

# ISOTOPE HYDROLOGICAL STUDIES ON THE SALT WATER FLOW ABOVE THE GORLEBEN SALT DOME

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## ABSTRACT

The Gorleben salt dome in northern Germany has been investigated for its suitability as a permanent repository for radioactive wastes since 1979. The cover deposits above and around the salt dome consist of unconsolidated Quaternary and Tertiary sediments up to 300 m thick. A subglacial erosion channel, the Gorleben channel, crosses the salt dome. In this channel permeable Quaternary sediments directly overlie the cap rock or are in contact with the salt itself. Brines are found in these areas.

The  $\delta^{18}\text{O}$  and  $\delta^{18}\text{D}$  values in groundwater samples from Gorleben generally correlate with the salinity distribution: The fresh water was formed under Holocene climatic conditions, while the saline water has a Pleistocene cold-climate signature. An exception to this pattern is a group of brine samples from the Gorleben channel with a warm-climate signature or signature that indicates mixing of Holocene and Pleistocene brines. The highest  $^{14}\text{C}$  values are in the freshwater samples and decrease with increasing salinity. Brines from the Gorleben channel with a warm-climate  $^{18}\text{O}$  signature are an exception and show higher  $^{14}\text{C}$  values. The presence of Holocene and of Pleistocene brines and a mixture of these brines within the Gorleben channel indicate post-Pleistocene groundwater circulation, which is progressively replacing the Pleistocene brines with Holocene groundwater.

## INTRODUCTION

The Gorleben salt dome in northern Germany is a possible site for the disposal of all types of radioactive wastes. The radioactive wastes would be deposited at depths of more than 1000 m. The salt dome is approxi-

mately 14 km long, up to 4 km wide, and its base is at a depth of about 3000 m.

A comprehensive hydrogeological site investigation begun 1979 was largely completed in 1986. In 1996 the investigations were extended to an area north of the River Elbe. These

investigations were completed in 1999. A total of 145 exploration boreholes were drilled to a maximum depth of 450 m, about 390 observation wells were drilled to depths between 10 and 275 m to monitor the groundwater in an area of about 400 km<sup>2</sup> above and around the salt dome. In the meantime the underground investigations of the salt dome have been suspended due to a moratorium by the Federal government and the electricity utilities.

### HYDROGEOLOGICAL STRUCTURE

The cover deposits above and around the salt dome consist of unconsolidated Quaternary and Tertiary sediments up to 300 m thick, forming a system of aquifers and aquitards (Fig. 1).

The base of the aquifer system above the Gorleben salt dome and the surrounding area consists of Oligocene and Eocene clays and clay more than 100 m thick (Fig. 1). Miocene lignite sands form a significant aquifer, which in the area around Gorleben is 100 to 150 m thick. These sands occur throughout the area of the rim synclines around the salt dome, but above the

ism. These lignite sands are overlain by the low-permeability Hamburg Clay, which is up to 120 m thick.

The Gorleben salt dome is crossed by a N-S subglacial channel formed during the Elsterian. Tertiary clays, which originally covered the salt dome were eroded in the center of the channel. The base of the channel fill consists of highly permeable sands and gravels, which in some places lie directly on the cap rock or even the Zechstein salt. They are overlain by the low-permeability Lauenburg Clay (Fig. 1).

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 an heterogeneous aquifer.

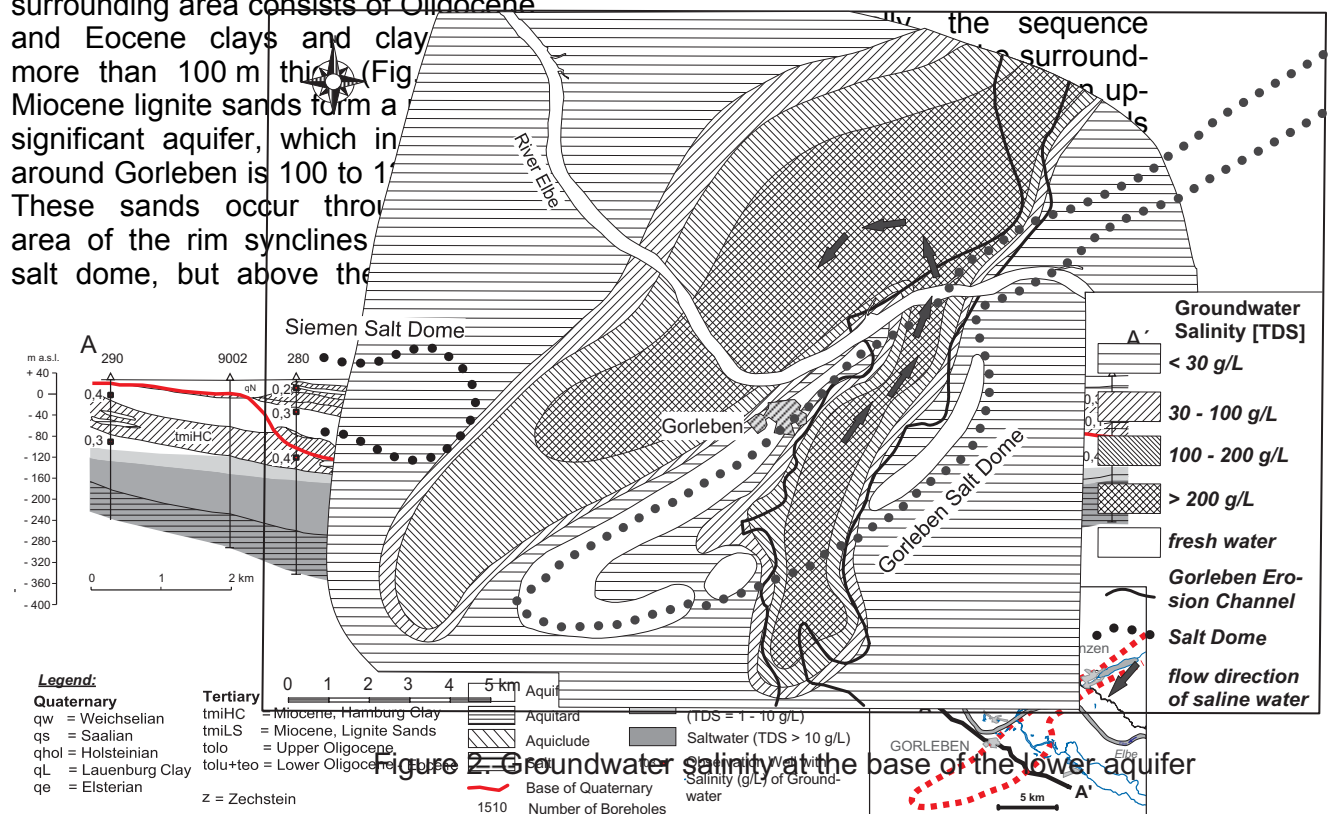


Figure 1. Hydrogeologic cross-section across the Gorleben salt dome they were eroded during the salt diapir-

deposits form the upper aquifer. The two aquifers are separated by the Hamburg Clay and Lauenburg Clay aquitards. In some parts, the Hamburg Clay has been eroded during the Quaternary, so that the two aquifers are in direct contact (Fig. 1).

### DISTRIBUTION OF FRESH WATER AND SALINE WATER

In the Gorleben area, like throughout the North German lowlands, there is an upper freshwater body of varying thickness and a lower body of salt water of varying salinity.

The freshwater/saltwater distribution above the Gorleben salt dome and in the surrounding rim synclines is shown in Figure 1. In the rim synclines to the northwest and southeast of the salt dome, the fresh water body is more than 100 m thick. Independent of depth, the fresh water has a low salinity of 200 mg/L to a maximum of 500 mg/L. The zone of transition from the fresh water in the rim synclines to the underlying salt water is 10 to 20 m thick. The freshwater/saltwater interface above the Gorleben channel is considerably higher (within the Weichselian and Saalian sediments of the upper aquifer) than in the rim synclines. Within the lower aquifer in the Gorleben channel, which is in direct

contact with the rock salt, the groundwater is highly saline to saturated due to dissolution of rock salt.

The distribution of salinity at the base of the lower aquifer is shown in Figure 2. It shows that the zone of high salinity includes the Gorleben channel and the adjoining rim syncline northwest of the salt dome. Exploratory boreholes in this area show that the pore water in the underlying Upper Oligocene silt has a lower salinity than the groundwater in the overlying aquifer (KLINGE et al. 1999). In contrast, the groundwater salinity at the base of the aquifer is relatively low (15 – 30 g/L) in the rim synclines south and northeast of the salt dome, and above the western part of the salt dome where the Zechstein salt is covered by clay.

From the salinity distribution it can be derived that the saltwater flow in the Gorleben channel is to the north. This is the same direction as the groundwater flow in the upper aquifer. There is no significant saline groundwater flow to the south. As the aquifer of the Gorleben channel north of the salt dome is in hydraulic contact with the Tertiary aquifer of the rim syncline north of the salt dome and because the density of brine is higher than that of fresh water, the salt water from the Gorleben channel flows to the deepest part of the

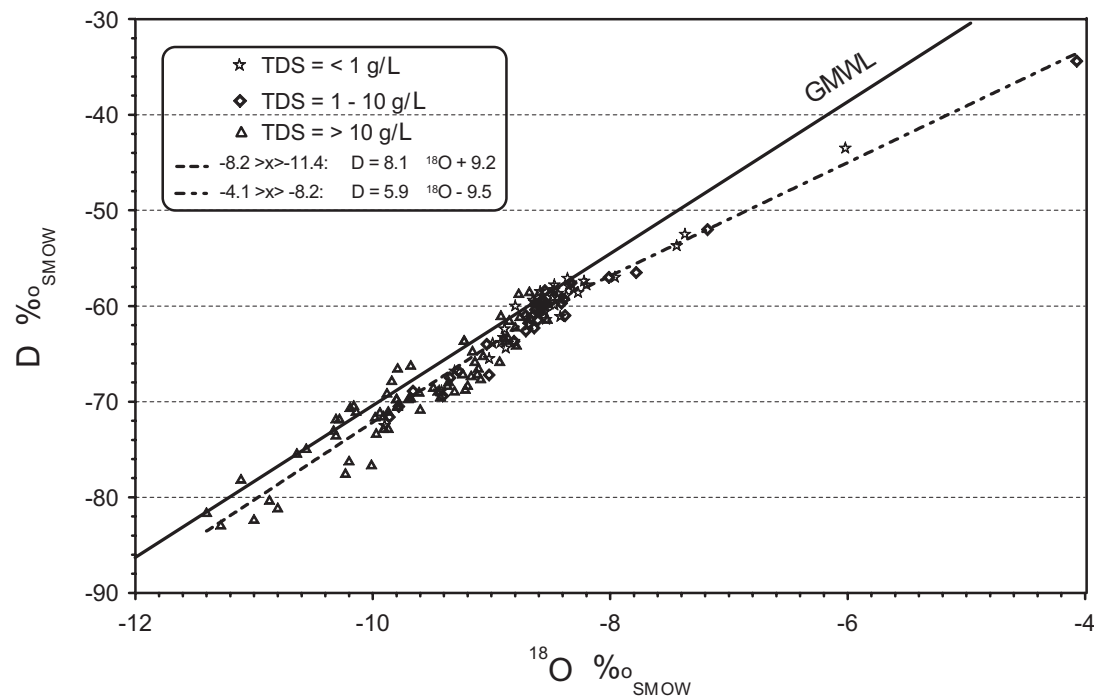


Figure 3. D versus  $^{18}\text{O}$

lower aquifer of the rim syncline. However, there is no significant flow of salt water into the near-surface part of the aquifer in the northern rim syncline, as shown by the considerable depth of the freshwater/saltwater interface in this area (Fig. 1).

## ISOTOPE HYDROLOGICAL STUDIES

### Introduction

The contact area between the Zechstein salt and the Quaternary sediments in the Gorleben channel represents a potential zone of migration of radionuclides into the hydrosphere. In general, migration of radionuclides from a permanent repository in the salt dome into the Gorleben channel would be possible only in association with saturated salt water. The basic objective of the isotope hydrological studies was to date the groundwater in order to reconstruct the salt water flow systems and to determine possible palaeoclimatic effects on the geohydraulic conditions.

The isotope hydrology studies were conducted by SUCKOW (1993) and RÜBEL (1999). These studies included measurements of tritium,  $^{14}\text{C}$ , stable oxygen and hydrogen isotope ratios, and noble gas concentrations. In addition, the stable isotope ratios and the

noble gas concentrations in the pore water in the aquitards were measured by RÜBEL. The results of the oxygen and hydrogen isotope and  $^{14}\text{C}$  measurements are discussed in this paper.

## RESULTS

### Stable Oxygen and Hydrogen Isotopes

The difference in the masses of the oxygen isotopes  $^{16}\text{O}$  and  $^{18}\text{O}$  and the hydrogen isotopes H and D is the reason for temperature-dependent isotopic fractionation during phase transitions, such as evaporation and condensation. The isotope ratios in the water at a specific location are a function of temperature (DANSGAARD 1964). This makes palaeoclimate studies possible, as well as providing a possibility to distinguish between Pleistocene and Holocene water.

A plot of  $\delta\text{D}$  versus  $\delta^{18}\text{O}$  is shown in Figure 3. The water samples are grouped as follows: fresh water ( $< 1$  g TDS/L), saline water (1 – 10 g/L), salt water ( $> 10$  g/L). Two straight lines fit the data:  $\delta\text{D} = 8.1 \delta^{18}\text{O} + 9.2$  for  $\delta^{18}\text{O}$  values between  $-8.2$  and  $-11.1$  ‰. This line passes through most of the data points and lies just below and nearly parallel to the Global Meteoric Water Line (GMWL) (CRAIG 1961) and can thus be interpreted as a local

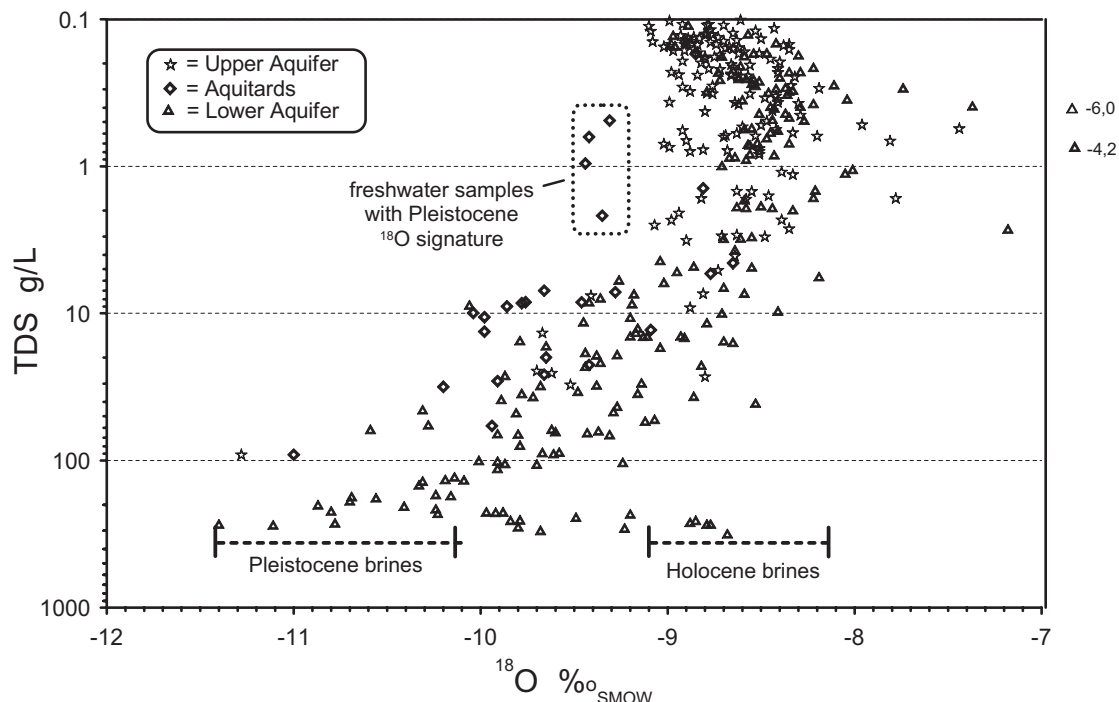


Figure 4. TDS versus  $^{18}\text{O}$ -values of groundwater

MWL. The other line,  $\delta D = 5.9 \delta^{18}O - 9.5$ , shows a good fit for eight water samples from shallow wells in areas with a high groundwater table. The slope of this line indicates that the water contains a component that has been subjected to evaporation.

The salt water samples along the first line are isotopically lighter than the fresh water samples. This indicates the salt water body was recharged under colder climatic conditions than the fresh water body.

The relationship between the salt water and fresh water samples is even more distinct in the plot of TDS versus  $\delta^{18}O$  (Fig. 4). The  $\delta^{18}O$  values for the fresh water samples – except for those affected by evaporation – cluster around a mean of  $-8.6 \pm 0.5 \text{‰}$ . The

$\delta^{18}O$  values for the salt water samples shift to increasingly negative values with increasing salt concentration to  $< -11 \text{‰}$  for concentrated brines. This distribution indicates recharge of fresh water during the Holocene and salt water during the Pleistocene.

The following exceptions to this general trend are observed:

1. A small group of fresh-water samples from the Lauenburg Clay and Hamburg Clay aquitards, which have clear Pleistocene isotope signatures. Analyses show that the pore water in these aquitards generally has a Pleistocene age (RÜBEL 1999).
2. A group of five brines with  $\delta^{18}O$  values of  $> -9 \text{‰}$ , indicating a Holocene age. On the basis of the dif-

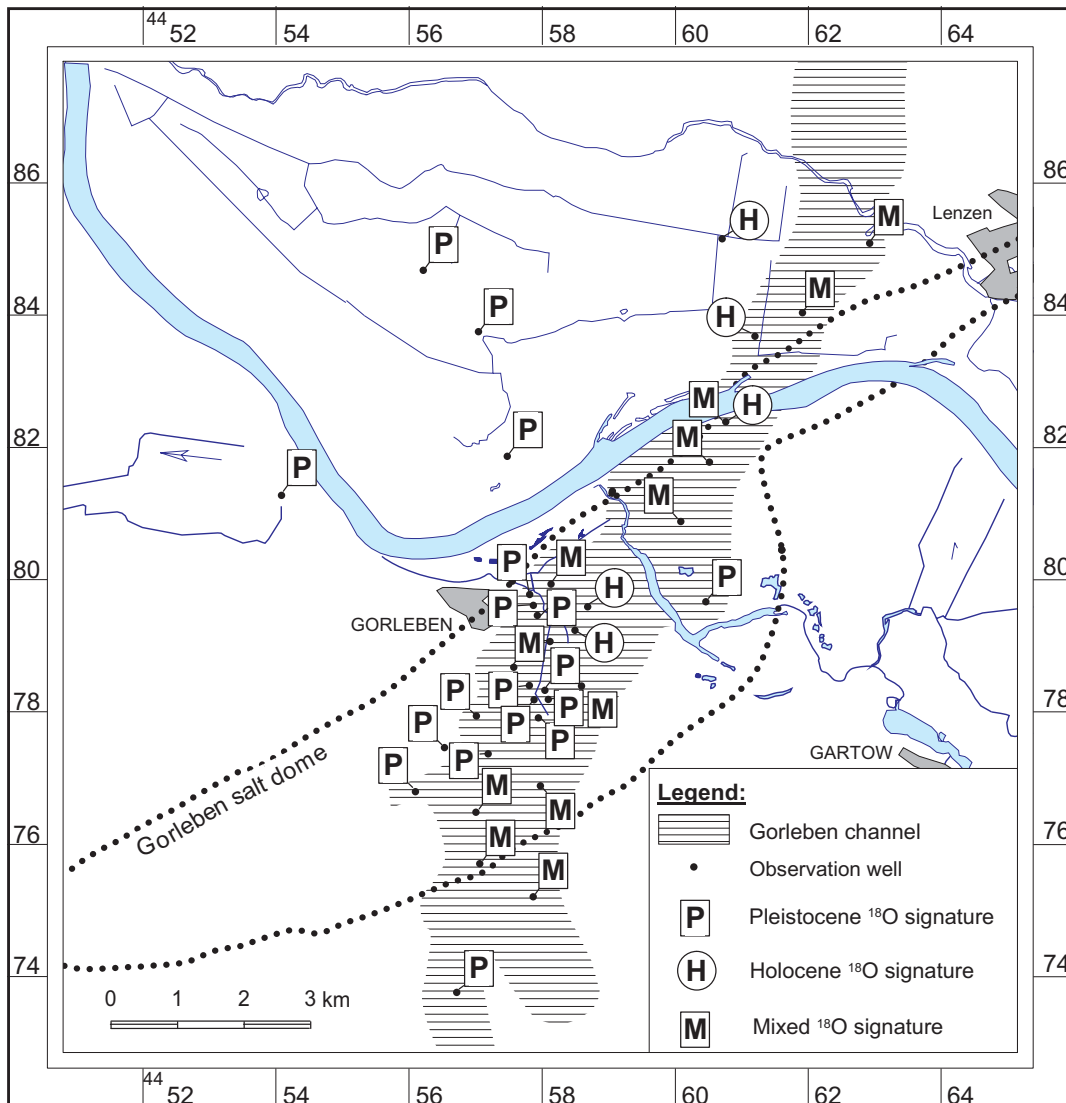


Figure 5.  $^{18}O$ -signatures of brines  $> 100 \text{ g/L TDS}$

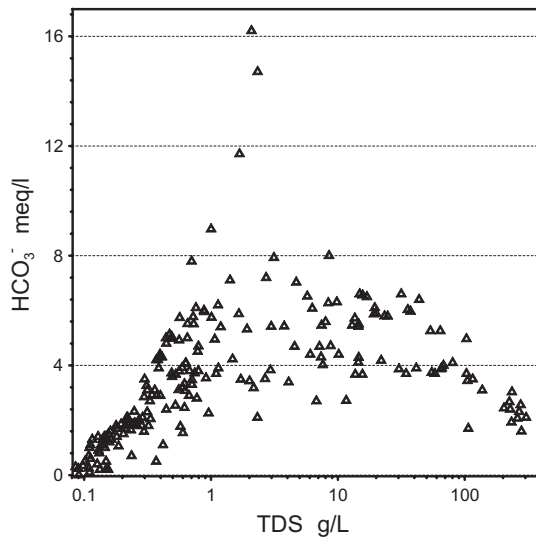


Figure 6.  $\text{HCO}_3^-$  versus TDS

ference in temperatures in the Pleistocene and Holocene, a difference of 2 ‰ may be expected for water originating in these two epochs. It can be seen in Figure 4, however, that many of the brine samples yielded  $\delta^{18}\text{O}$  values between -9 and -10 ‰. These samples indicate mixing of brines of Pleistocene and Holocene ages.

The distribution of  $\delta^{18}\text{O}$  signatures of the brines (> 100 g TDS/L) in the study area is shown in Figure 5, with the following classes: Holocene brines ( $\delta^{18}\text{O} > -9$  ‰), Pleistocene brines ( $\delta^{18}\text{O}$

< -10 ‰) and mixed brines ( $\delta^{18}\text{O} = -9$  ‰ to -10 ‰). It can be seen that brines in the northern rim syncline all have Pleistocene signatures, whereas in the Gorleben Channel all three types of brines are present and the  $\delta^{18}\text{O}$  signatures vary from place to place.

## RADIOCARBON

In ideal cases, absolute water ages can be calculated from the  $^{14}\text{C}$  abundances and  $\delta^{13}\text{C}$  values for the dissolved inorganic carbon in groundwater. In the Gorleben study area, this is not possible due to secondary changes in the  $^{14}\text{C}$  abundances resulting from chemical reactions in the groundwater, such as reduction of sulfate. Except in the near-surface oxygen-rich zone, sulfate in groundwater is reduced by bacteria together with oxidation of organic material with the formation of carbon dioxide and thus bicarbonate.

The effect of sulfate reduction on the bicarbonate concentration in the groundwater can be seen in Figure 6. Except for the near-surface water, which has a very low mineral content, and the brines (> 200 g TDS/L), nearly all of the groundwater samples have an elevated bicarbonate content.

If no fossil organic material is oxi-

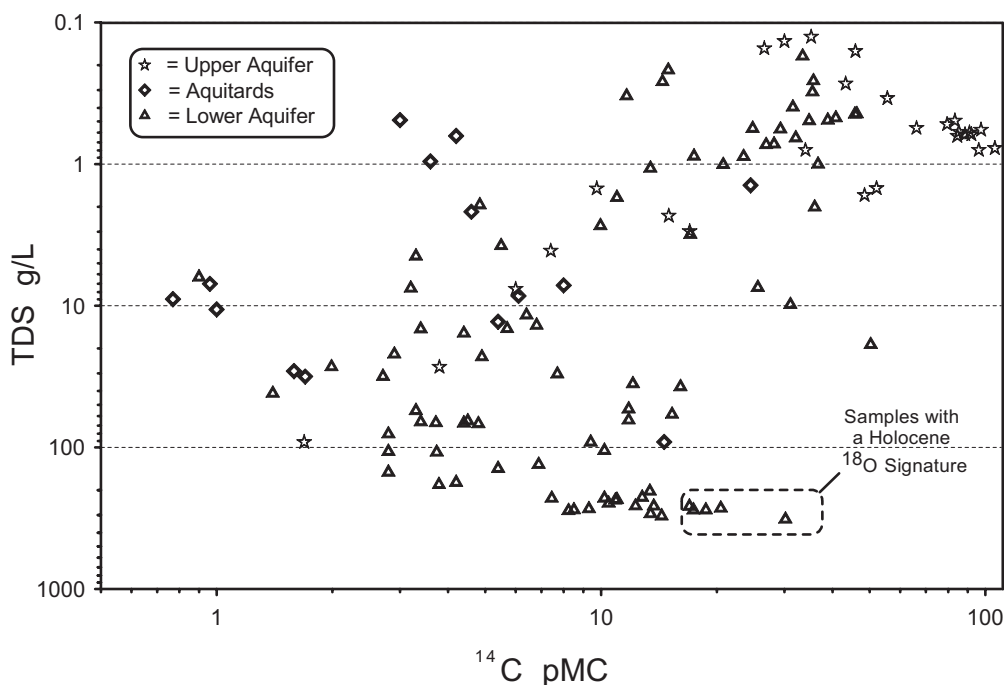


Figure 7. TDS versus  $^{14}\text{C}$

dized, a correction of the  $^{14}\text{C}$  values can be made on the basis of the  $\delta^{13}\text{C}$  values (e.g., PEARSON & HANSHAW 1970). In the Gorleben area, the aquifers contain fossil,  $^{14}\text{C}$ -free organic material from the Tertiary lignite sands that are present in the Quaternary sediments. For this reason, the  $^{14}\text{C}$  values were not converted to  $^{14}\text{C}$  ages.

A log-log plot of the salt concentration versus  $^{14}\text{C}$  values is shown in Figure 7. As expected, the fresh water samples have the highest  $^{14}\text{C}$  abundances, with decreasing abundance with increasing salt concentration. The brines with a Holocene  $\delta^{18}\text{O}$  signature deviate from this pattern; they have significantly higher  $^{14}\text{C}$  values than the other brines. Thus, the  $^{14}\text{C}$  values support the thesis derived from the  $\delta^{18}\text{O}$  values that the fresh water and a small group of brines were formed during the Holocene while the saline water was formed during the Pleistocene under cold climate conditions.

## CONCLUSIONS

The basic objective of the isotope hydrological studies was to reconstruct the salt water flow system in the Gorleben channel and in the lower aquifer to the north of the salt dome and to determine possible palaeoclimatic effects on the geohydraulic conditions.

The isotopic and geochemical patterns of the Gorleben groundwater support the following conceptual model of saltwater transport out of the Gorleben channel:

1. Brines within the lower aquifer to the north of the salt dome have a predominantly late Pleistocene origin. Since these brines were formed by dissolution of rock salt within the Gorleben channel further south the salt water transport out of the channel occurred predominantly within the Pleistocene epoch.

2. The presence of Holocene and of Pleistocene brines and a mixture of these brines within the Gorleben channel indicate post-Pleistocene groundwater circulation that is progressively replacing the Pleistocene brines with Holocene groundwater.

## REFERENCES

- CRAIG, H. (1961). Isotopic variations in meteoric waters. *Science* 133: 1702-1703.
- DANSGAARD, W. (1964). Stable isotopes in precipitation. *Tellus* 16: 436-468.
- KLINGE, H., BOEHME, J. & LUDWIG, R. (1999). Fresh-water/salt-water distribution in the aquifer system above the Gorleben salt dome: Results of the Gorleben site investigation programme. SWIM 15<sup>th</sup> Ghent. *Natuurwet. Tijdschr.* Vol 79 (1999): 172-177.
- PEARSON, F.H. Jr. & HANSHAW, B.B. (1970). Sources of dissolved carbonate species in groundwater and their effects on carbon-14 dating. *Isotope Hydrology IAEA-SM-129/18*. Vienna. pp 271-286.
- RÜBEL, A. (1999). Stofftransport in undurchlässigen Gesteinsschichten – Isotopenuntersuchungen im Grund- und Porenwasser. Doctoral dissertation, Naturwissenschaftliche-Mathematische Gesamtfakultät, University of Heidelberg.
- SUCKOW, A. (1993). Isotopenhydrologische und Edelgaspaläotemperatur-Untersuchungen im Deckgebirge über dem Salzstock Gorleben. Doctoral dissertation, Naturwissenschaftliche-Mathematische Gesamtfakultät, University of Heidelberg.