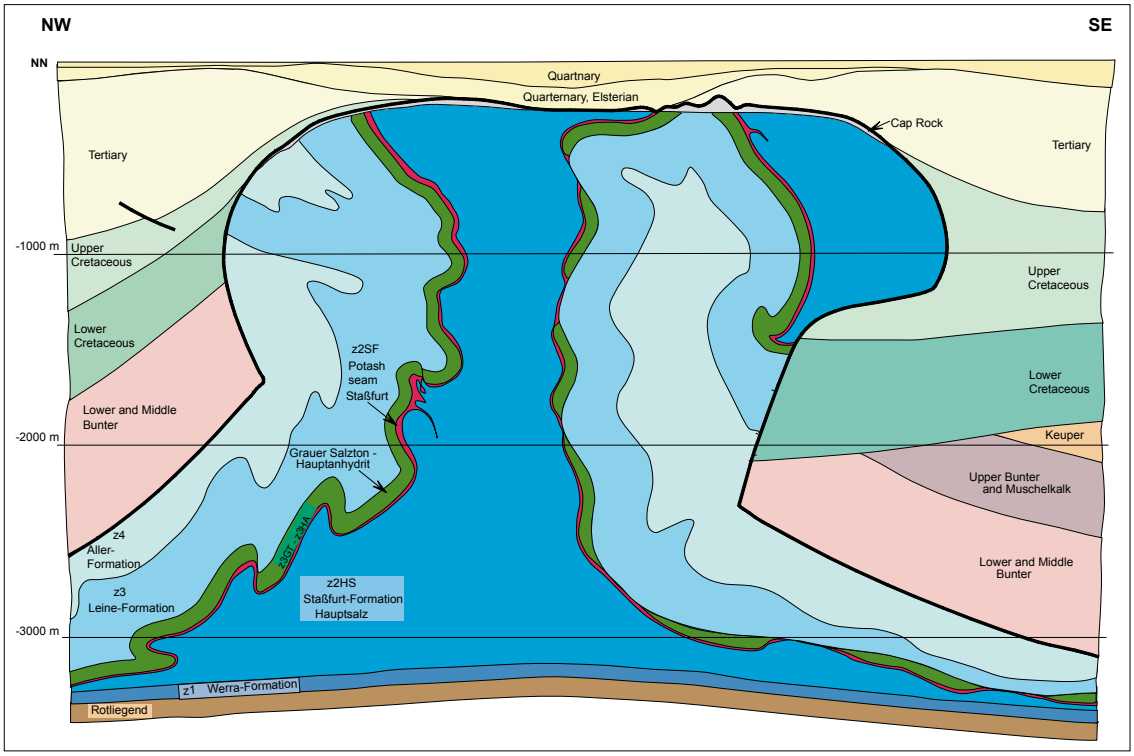


Fig. 1: Typical cross-section through a salt dome, using the Gorleben salt dome as an example.

The following special geological aspects need to be taken into consideration when investigating rock salt deposits in Germany:

- Only the Hauptsalz of the Staßfurt-Formation in North Germany is known to have uniformly good host rock properties throughout, and to form very thick deposits.
- The Rotliegend rock salt which is very thick in places occurs in double salt structures in North-west Germany at the depth specified for nuclear repositories. However, it generally occurs in salt domes with very complicated internal structures. Although the high concentration of clay in the salt-clay mixture known as the “Haselgebirge” improves the otherwise very low sorption capacity for toxins and radionuclides, it also reduces the otherwise good heat conductivity of pure rock salt.

- The stratiform salt deposits (flat bedded) at the southern margin of the Zechstein Basin (in the Lower Rhine Bay, Solling-High, Calvörde-High) can be considered as back-up options with respect to their depths, effective barrier thickness and tectonic situations.
- The stratiform salt deposits (flat bedded) of the Werra district (Zechstein 1) in the Thuringian Basin are not taken into consideration because only narrow homogenous rock salt units with thicknesses > 100 m are present outside of the active mining regions.
- The Zechstein rock salts of the Aller- to Mölln-Formation are too thin to be worthy of further investigation. The same applies to the Upper Bunter, Muschelkalk and Tertiary rock salts. The Keuper salts are not suitable as potential host rocks because of their depth. The Upper Jurassic rock salt has extensive intercalations of anhydrite and claystone, and is therefore classified as not worthy of additional investigation.

In addition to its evaluation of the Gorleben salt dome, BGR re-evaluated the salt domes in North Germany in 1995 on the basis of the available data. This assessment is still valid. According to the selection criteria on which the study was based, four more structures were identified, as shown in Figure 3.

Argillaceous rock formations

Argillaceous rock formations also occur at different stratigraphic levels and geographic regions in Germany (Table 3). When depth and thickness are taken into consideration, argillaceous rocks in relevant positions can be identified in the Tertiary, Cretaceous and Jurassic in North Germany and South Germany. Figure 2 shows a cross-section through a geological structure with an argillaceous rock formation.

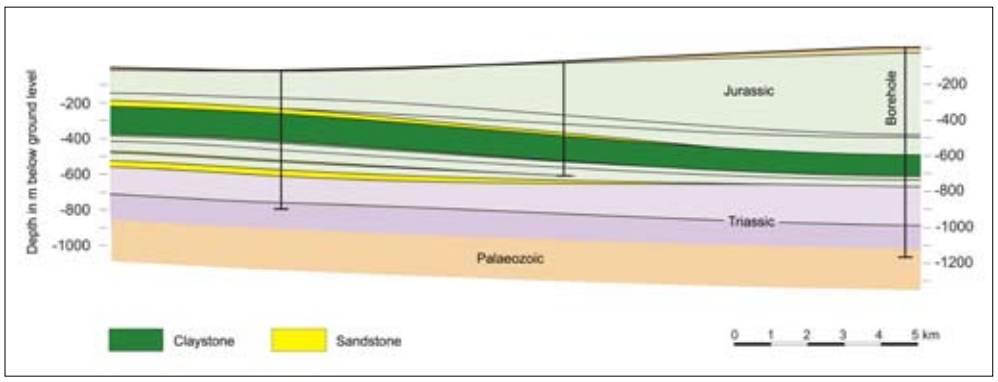


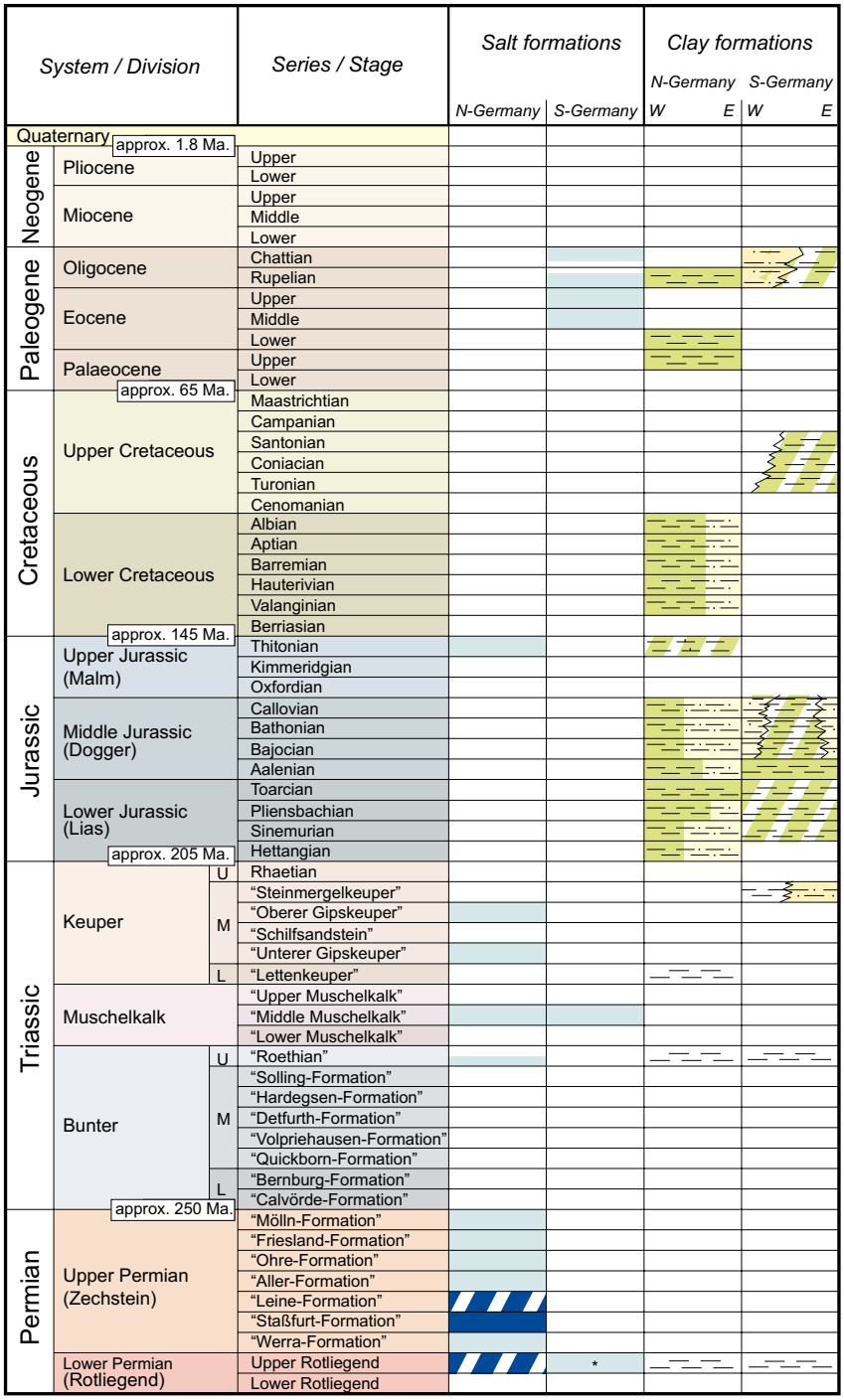
Fig. 2: Typical cross-section through a geological structure with an argillaceous rock formation (dark green).

The following additional restrictions must be taken into consideration when selecting argillaceous rock formations as potential nuclear repository host rocks:

- All of the argillaceous rock formations in the Upper Rhine Graben have been classified as not worthy of further investigation because of partial exclusion by being located in an earthquake zone graded as higher than 1, and because of the tectonic conditions (dense and extensive fault patterns).
- Although the Tertiary clays in North Germany are important hydrogeological barriers, their suitability as host rock is considered to be highly restricted because of their low level of consolidation. They can therefore be important as barrier rocks for a nuclear repository if the overall geological setting is favourable, but they are not taken into consideration for the potential host rock situation evaluated here.
- Because of their significant lithological variability compared to the other argillaceous rock formations, the Tertiary clays and claystones of the Alpine Foreland Basin are difficult to characterise and extrapolate. In addition, most of them have only undergone minor consolidation. They are therefore not investigated further as potential host rocks.
- The potential use of the Opalinus Clay Formation as a host rock is restricted in part of its area of distribution in South Germany by the presence of a major exploited karst aquifer in the overlying rocks.
- Sub-areas of the Opalinus Clay Formation in South Germany are excluded because they lie in an earthquake zone graded as higher than 1.
- Areas with extremely steep bedding in the vicinity of salt structures are classified as not worthy of further investigation because of the difficulty in characterising them and extrapolating the information.

This leaves regions with thick argillaceous rock formations in the North German Cretaceous sequence and in the North and South German Jurassic sequences (Fig.3).

Table 3: Stratigraphic position of rock salt and argillaceous rock formations in Germany.



Salt deposits

- Worthy of investigation
- Limited regional investigation worthiness
- Not worthy of investigation
- * Age of Haselgebirge in the Alps questionable (Permo-Trias)

Clay and claystone deposits

- Formations with high proportions of clay/claystone
- Regional and local distribution of argillaceous rocks with good predictability
- Regional and local distribution of argillaceous rocks difficult to predict
- Formations with high proportions of coarse clastics (sandstones, siltstones)

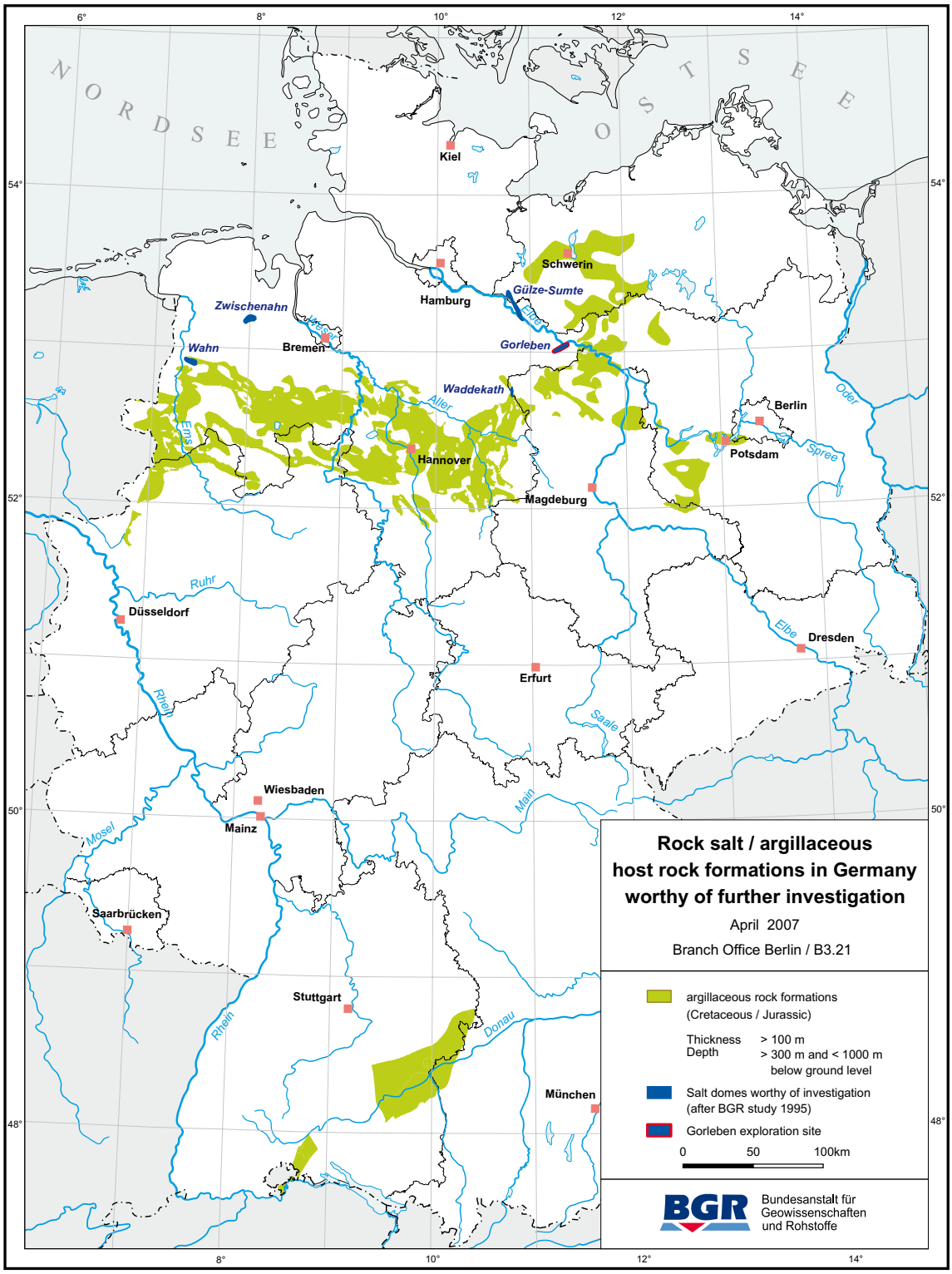


Fig. 3: Map of rock salt and argillaceous rock formations in Germany worthy of further investigation.

7 Summary and conclusions

The selection process for potential host rocks for nuclear repositories in deep geological formations in Germany was based on internationally recognised geoscientific exclusion criteria and minimum requirements, as well as other criteria considered crucial from a geoscientific point of view. Crystalline rocks were dropped from further evaluation because unfractured zones are of inadequate extent, and the fractured zones usually have excessive permeabilities. Deposits of unconsolidated Tertiary clays were also left out because of their unfavourable mechanical properties and the associated complex and expensive engineering involved if they were to be used as host rocks.

The results shown on the location map (Figure 3) shortlists salt domes evaluated by BGR in 1995 alongside the Gorleben salt dome, as well as argillaceous rock formations of Lower Cretaceous age in North Germany, and Jurassic age in North and South Germany. This report was prepared using all of the available data from maps, archives and boreholes.

BGR, Berlin.

Hannover/Berlin, April 2007

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