Water-Conducting Features in a Geologic System Consisting of a Salt Dome and Overlying Unconsolidated Sediments

Klaus Schelkes, Hans Klinge, Friedrich Schildknecht, Jan Richard Weber
Federal Institute for Geosciences and Natural Resources (BGR), Germany

Abstract

In Germany, salt formations have been selected as geologic media for radioactive waste disposal sites. The Gorleben salt dome is under investigation as a potential site for all types of radioactive waste. At the Morsleben salt dome, a repository for low-level waste is in operation. Extensive hydrogeological and geophysical studies have been conducted at both locations for site characterization and long-term safety assessments.

Because rock salt is generally almost impermeable, migration of radionuclides from a repository to the biosphere would only be possible if a fracture system is opened in the salt formation. Suitable methods for detecting fractures are small-scale methods such as borehole radar, geoelectrical measurements and hydraulic borehole tests. Migration paths would follow such fractures into the base of the caprock and proceed from there through fractures in the caprock and/or (at the Gorleben site) a breccia into the overlying sediments. Information on water-conducting features in the caprock can be obtained mainly from boreholes, geophysical measurements and hydraulic tests in boreholes. Long-term pumping tests can be used to determine the connectivity between the caprock and the overlying aquifers of the sedimentary cover. Here, in the sedimentary cover, the density of information obtained from boreholes is sufficient to characterize its hydrogeologic features on a regional scale. Rock samples were used for laboratory measurement of bulk porosity, permeability, grain-size distribution, adsorption capacity, etc. Results of pumping tests form the data base for permeability characterization of the different hydrogeological units. Geophysical borehole measurements help in determining porosity.

As is common in an aquifer system above a salt dome like the Gorleben salt dome, an upper fresh water body is underlain by saline water. Radionuclides that might escape from a future repository would be dissolved in saturated brine. The present distribution of fresh water and salt water, therefore, can provide information for identifying flow paths from the repository to the biosphere. Information from stable isotope analysis helps, for example, to identify connected pathways. Direct information on flow paths can also be obtained from single-borehole tests using radioactive tracers. But groundwater flow and transport models have to be used for a more exact study and characterization of flow paths through this hydrogeological environment. They help in finding acceptable parameters such as dispersion values and allow all the uncertainties in the structural description and the site specific data to be taken into account.
1. Introduction

In Germany, sedimentary rocks and salt formations have been selected as geologic media for radioactive waste disposal sites. Most investigation activities are at two salt dome locations. The Gorleben salt dome is under investigation as a potential site for all kinds of radioactive waste. The repository will be constructed within the salt dome. At the Morsleben salt dome, a repository for low-level waste is in operation. Extensive hydrogeological and geophysical studies have been conducted at both locations for site characterization and long-term safety assessments. Numerous experiments have been carried out to obtain information about the hydrogeology, hydraulic and transport parameters as well as groundwater movement. Mainly results of the investigations at the Gorleben site will be discussed, together with some results from the Morsleben site.

The geology of the Gorleben site consists of the Gorleben salt dome, its fractured caprock and overlying unconsolidated sediments. Rock salt in salt domes is generally almost impermeable. Only in brittle layers, like anhydrite, can fractures be found (see Fig. 1). The caprock on top of the salt dome is considered to be a fractured, in some parts karstic aquifer with fissures filled mainly with clay and silt. One important feature in the caprock at this site is a breccia consisting of caprock material embedded mostly in a matrix of sand, clay and sand cemented with gypsum and salt. Above the salt dome and caprock, Tertiary and Quaternary sediments form a multiple aquifer system up to 300 m thick. Low-permeability layers of boulder clay, silt, and clay are intercalated in the aquifer system.

![Core sample with boundary between rock salt (left) and anhydrite (right)](image)

2. First subsystem: the salt dome

The first subsystem for possible radionuclide transport is in the salt dome. Because nearly no interconnected porosity is found in the salt itself, pressure-driven fluid flow is almost impossible. The isolation potential of a salt dome is only reduced in
- domains containing fluids in pore networks (brine pockets),
- fractured domains, which might exist in brittle evaporites (anhydrite), and
- domains that are disturbed due to mining activities (excavation-damaged zones).

In salt domes, an initially evenly distributed brine, a natural component of salt structures, is therefore found in brittle layers, pore networks and at boundaries between layers with different deformation behaviour. The composition of the fluids found for example in the Gorleben salt dome show that they are syngenetic or diagenetic fluids originating from the salt formation itself.

Natural advective transport can generally take place only in pore networks and fractures in brittle evaporites in the dome of which the anhydrite is the most important. The fractures or fracture systems are typically several meters to tens of meters apart. Suitable methods for identifying water-conducting features in salt domes are small-scale methods such as hydraulic borehole tests, geoelectrical measurements and borehole radar. The latter methods use the fact that in domains that contain brine the dielectric coefficient and the electrical conductivity are much higher than in dry rock.

Geoelectrical measurements detect fractured zones by localizing areas of high electrical conductivity. They can be performed using electrode arrays in boreholes or electrode profiles in mine galleries and rooms [11]. The use of three-dimensional combinations of electrode arrays and profiles allows the application of tomographic modes to determine the spatial distribution of the water content. The spacing of the electrodes is adjusted to suit the required resolution and the volume of the investigated rock. Geoelectrical measurements provide information on the rock volume penetrated by the electric current, e.g. the locations of boundaries where the electrical properties change. Fractures, which might exist in anhydrite layers, can be detected by these measurements if they are at least partially filled with brine. But since information on the areal extent of fractures is of more interest than their volume, electromagnetic measurements are more suitable.

Figure 2: Vertical section with reflector horizons measured with borehole radar in a shaft in a salt dome (from [1])
Water-filled fractures that are not intersected by a borehole can be detected with electromagnetic reflection measurements or borehole radar. A high-frequency electromagnetic wave is transmitted into the rock. Boundaries between layers with different dielectric coefficients partially reflect the wave. The reflected signal is received and the distance to the heterogeneity calculated from the travel time of the wave. The transmitting and receiving antennae can be located in various configurations in boreholes and galleries depending on the extent of the rock volume investigated and the location and arrangement of heterogeneities. Borehole radar can locate major structures in rock salt at a distance of up to 200 m. An example of the interpretation of a borehole radar record is shown in Figure 2. [1]

Hydraulic borehole tests provide information on the extent of fractures or fracture systems, possible connectivity between fractures, as well as fracture parameters such as permeability. In tight rock salt they were performed as pulse tests, in highly permeable domains as constant rate tests. Permeable domains are normally restricted to the anhydrite layers, as can be exemplified by the results of borehole tests (Fig. 3) and also directly by drill cores (Fig. 1). In addition, hydraulic borehole tests are helpful in determining the extent of the excavation-induced damaged zone around galleries and rooms. From the available data on the fractures in boreholes and drifts, conclusions can be drawn about their orientation, frequency and mean extent.

![Figure 3: Results of hydraulic tests in a borehole showing the change in permeability from rock salt to anhydrite](image)

3. **Second subsystem: the caprock**

Local information on water-conducting features in the caprock, the second subsystem, can be obtained mainly from boreholes, geophysical measurements and hydraulic tests in boreholes. Analysis of rock samples from the boreholes provided information about fissures, fractures, karstic cavities and fill. More borehole testing and geophysical logging has been carried out on the caprock at the Morsleben site than on that at the Gorleben site. Acoustic imaging, involving high-resolution acoustic scanning of the borehole wall, allows the fractures and fracture systems to be located in space and their orientation and aperture widths to be determined. Acoustic imaging tools (televiewers) are used in the uncased boreholes to locate these features in the caprock.
Fluid-logging provided the initial data on the hydraulic properties of fractures and their fluid content. It is only possible to obtain in-situ information on their hydraulic efficiency by localising fractures. With this method low permeability fractures that are detectable by no other method can be found, precisely positioned and characterised. In a fluid-logging experiment, the water in a borehole is completely exchanged for water with a very low electrolyte concentration to guarantee a high contrast in the electrical conductivity between the water in the borehole and the water in the surrounding geological formation. The water level in the hole is lowered and the level kept constant by continuous pumping. A flow of formation water into the hole is induced. The water enters preferentially by way of fractures and moves upwards towards the pump, which is positioned near the water level. The movement of the water inside the hole is repeatedly monitored using salinometer logs. The locations where formation water enters the borehole from fractures and karstic features can be determined by running electrical conductivity logs in the borehole. Figure 4 shows the measured and calculated electrical conductivity as a function of depth at different times during a fluid logging experiment. Further interpretation of the velocity distribution of the flowing water provides an estimate of the transmissivity of fractures and the salinity of the water entering the borehole.

The results of acoustic imaging and fluid logging were used to define intervals for hydraulic testing, to determine fracture transmissivity and estimate fracture connectivity. Fractured zones identified in the uncased boreholes were isolated with packers for hydraulic testing. Various kinds of tests are used to provoke a reaction of the rock within the packer interval in the form of pressure or flow changes. Models simulating the reaction of the rock provided reliable information about the transmissivity and the extent and connectivity of identified fractures or fracture zones.
Information on the connectivity of the fractures on a more regional scale is obtained from long-term pumping tests. At the Gorleben site, such tests were carried out in the sedimentary cover to study the connectivity between the different aquiferous zones. The results showed that the caprock, especially the breccia, and the overlying aquifers were connected. As an example, in Figure 5 the hydrograph of an observation well with a screen in the caprock shows the reaction of the water level on three long-term pumping tests carried out in 1984 and 1985. The mean permeability between the pumping location and the observation wells in the caprock was calculated. The caprock and the surrounding sediments must, therefore, be considered as a single aquifer system.

4. Third subsystem: the sedimentary cover

At the Gorleben site, the third subsystem, the sedimentary cover above the salt dome and cap rock, consists mainly of unconsolidated Quaternary and Tertiary sediments, such as sand, silt, boulder clay, gravel and clay, and is up to 300 m thick. Most of the data for characterizing this subsystem originates from more than 170 exploratory boreholes drilled to the base of the aquifer system, sometimes down to a depth of 450 m, and from about 400 observation wells installed in an area of about 380 km² [3]. The density of information obtained from these boreholes is sufficient to characterize the hydrogeological features on a regional scale (see Fig. 6). Moreover, a high-resolution reflection seismic survey was carried out above the salt dome to obtain detailed information.

Seen at a scale of several tens of meters to several kilometers, the Gorleben area is characterized by the predominance of aquifers with intercalated aquitards and aquicludes. The deposits comprise subhorizontal layers with different hydrogeological properties a few meters to a few tens of meters thick and a lateral extent of several tens of meters to a few kilometers. The extent of homogeneous bodies is related to the frequency and extent of facies changes. In the Quaternary, homogeneous bodies tend to be smaller than in the Tertiary. [5]

Figure 6: Hydrogeological and hydrochemical cross section along the buried channel at Gorleben (TDS = Total dissolved solids)

The base of the hydraulic system above the Gorleben salt dome and in the surrounding area is formed by Eocene and Oligocene low-permeability clays over 100 m thick. In the same area the overlying Miocene lignite sands form a regionally significant aquifer, which is overlain by the low-permeability Hamburg Clay. The Gorleben salt dome is crossed by a N–S buried channel, which was
formed during the Elsterian Ice Age (see Fig. 6). Tertiary clays, which originally covered the salt dome, were eroded in the center of this channel. The base of the channel fill consists of highly permeable sand and gravel, which in some places lie directly on the caprock or even the Zechstein salt itself. They are overlain by the low-permeability Lauenburg Clay. The inhomogeneous sequence of Weichselian and Saalian deposits consists of a vertically and laterally highly variable sequence of gravel, sand, silt, boulder clay and clay, which can be generally viewed as a heterogeneous aquifer. Hydrogeologically, the sedimentary cover in this area can be subdivided into an upper and a lower aquifer system. Lignite sands and Elsterian channel sands north and south of the salt dome are hydraulically connected, forming the lower aquifer system. The Weichselian and Saalian deposits form the upper aquifer system. The two systems are separated by an aquitard consisting of the Hamburg Clay and/or the Lauenburg Clay (Fig. 6).[3, 4]

4.1 Determination of the hydraulic parameters in the sedimentary cover

Bulk porosity, permeability, grain-size distribution, adsorption capacity, etc. were determined on rock samples in the laboratory. Hydraulic conductivity was derived from the grain-size distribution using various empirical formulas. Local permeabilities at the depths of the screens in the observation wells were derived from single-well pumping tests. Long-term pumping tests were carried out in four different areas, especially in the deeper parts of the aquifer system. The results provided permeability values on a more regional scale (as well as storativity values and leakage coefficients). Together with data from a regional data base, these values form the data base for the permeability characterization of the different hydrogeological units (means values and confidence limits).

One aim of geophysical borehole logging in the sedimentary cover was to determine porosity. Several lithology logging tools are sensitive to porosity, but compensated density devices are generally considered the best method available. The density probe emits gamma rays into the wall-rock formation and the intensity of the backscattered signal, measured by the same probe, is recorded. It correlates with the bulk density of the formation, a quantity that can, making certain assumptions, be converted into formation porosity. Generally, density logs were therefore used to determine porosity. Only when the results were dubious, were neutron-logs used instead. Porosity determined from the density log is the total porosity, the overall porosity which includes the hydraulically ineffective pore space in clayey parts of the sediments. To derive a quantity that is more closely related to the hydraulically important effective porosity, a correction is applied to the data to allow for the proportion of clay present. The clay fraction is determined from the intensity of the natural gamma radiation of the formation (gamma-ray log) because the natural gamma radiation of sedimentary rocks correlates closely with the proportion of clay in the sediment. Using this procedure, profiles of clay-corrected porosity were prepared and serve as an approximation to the effective porosity (see e.g. Figure 7).
Diffusion data, which is important for determining transport in low-permeability layers, can be derived from isotope analysis of rock samples. But site-specific dispersion data are difficult to obtain – except from laboratory experiments, which are valid only at the laboratory scale. Normally, models were used to find acceptable dispersion values by comparison of model results with measured salinity data. The model calculations showed that longitudinal dispersion lengths are in the range of several tens to several hundreds of meters, whereas very small transversal dispersion lengths (down to zero meters) must be assumed [9]. Sorption data for all relevant radionuclides were derived from laboratory experiments on over thirty different natural sediment-groundwater systems. Nearly all known combinations of sediment-groundwater systems were investigated in these experiments and many parameters were studied, e.g. redox potential, pH, radionuclide concentration, possibility of forming complexes and colloids. The clay content of the sediment and the salinity of the groundwater were shown to be important influences on the sorption behavior of the water-conducting features. However, it is generally not possible to carry out in-situ field experiments to obtain dispersion and sorption data owing to the long time span needed for such experiments, and/or owing to environmental regulations.

4.2 Identification of transport pathways in the sedimentary cover

As mentioned before, long-term pumping tests were also used to identify the connectivity between different aquiferous zones in the sedimentary cover. It was shown, for example, that the deep Elsterian channel aquifer above the Gorleben salt dome is connected to the Tertiary aquifer surrounding the salt dome and to a sand layer filling a pre-Elsterian subrosion depression in the western part of the salt dome. However, no connection was identified between the upper and lower aquifers, which are separated by a heterogeneous clay-rich sequence. This demonstrates that the value of such long term pumping tests is limited. Although no drawdown was measurable within the time frame of the pumping test, this result is no proof that zones of relatively high permeability are absent from a heterogeneous clay-rich sequence of this kind. This is especially true if contaminant transport is considered over very long periods as in long-term safety studies. In this case, better information on possible pathways can be derived from chemical and isotope studies.

Some information on pore-water density distribution can be derived from geophysical borehole logs, particularly resistivity logs. The electrical conductivity of sedimentary rocks and inversely the resistivity depend on porosity, electrical conductivity of the pore water as well as on the electrical conductivity of the rock matrix. In the sediments investigated, which were mainly composed of clay and sand, the conductivity of the matrix varies with the clay/sand ratio. Therefore, formation resistivity log, gamma-ray log and compensated density log were used to determine the groundwater conductivity and hence salinity immediately around the boreholes as a function of depth. Calculation of the electrical conductivity of groundwater is based on a
A physical model of a sedimentary rock, the so-called parallel conductivity model. This model was used in a form which takes variable clay content into account [2]. The parameters are the total porosity and empirically determined inner resistivity factors for clay and sand. Finally, electrical conductivity of the groundwater is transformed to water density using an empirical relation between water conductivity and density derived from laboratory measurements on water samples [6]. Figure 8 shows the density of water samples from an area above the Gorleben salt dome versus depth together with density logs of the groundwater in the immediate surroundings of three wells located in that area.

Extensive physicochemical, hydrochemical and isotopic data have been analyzed and provide a basis for determining the distribution of density and the various chemical constituents and isotopes as spatial functions. These data were combined with the results of the geophysical borehole logging. Additional geoelectrical investigations were carried out from ground level to complement the data from chemical water analyses and geophysical borehole logs.

As is common in an aquifer system above a salt dome, the fresh groundwater body in the Gorleben area is underlain by saline groundwater [3]. Figure 6 shows the freshwater/saltwater distribution above and around the Gorleben salt dome in a cross-section and gives an impression of the spatial variability of fresh water and saline water in a heterogeneous groundwater system. The thickness of the freshwater body varies considerably from place to place. The fresh water has a low salinity of about 200 mg/L, max. 500 mg/L, which is independent of depth. Saline water is found locally in shallow aquifers.

The groundwater in the Gorleben erosion channel, a buried erosion channel above the Gorleben salt dome, is highly saline because here Quaternary sediments are in direct contact with the Zechstein salt. Dissolution of salt can take place in this contact area, which also represents a potential zone for migration of radionuclides into the hydrosphere. In a salt dome environment, radionuclides that might escape from a future repository would be dissolved in saturated brine. The present distribution of fresh water and salt water, therefore, can provide information useful for identifying flow paths from the repository to the biosphere.

\[\text{Figure 9: Groundwater salinity at the base of the lower aquifer system indicating saltwater flow paths}\]
The distribution of the salt concentration at the base of the lower aquifer system is shown in Figure 9 [4]. The salt concentration within the Gorleben erosion channel is generally about 200 g/L in the area of the salt dome. The zone of high salinity includes the northern part of the erosion channel and the adjoining area northeast of the salt dome. In contrast, the base of the lower aquifer is found to have a relatively low salinity (15 – 30 g/L) south and northeast of the salt dome, above the western part of the salt dome (where the Zechstein salt is overlain by clay) and in the southern part of the Gorleben erosion channel. This indicates that saltwater flow in the Gorleben erosion channel is towards the north, whereas there is no significant saltwater flow towards the south. As the aquifer of the Gorleben erosion channel north of the salt dome is in hydraulic contact with the lower Tertiary aquifer of the rim syncline north of the salt dome and since it has a higher density than fresh water, the salt water collects in the center of the rim syncline at the base of the lower aquifer system. Information on flow paths can be derived not only from the distribution of the highly saline water but also from other hydrochemical data, for example the salinity distribution at the surface indicates the positions of possible outflow areas.

Chemical analysis of groundwater and trace element analysis are important for characterizing water-conducting features [7]. At Gorleben, stable isotope analysis (oxygen and deuterium) of water samples indicate under what climatic conditions the groundwater has been recharged. Figure 10A shows the oxygen isotope composition versus groundwater salinity. In general, the fresh water was formed under warm climatic conditions, while saline water has a cold-climate signature except for a group of brines from the deepest part of the Gorleben erosion channel, which have a warm-climate isotope signature. Radiocarbon values show the same trend (Fig. 10B). Freshwater samples have the highest values, while in saline water samples $^{14}$C decreases with increasing salinity except in the case of brines with a warm-climate $^{18}$O signature. These samples have relatively high $^{14}$C values. In general it can be concluded that the fresh water in the Gorleben area was formed during the Holocene while the saline water – except for the samples mentioned above – was formed during the Pleistocene under cold climate conditions [8]. This information helps, for example, to identify connected pathways. On the other hand, the information obtained from chemical and trace element analysis is limited by the fact that the saline water composition shows very little variation, since saline water is generally formed by dissolution of rock salt.

![Figure 10: $^{18}$Oxygen (A) and $^{14}$Carbon (B) contents of groundwater versus TDS (after [8])](image-url)
Direct information on flow paths can be obtained from single-borehole tests using radioactive tracers. They indicate flow directions and velocities at the levels of the screens of selected boreholes. But, besides local information, these values can only provide a general impression of the regional groundwater flow and transport field and its variability. Groundwater flow and transport models have to be used for a more exact study and characterization of flow paths through this hydrogeological environment. This characterization should take into account all the uncertainties in the structural description and the site specific data. [5, 11]

5. Conclusions

Only if the natural isolation potential of a salt dome like the Gorleben salt dome is reduced by external stresses, e.g. heat induced stresses, might it be possible for radionuclides to migrate from the repository to the biosphere. Three subsystems can be distinguished in which possible flow paths can be identified: the salt dome, where flow can only take place if a fracture system is opened, the fractured cap rock and the sedimentary cover. Various laboratory and field methods (geological, geophysical, hydrogeological and hydrochemical) are available and have been used to identify and characterize the water-conducting features in these subsystems. Especially hydrochemical information and hydraulic experiments can help in identifying possible pathways. Integration of all this information provides a comprehensive, although sometimes insufficient, basis for characterization of the present groundwater system and for consideration of its past behavior and its future evolution, including possible failure of the barrier system. Groundwater-flow and transport models have to be used for determining additional parameters and for making a more detailed study of possible flow paths.

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