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Comprehensive Interim Report on Results to Date of Site Investigation in Gorleben

Physikalisch-Technische Bundesanstalt, Department of Interim Storage and Final Isolation of Radioactive Wastes

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* By LANGUAGE SERVICES, Knoxville, Tennessee

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1. Introduction

Now that the major portion of the investigative program to be carried out from above ground at the Gorleben site is completed, the next task is the underground exploration of the salt dome. This exploratory work requires the sinking of two shafts.

Because of the importance of the planned measures, and also because of the estimated total expenditure of 1 billion DM by the year 1994, a comprehensive interim report on the results obtained to date in the Gorleben site investigation is hereby presented as a basis for interdepartmental discussion and for a decision of the federal government concerning these measures.

The report discusses the findings to date regarding the utilization of the salt dome for the final isolation of radioactive wastes, to the extent that it is possible to discuss this issue at the present time.

A final statement on suitability will not be possible until the underground exploration of the salt dome has been completed, when researchers will be sufficiently familiar with the 'final repository' system (total geologic situation, mine, radioactive wastes) so that the site-specific safety analyses can be carried out which are to demonstrate the feasibility of fulfilling protective goals.

As another requirement for the implementation of realistic safety analyses, results of research and development work and of tests [1] will be necessary. Only then will the scientific tools be available with which the complex processes covered by the safety analyses can finally be treated, both individually and in interaction with one another. This research must be completed in sub-areas concurrently with execution of the overall project.

Because of its purpose, the present report is limited to the treatment of site-specific aspects, particularly the suitability of the total geologic situation for the construction of a final mined repository and the long-term safety of such a repository.

The following persons and organizations besides PTB [Physikalisch-Technische Bundesanstalt] have participated in the writing of this report:

- Bundesanstalt für Geowissenschaften und Rohstoffe [Federal Institute of Geosciences and Raw Materials], Hannover (Chap. 3.-3.1.6, 3.1.8-3.2.3, 6.1-6.2.4)

- Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH [German Corporation for the Construction and Operation of Final Repositories for Waste Materials], Peine (Chap. 4)

- Prof. Dr. A. G. Herrmann, Geochemisches Institut der Universität Göttingen [Geochemical Institute of the University of Goettingen] (Chap. 3.1.7)

- Projekt Sicherheitsstudien Entsorgung [Waste Management Safety Study Project] (Chap. 6.4).

2. The Site

2.1 Official Naming of the Site

After the state government of Lower Saxony had declared its willingness in February 1977 to examine applications for the construction of an integrated nuclear waste management center (German abbreviation: NEZ) at the Gorleben site, the federal government agreed to this preliminary selection of the site on July 5, 1977.

2.2 Site Investigation

On July 28, 1977, PTB applied to the Minister of Social Affairs for Lower Saxony for approval to carry out a plan verification process for the federal facilities for interim and final storage of radioactive wastes that would be integrated in the NEZ. For the purpose of initiating exploration of the salt dome, applications were filed with the Mining Office in Celle in July 1977 and in April and September 1978 for approval of the location operation plans for the first salt dome exploratory boreholes. After an overall operation plan for a hydrogeologic research program was submitted in September 1978, an application for approval of 7 hydrogeological exploratory boreholes, 26 water-level observation holes and 2 salt surface boreholes (the so-called 1st drilling lot) was submitted to the mining office mentioned previously, for the purpose of investigating the hydrogeologic conditions above and around the salt dome.

Drilling work could only begin after the symposium entitled 'Rede - Gegenrede' ['Statement and Counterstatement' --the meeting known as the Gorleben Hearing] (March 28-31, April 2-3, 1979), which the state government of Lower Saxony had made a precondition for the initiation of the Gorleben site investigation--apart from the NEZ licensing process as required by the German Atomic Energy Law. After the operation plan license for the 1st drilling lot was granted on April 5, 1979, drilling work began on April 17, 1979. On July 24, 1979, the operation plans for the deep borehole referred to as Gorleben 1003 were approved and drilling work was begun on January 4, 1980, once a safe drilling site was established.

2.3 Site Investigation Program

In order to determine the suitability of the proposed site, Gorleben, for the construction of a mined repository for radioactive wastes in the Gorleben salt dome, exploration work both above and below ground must be carried out in accordance with generally recognized principles, which have also been laid down in the recommendation of the Reaktorsicherheitskommission (RSK) [Reactor Safety Commission] of September 15, 1982, entitled 'Safety Criteria for the Final Isolation of Radioactive Wastes in a Mine' [1]. The exploratory operations are intended to clarify the geologic and hydrogeologic conditions at the site. In addition, they are to provide basic material and data for further research and safety analyses that will ultimately make a suitability statement possible. The research is also expected to obtain data required for a site-dependent plan for the mined repository. The objectives of the exploration operations carried out to date above ground are both to investigate the overburden—including the hydrogeologic conditions—and the salt dome and to determine suitable shaft drilling locations. The Physikalisch-Technische Bundesanstalt (PTB) [German Federal Physicotechnical Institute] is carrying out the exploration work with the help of numerous companies and institutions, and the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR)* is in charge of the geoscientific planning, supervision and evaluation of the work and advises PTB on geoscientific issues. In the course of the project the Deutsche Gesellschaft zum Bau und Betrieb von Endlagern für Abfallstoffe mbH (DBE)* has been commissioned to an increasing extent with carrying out the field work. The goal of the hydrogeologic research program is to explore the hydrogeologic conditions and the geology of the strata lying above the Gorleben Salt Dome and in its environs. The particular objective of the research is an evaluation of the effects of the ground water on the salt dome and the consequences of a mined repository for the ground water.

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* See translation on page 4--Translator's Note.

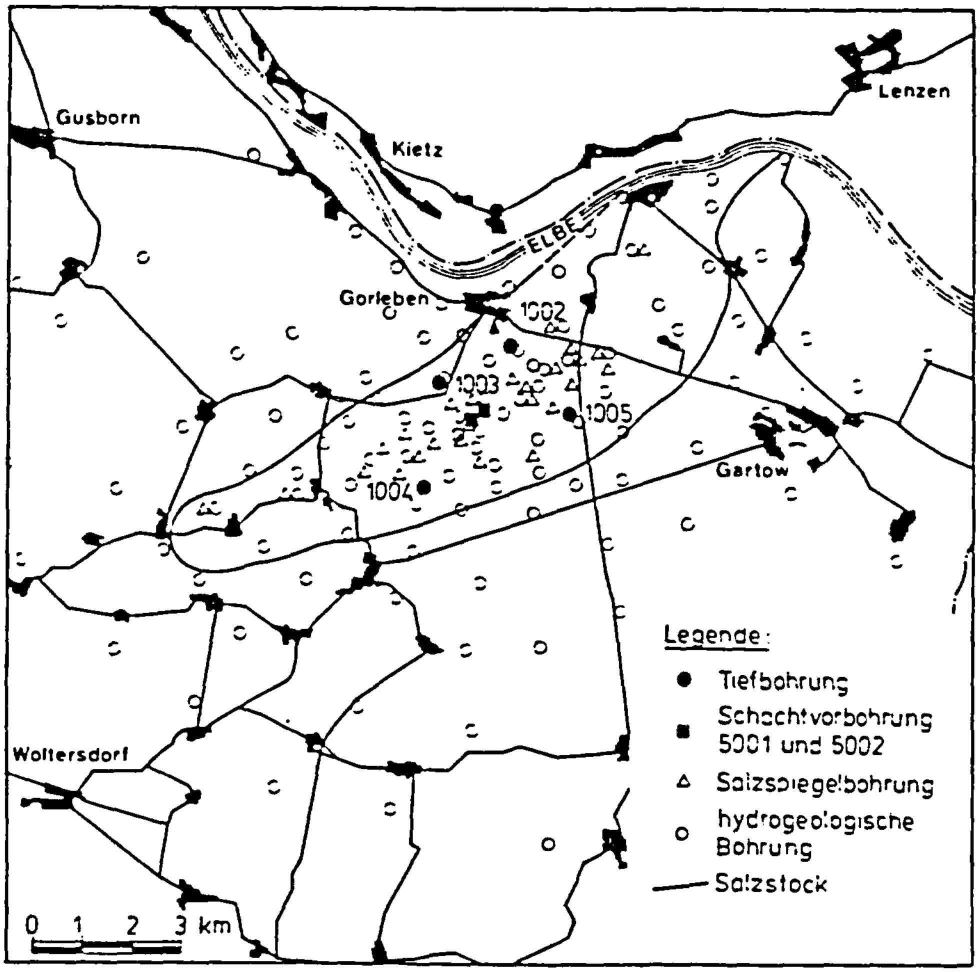


Figure 1. Gorleben exploration area

Key:
- ● deep borehole
- ■ preliminary shaft boreholes 5001 and 5002
- △ salt surface borehole
- ○ hydrogeological borehole
- —— salt dome

In conjunction with the hydrogeologic studies, 125 exploratory drill holes, 270 observation holes (ground-water measuring stations) and 9 core holes were drilled over the area visible in Fig. 1--300 km^2--in the period from mid-April 1979 to mid-February 1983. The program is largely completed, although several compaction holes are still planned. The results of the hydrogeologic research are presented in Sec. 3.2.

An overview of the tests and studies carried out in connection with the hydrogeologic research, together with the participating institutions, is given in Fig. 2, the 'Gorleben Hydrogeologic Exploration Program Organization Chart.'

Figure 2. Gorleben Hydrogeologic Exploration Program Organization Chart [see fold-out page 10].

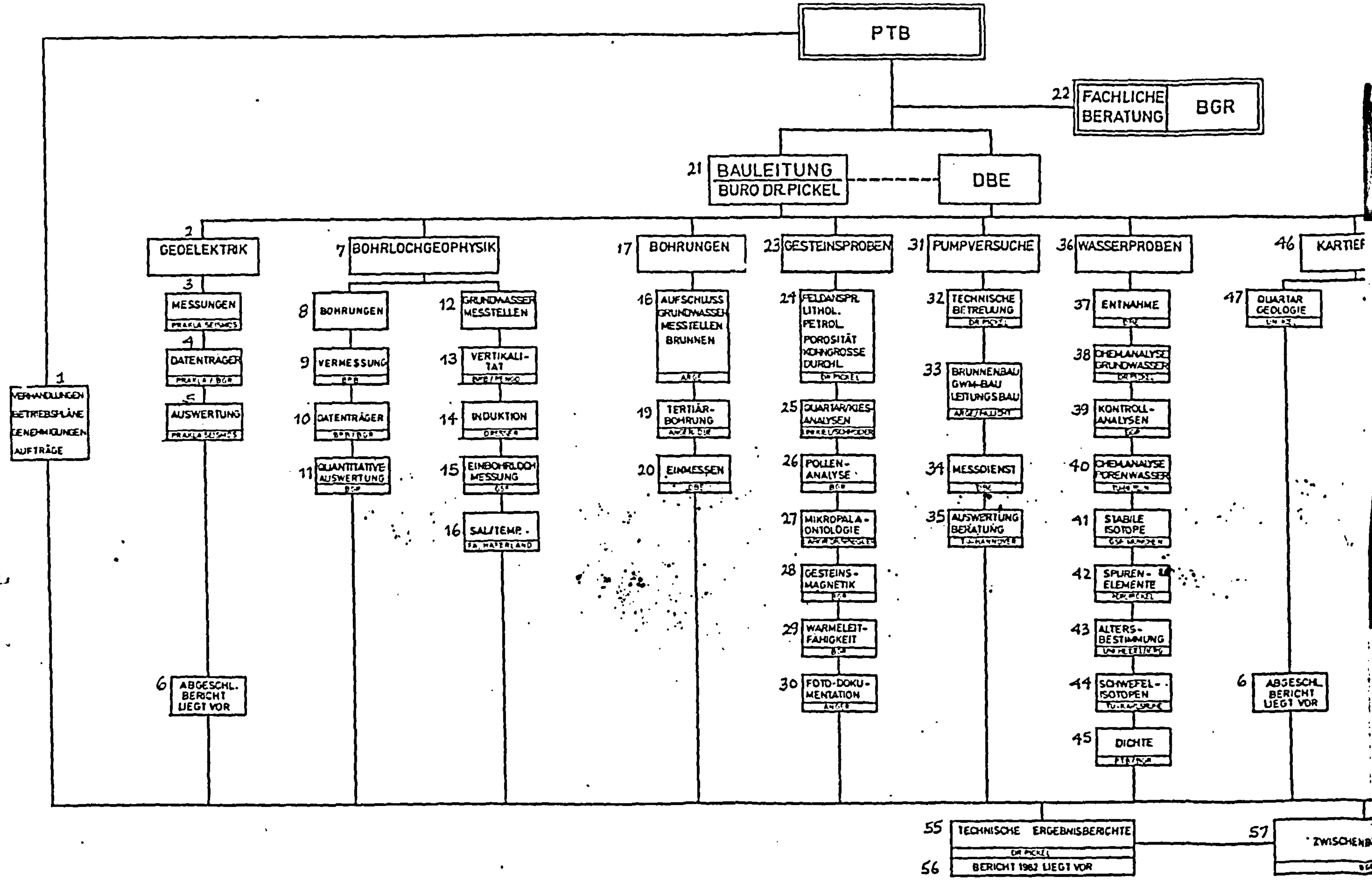
Key: [Only project areas are translated--company or institution names and acronyms are not translated--Translator's Note]

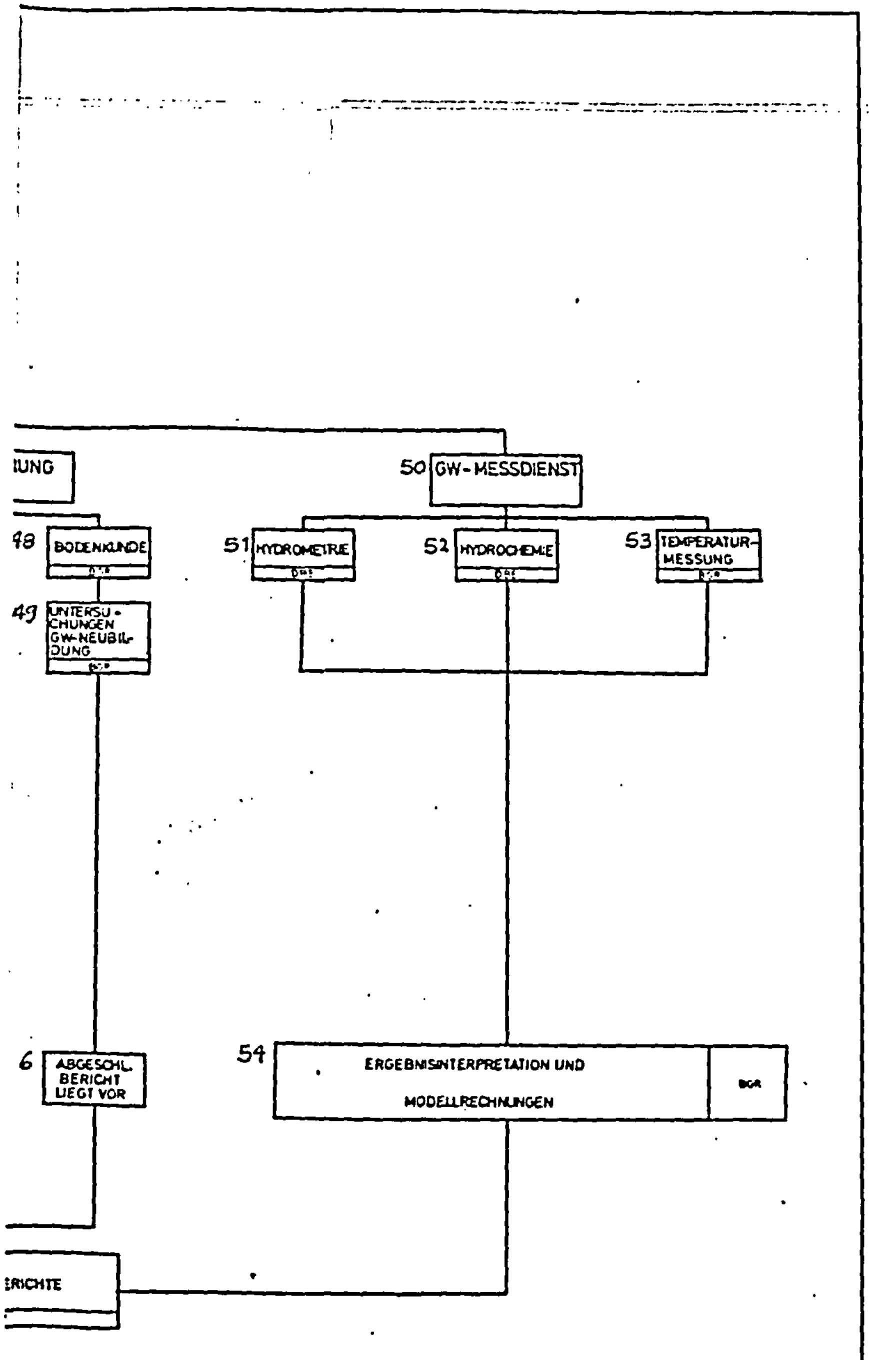
1 negotiations, operating plans, licences, contracts
2 geoelectrics
3 tests and measurements
4 data media
5 evaluation
6 final report is presented
7 borehole geophysics
8 boreholes
9 surveys
10 data media
11 quantitative evaluation
12 ground-water measuring stations
13 verticality
14 induction
15 single borehole measurement
16 ...*/temp.
17 boreholes
18 exploration, ground water measuring stations, wells
19 tertiary drilling
20 surveying
21 project director's office, Dr. Pickel
22 technical consulting
23 rock samples
24 field ...*, lithology, petrology, porosity, grain size, permeability
25 Quaternary and gravel analyses
26 pollen analyses
27 micropaleontology
28 rock magnetics
29 thermal conductivity
30 photographic documentation
31 pumping tests
32 technical supervision
33 well drilling, ground-water measuring station construction, pipeline construction

34 test service
35 evaluation, consulting
36 water samples
37 sampling
38 chem. analysis of ground waters
39 validation analyses
40 chem. analysis of pore water
41 stable isotopes
42 trace elements
43 age determination
44 sulfur isotopes
45 density
46 mapping
47 Quaternary geology
48 soil science
49 studies of recharge of ground water
50 ground-water measurement service
51 hydrometry
52 hydrochemistry
53 temperature measurement
54 interpretation of results and model calculations
55 technical result reports
56 1982 report is presented
57 interim reports

* Abbreviation unexplained and untranslatable--Translator's Note.

Organisationsplan - Hydrogeologisches Untersuchungsprogramm Gorleben, Stand 1982





IUNG
50 GW-MESSDIENST
48 BODENKUNDE
51 HYDROMETRIE
52 HYDROCHEMIE
53 TEMPERATUR-MESSUNG
49 UNTERSU-CHUNGEN GW-NEUBIL-DUNG
6 ABGESCHL. BERICHT LIEGT VOR
54 ERGEBNISINTERPRETATION UND MODELLRECHNUNGEN
BGR
ERICHTE

Abb. 2

A continuously cored Tertiary profile was obtained by means of a so-called Tertiary borehole in the southern rim syncline of the salt dome in order to be able to better classify the Tertiary formations above the salt dome, which were otherwise only incompletely researched by drilling. With this hole, which was drilled from the beginning of November 1982 to April 1983, the ground water in the deeper basement is also being investigated.

In the period from January to June and from October to December 1980 a supplementary geoelectric program was carried out with a total of 540 deep soundings.

For the purpose of more accurate investigation of channel areas the application possibilities of a special areal seismic method was tested, but it did not achieve the success hoped for, and the major one-month test that had been scheduled was not implemented.

The hydrogeologic exploration program is being supplemented by studies at the Free University in Berlin on the occurrence of local salinization in the ground water close to the surface in the environs of the Gorleben salt dome. These studies will be completed by mid-1985.

Another area related to the hydrogeologic research is covered by hydrologic studies of the receiving streams which drain the area under investigation. This research is being planned and evaluated by the Bundesanstalt für Gewässerkunde (BfG) [Federal Institute of Land Hydrology]. In conjunction with this program five permanent measuring stations were set up, in addition to measuring stations for periodic measurements.

More accurate values for the spatially dependent hydraulic permeabilities are to be determined by pump tests for the purpose of ground-water hydraulic model calculations. Two wells for pump tests from the freshwater and brine horizons were drilled in the period from October 1982 to February 1983. Additional pump tests are planned for at least two additional sites.

Tracer tests were carried out using the one-hole method in 12 ground-water measuring stations in order to make possible initial estimates of ground-water flow velocities in the deeper ground-water horizons. Additional measurements are planned.

Salt surface boreholes have been used to explore both the overburden and the salt dome itself and have explored in particular the location and characteristics of the caprock, the type of transition between the caprock and the salt, and the bedding and stratigraphy of the salt strata found. These boreholes were also expected to provide information concerning the seal between the salt dome and the overburden and the existence and type of leaching points. They have also been used, together with the results of deep drilling, for mapping the top of the salt dome and exploring suitable shaft location areas.

In the period from mid-November 1979 to April 1983, 37 salt surface holes were drilled that extended a maximum of 80 m into the salt.

The drilling work for several planned compaction holes, particularly for the purpose of further exploration in the area of the Quaternary channel, is continuing.

Likewise, seismic reflection testing planned for 1983 on a profile totalling 156 km will be used for the investigation of both the overlying rock and the salt dome with respect to its external shape and flank formations. Supplementary gravimetric measurements were carried out in May 1983.

Investigation of the salt dome itself was carried out essentially by means of a deep drilling program intended to provide information about the mineral composition and the stratigraphic structure of the individual Zechstein cycles and also indications about the extent of such cycles in the Gorleben Salt Dome. Furthermore, deep drilling was to provide initial information about the structure of the salt dome and about the location of suitable shaft drilling areas. In conjunction with this program four salt dome exploratory boreholes about 2000 m deep were drilled in the period from the beginning of January 1980 to mid-March 1981. This completes this exploration program. The results of the investigations are presented in Sec. 3.1.

In the shaft location areas discovered by evaluating the salt dome exploratory boreholes and the salt surface boreholes, the suitability of the planned shaft location points was investigated by means of preliminary shaft boreholes. With these boreholes researchers obtained the necessary data for planning the freezing process necessary for shaft sinking and also information necessary for the selection and design of the shaft lining in the freezing shaft section and for planning the sinking operations. The existence of salt strata especially suited for shaft sinking (older sections of Leine rock salt) was detected in the salt rock. Moreover, data was obtained which are necessary for the evaluation of the stability of the shaft casing, of an eventual lining in the salt shaft section, and of favorable locations for the bottom landings.

Besides being used for exploration and data acquisition, the preliminary shaft boreholes are used in the freezing process as central holes for pressure relief of the ice cylinder. Therefore they had to be drilled with great accuracy as complete core holes. The two preliminary shaft holes were drilled in the period from February to November 1982. Since they have provided the desired data and demonstrated the suitability of the two shaft drilling sites, this program is also completed. Details about the results are given in Sec. 3.1.3.

3. Geologic Conditions

The Gorleben Salt Dome and its environs lie on the so-called Pompeckj Block. This area, which is relatively uniform geologically, includes the entire northern section of Lower Saxony, Schleswig-Holstein and several adjacent areas in East Germany. It has been characterized for hundreds of millions of years by subsidence and the deposition of sedimentary rock about three to eight kilometers thick. Within these sequences of sediment saliniferous rocks were deposited in the Zechstein in thicknesses of sometimes more than one thousand meters. There were, however, also upheaval periods lasting from millions to tens of million years, in which as much as several hundred meters of rock were removed.

The presaliniferous base of the Pompeckj Block has a simple structure. It is only interrupted by a small number of major faults. The saliniferous rocks are no longer in their original position. They have coalesced to form salt pillows and salt domes and have therefore exercised a decisive influence on all strata from the Permian period up to the most recent geologic past. The reasons for the migration of the salt rocks are their fluidity, their relatively low density, and also displacements of strata which resulted in unequal loading of the salt deposits. One of the approximately 200 salt domes of the Pompeckj Block is the Gorleben Salt Dome.

3.1 The Salt Dome

3.1.1 Stratigraphy

The six deep drillings (including the preliminary shaft drillings) and the 37 salt surface boreholes have explored virtually the entire stratigraphic sequence expected in the Gorleben Salt Dome (Tab. 1) from Stassfurt rock salt (z2) to clay fragment salt ('Tonbrockensalz') [2]. The location of the individual boreholes is shown in the basic plan (Fig. 3).

The strata Zechstein 2 and 3, which are important for final isolation, were struck repeatedly in the deep boreholes Go 1002 and 1003. The less important Zechstein 4 strata were only found in the borehole Go 1004, but in several repetitions due to folding. The salt surface hole GoHy 3010 intersected Na4α below the surface of the salt formation.

Stassfurt Series (z2)

Stassfurt rock salt (Na2) can be broken down into three stratigraphic sequences: Na2α (base salt), Na2β (main salt) and Na2γ (upper salt). To date, however, only the main and upper salt strata have been found by drilling.

The main salt is dark gray to light gray in color, medium- to coarse-crystalline, and consists primarily of rock salt with admixtures of anhydrite. In the direction of the upper salt there is also some secondary interstratification of polyhalite. Characteristic are large rock salt crystal fragments and eyes. Some of the rock salt crystal fragments exhibit internal lamination due to small brine or gas inclusions or anhydrite dust. The stratification is generally only indistinct and cloudy. It is structured by ragged anhydrite lines and balls and by finely distributed clay material in non-continuous layers, bands and stripes. Towards the top the main salt is very pure. There it consists primarily of rock salt crystal fragments which are aligned preferentially with their longitudinal axes in the bedding.

Table 1

Stratigraphic Sequence of Zechstein 2-4, According to Richter-Bernburg (1953)

	boundary anhydrite	A4r
	clay bank salt	Na4tm
	clay fragment salt	Na4δ
Zechstein 4 (z4)	rose salt	Na4γ
(Aller Series)	snow salt	Na4β
	base salt	Na4α
	pegmatite-anhydrite	A4
	red salt pelite	T4
	clay band salt	Na3tm
	Riedel potash seam	K3Ri
	swath salt	Na3ϑ
	anhydrite band salt	Na3am
	colored salt	Na3ζ
Zechstein 3 (z3)	bank salt	Na3δ
(Leine Series)	Ronnenberg potash seam	K3Ro
	orange salt	Na3γ
	line salt	Na3β
	base salt	Na3α
	main anhydrite	A3
	gray salt pelite	T3
	banded cover anhydrite	A2r
	cover rock salt	Na2r
Zechstein 2 (z2)	Stassfurt potash seam	K2
(Stassfurt Series)	kieseritic transition strata	Na2(K)
	Stassfurt rock salt	Na2α-γ

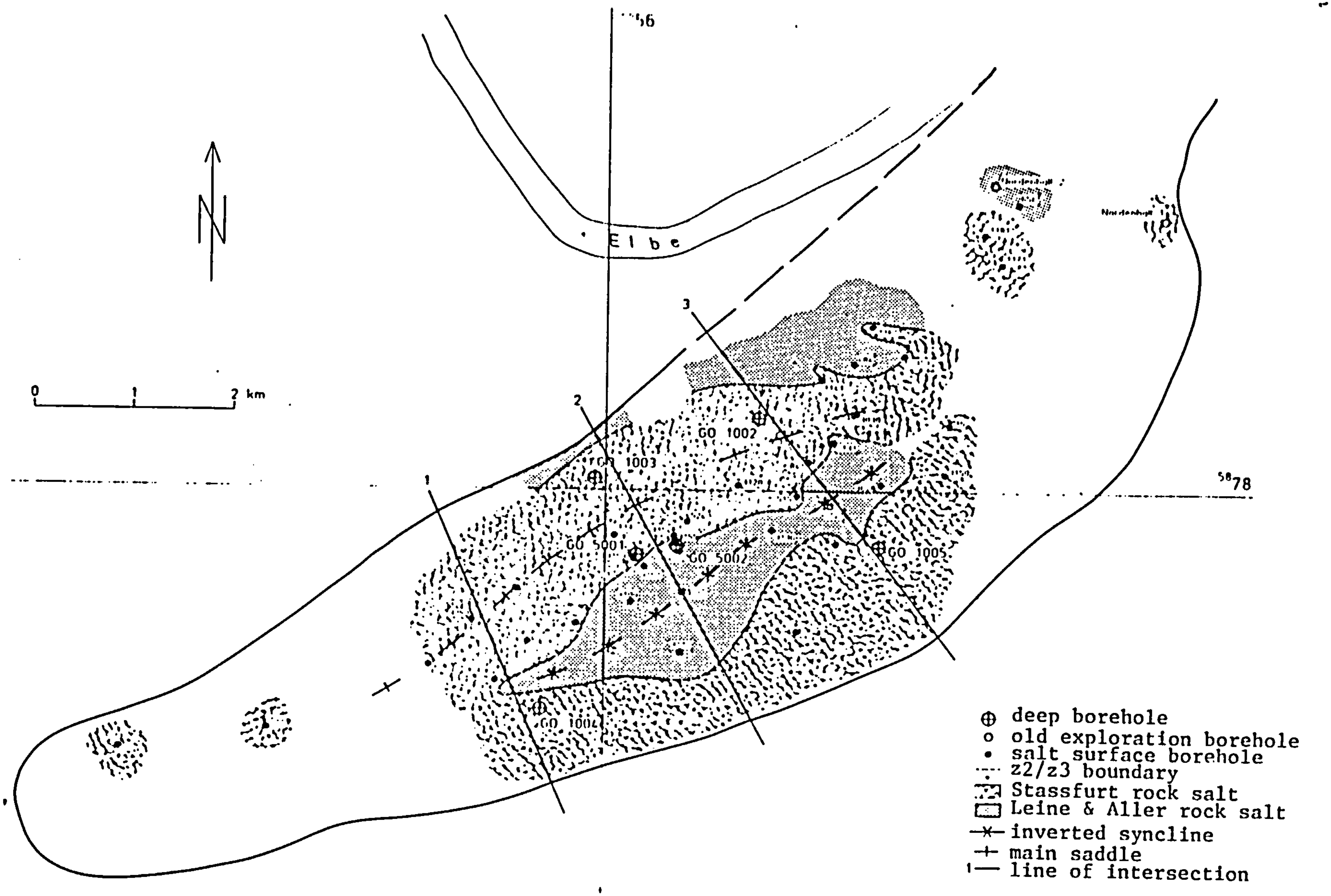


Fig. 3. Location of drilling and profiles

In the high Na2β several small brine-filled joints and nodes were observed in two deep boreholes. When the salt rock was tapped, small amounts of hydrogen sulfide were released. It occurs in part in the salt rock crystal fragments and in part in the rock salt matrix. In some areas an intense odor of hydrocarbons was also detected.

The transition to the overlying upper salt is completed gradually over several meters. The upper salt is gray, primarily fine-crystalline but also medium-crystalline in some places. Characteristic is the continuous and regular alternating sequence of approximately 2 cm to 10 cm wide pure salt strips and 3 cm to 10 cm wide sulfatic strips with dark-gray, anhydritic-argillaceous flaky lines. Rock salt crystal brines and fragments are not present here.

The primary thickness of the upper salt cannot be estimated because it is highly swollen and intensely folded. The thickness of the upper salt ranges from 10 m to 20 m.

The kieseritic transitional strata (Na2K) consist primarily of gray, fine-crystalline rock salt with dark-gray, anhydrite stripes and bands. The strata contain kieserite and polyhalite. The kieserite content increases sharply towards the top. Langbeinite has also been detected in scattered instances. The kieseritic transitional strata are about 10 m thick.

The Stassfurt potash seam (K2) has been found to date only in the form of detrital carnallitite. Broken layers and hard rocks of kieserite, anhydrite and rock salt float in a matrix which consists of red and violet carnallite and light gray rock salt. The thickness of the K2 fluctuates greatly from a few meters to approximately 70 m in the deep borehole Go 1002 as a function of the tectonic position.

The cover rock salt (Na2r) generally consists of red-brown, fine- to medium-crystalline rock salt with a thickness of 0.2 m to 0.5 m.

The z2 strata end with banded cover anhydrite (A2r). It consists of an interstratification, in places finely layered, of black clay and white to light gray anhydrite. Its thickness is usually less than one meter.

Leine Series (z3)

Gray salt pelite (T3) forms the base stratum of the Leine Series. It is divided into two subzones. In the underlying bed there is a formation of black, sometimes anhydritic clay rock, characterized by small white anhydrite trees with different growth forms. Toward the top the T3 formation is gray-brown in color and consists primarily of magnesite with only a small proportion of clay. Spherical anhydrite aggregates up to 3 mm in size with round and oval cross sections are likewise characteristic and in some areas lithogenetic. T3 is intensely jointed. The joints are filled with fibrous rock salt and fibrous carnalite. The average thickness of T3 is ca. 5 m to 6 m.

The main anhydrite (A3) is blue-gray and gray, fine-crystalline, and the stratification is indicated by dark-gray-brown clay anhydrite or carbonate schlieren, flasers and lamellae. In subzones it is intensely jointed. The individual joints are filled primarily with carnallite, sylvin or rock salt. Worth noting is the occurrence of small nodes and tubes which are filled with red carnallite and are spread throughout the entire main anhydrite formation in different intensities. The average thickness of the main anhydrite is approximately 70 m.

The main anhydrite is separated from the base salt (Na3α) by a sharp boundary. The base salt is brownish gray and brownish yellow, at the bottom fine-crystalline and coarse-crystalline towards the top, broken by gray anhydritic lines up to 0.5 cm thick, the distances between which increase towards the top. Between the lines the rock salt is color-banked and color-layered. In the base salt several massive anhydrite layers were also found by drilling in an irregular distribution. They are light gray, usually unstratified, and have a maximum thickness of 50 cm.

The boundary between base salt and line salt (Na3β) is characterized by the color change in the rock salt from brownish-yellow and brownish-gray to light-gray transparent. This change is completed over several meters of the profile. The line salt is usually gray-transparent or light-gray-transparent, fine- to medium-crystalline, and regularly broken by anhydritic lines up to 1 cm thick, the spacing of which increases toward the top.

It is striking that nodes and layers of carnallite occur in irregular distribution in the line salt. This is especially true of boreholes Go 1003 and 1002 on the NW flank of the salt dome, whereas in boreholes Go 1004 and 1005 such nodes and layers only occur in scattered instances. The individual carnallite layers are usually about 1 cm thick, sometimes even 10 cm thick, and oriented primarily concordantly. When these layers are tapped, the carnallite crackles and small amounts of an odorless gas are released. Special tests on this material must still be done. Detailed logging of the strata revealed that the carnallite layers are formed primarily in the upper sections of the anhydrite lines. Both are usually separated by a thin rock salt layer. Furthermore, it is found that the carnallite layers follow the anhydrite lines, even with intense folding of the strata. The position in the upper section of the line is maintained. These findings confirm the assumption that sedimentary carnallite is usually involved and not joints which were filled by carnallite. However, those also occur secondarily.

The boundary between line salt and orange salt (Na3γ) is fluid and is characterized by a color change in the salt rock from gray transparent or light gray transparent to orange and brownish orange. The orange salt (Na3γ) forms the upper section of the salts characterized by lines (Na3α-γ). It is fine to medium-crystalline in structure, orange in color, and broken by regular anhydrite lines up to 1 cm thick and by anhydritic and polyhalitic flaky lines. Between the lines orange and yellow colored interlayers are visible in alternation. They are diffuse in transmitted light. Occasionally a weak kieserite vein is detectable. In contrast to the Hannover area, pronounced rock salt crystal eyes are lacking, and rock salt crystal fragments only occur secondarily, sometimes in layers.

A 0.01 m to 0.5 m thick finely laminated anhydrite bed with underlying and overlying secondary layers was found in almost all profiles by drilling. The anhydrite layer and its secondary layers are referred to as the 'Gorleben Stratum' because of its importance as the stratigraphic key horizon in the Gorleben Salt Dome. In the lower part the orange salt contains anhydritic or polyhalitic flaky lines and in the upper section anhydrite lines, which likewise change to anhydritic or polyhalitic flaky lines when they approach the bank and banded salt. Single carnallite nodes of the mm to cm size are distributed irregularly through the entire orange salt formation. Overall, the base to orange salt has a thickness of approximately 100 m.

The Ronnenberg potash seam (K3Ro) was found in borehole Go 1003 in the form of a potash seam of a detrital carnallitite formation with a low K_2O content. It is lacking in most of the other deep and salt-surface boreholes. Only in the preliminary shaft borehole Go 5001 was a rock salt stratum encountered shortly before the final depth was reached that contains polyhalite, anhydrite, langbeinite, kieserite and sylvin as accessory minerals. Because of the mineral content this stratum was designated as the Ronnenberg seam horizon (K3Ro). The thickness of the potash seam intersected by borehole Go 1003 is approximately 20 m.

The bank and banded salt (Na3δ–ε) is a primarily fine- to medium-crystalline rock salt of a light gray color, contaminated by anhydritic or also polyhalitic flaky lines and layers. Carnallite and kieserite occur rarely in small nodes and flakes. The bank and banded salt together had a thickness of ca. 5 m to 10 m.

The colored salt ('Bunter Salz') is fine- to medium-crystalline and is characterized by red-orange, orange, dark gray and brown rock salt layers and beds in alternation. Impurities consists of black clay flakes, light gray anhydrite schlieren and flasers in irregular distribution, and finely distributed anhydrite dust. It is ca. 5 m to 10 m thick.

The anhydrite band salt (Na3am) consists of fine- to coarse-crystalline red-orange rock salt in the form of pure salt zones. The layers alternate with zones contaminated by clay and anhydrite, in which anhydrite beds and layers of differing thickness and with varying spacing are also embedded. In addition, nodes and interparticle filling of carnallite that was probably formed secondarily have been found in irregular distribution. The salt surface borehole GoHy 3130 intersected in Na3am an additional potash seam having a detrital carnallitite structure, a seam several meters thick. The anhydrite band salt is about 40 m thick.

The swath salt ('Schwadensalz': Na3ϑ) is primarily fine- to medium-crystalline and contains so-called 'swath zones.' These are rock salt layers which are contaminated by admixtures of finely distributed anhydrite and black clay. Occasionally anhydrite layers also occur. Dark red carnallite occurs secondarily in nodes and flakes, irregularly distributed. The thickness of the swath salt is between 15 m and 20 m.

Above the swath salt is a potash seam which very probably corresponds to the Riedel potash seam (K3Ri). It is primarily brown in color and has a carnallitite structure. It has only been found to date in the borehole Go 1004. Its thickness fluctuates between 5 m and 10 m.

The strata of the Leine Series conclude with the clay band salt (Na3tm). It consists of reddish brown, fine- to medium-crystalline rock salt with reddish brown clay in layers, the so-called clay bands. Single thin anhydrite layers have also been observed in the clay bands. The clay band salt has a thickness ranging from 30 m to 40 m.

Aller Series (z4)

The red salt pelite (T4) consists primarily of brownish red clay, interspersed with individual nodes of reddish brown rock salt. In the lower section it has a greenish color. The red salt pelite is in some places highly jointed, and the joints are filled with fibrous rock salt. The thickness of this stratum is 20 m.

The pegmatite anhydrite (A4) is characterized by the massive occurrence of pseudomorphisms of anhydrite after gypsum. The former gypsum porphyroblasts reach maximum sizes of 10 cm. The interspaces and cavities between and in the porphyroblasts are filled with orange-brown, fine-crystalline rock salt. Stratification is visible because of a few 1 cm to 3 cm thick, light olive brown, argillaceous anhydritic layers. The thickness of the pegmatite anhydrite is about 1.5 m.

The base salt of the Aller Series ($Na4\alpha$) is orange in color and primarily fine-crystalline. It is characterized by light gray anhydrite lines up to 2 cm thick, the upper boundary of which is sharp, whereas the lower boundary appears fringed. In transmitted light a light to dark color change is visible between the anhydrite lines caused by the interstratification of brown clay flakes. In the passages discovered to date the base salt is intensely deformed by small folds.

Snow salt ($Na4\beta$) has not been found by drilling. At the present time it is still unclear whether this strata series is represented facially by other strata or whether a stratigraphic gap exists.

The rose salt ($Na4\gamma$) is orange-pink in color, fine- to medium-crystalline, and contains single coarse-crystalline rock salt crystal eyes. It is interspersed with light gray, 1 mm to 2 mm thin anhydrite dust layers with varying spacing.

The clay fragment salt ($Na4\delta$) is primarily medium-crystalline, orange-brown and sometimes also orange-pink in color. Transparent rock salt crystal eyes, up to a maximum size of 8 cm, occur in irregular distribution. In layers from 2 cm to 5 cm thick the salt is contaminated by thin clay flakes and brown clay fragments up to a maximum size of 5 cm. Anhydrite occurs in dispersely distributed dust, in small anhydrite fragments and hard-rocks ranging in size from 0.5 cm to 2 cm. In addition, at least two anhydrite beds about 0.5 m thick have been found by drilling. Small nodes of carnallite have only been encountered to a limited extent and in irregular distribution.

The total thickness of the section of the Aller rock salt (Na4α - Na4δ) intersected by drilling is approximately 70 m.

The Caprock of the Salt Dome

To date the caprock of the salt dome has been intersected by drilling in 35 salt surface boreholes and 6 deep boreholes. In two salt surface boreholes in the region of the Quaternary channel, no caprock was encountered. Its thickness varies from 0.15 m to 110 m, whereby the mean thickness can be given as approximately 30 m.

Where the caprock was found to have a greater thickness than 50 m, one can assume that it contains large blocks of main anhydrite and gray or red salt pelite, in which case the main anhydrite is still preserved primarily as anhydrite.

The caprock contains several types of rock, although gypsum rock prevails. Anhydrite rock, anhydrite and gypsum hybrid rock, carbonate rock and washed-in, Quaternary clay, fine sand and nordic pebbles occur secondarily as cavity filling.

In normally developed caprock one can distinguish several caprock types from the top to the salt surface that have different structures and characteristics and that can be encountered in many salt surface boreholes. It is therefore usually not possible to come to any conclusion about the underlying salt rock by means of the rock characteristics in the caprock.

It is worth noting that during drilling in the caprock, only little mud loss occurred in contrast to many other salt domes. Most of the former cavities were filled with washed-in Quaternary material.

3.1.2 The Evolutionary History of the Salt Dome

The general features of the evolutionary history of the Gorleben Salt Dome are known [3]. It can be derived from a geological section of the salt dome and the adjacent areas (cf. Fig. 4). Initial indications of the formation of a salt pillow are given by the thickness of the stratigraphic sequence in the time period from Upper Bunter to Muschelkalk. It is smaller at the top than at some distance from it. The thickness distribution in the Keuper Stage indicates very clearly a large salt pillow. In the course of the Jurassic this developed further, until in the period between Upper Jurassic and Lower Cretaceous there was a break-through through the overlying rock. The supply of salt to the forming salt dome took place initially only from the SE flank. The Lower Cretaceous age of the sediments of the SE rim syncline was demonstrated with samples from the borehole Go 1005. Fig. 4 and 5 in Fig. 4 show the further development of the salt dome and its rim synclines in the Upper Cretaceous and in the Tertiary. In the Tertiary the salt flow from the NW flank prevails. The processes in the Tertiary and Quaternary recognizable from the evolution of the overburden are described in Sec. 3.2.

Quantitative data on the uplift rates of the salt dome at different periods cannot yet be provided with satisfactory accuracy. In the current research project entitled 'The Dynamics of the Gorleben Salt Dome' (Research Project KWA 5110 5), appropriate calculations will be made. The planned seismic reflection studies will provide a good data base for these calculations. Already, however, it is possible to estimate that in the break-through period the uplift rate was in the range of tenths of millimeters per year. For the period since the beginning of the Tertiary--i.e. the last 65 million years--it was on the average a maximum of two hundredths of a millimeter per year. By the geologic present it probably decreased to a maximum of one hundredth of a millimeter per year [3]. Other claims advanced by Professor Duphorn [4] can be viewed as unconfirmed with regard to the data used and the research method employed [5].

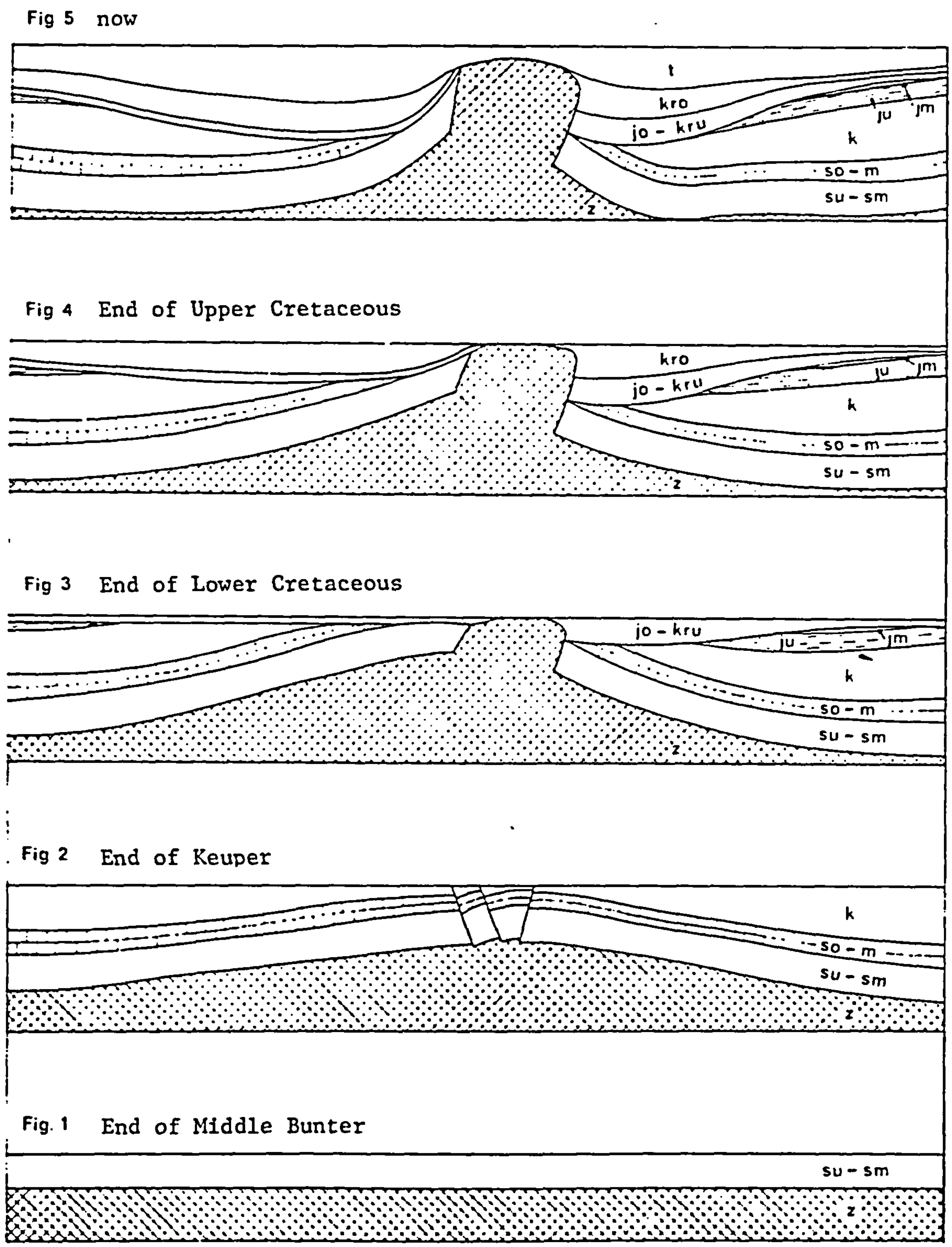


Fig. 4. Evolutionary diagram of the Gorleben Salt Dome. NW-SE section.

3.1.3 The Tectonics of the Salt Dome

As might be expected, the strata throughout the entire salt dome are highly folded. In the cores of the folds the accumulation results in stratigraphic thicknesses which are many times greater than the original thicknesses. On the fold flanks, on the other hand, more or less pronounced thinning of the strata results. Mudstone and anhydrite tend to break. Therefore both the main anhydrite and the salt clays should not be considered continuous strata, as is projected in the cross sections (Fig. 5-6) due to a lack of data, but what is probably involved are individual isolated blocks which have become divorced from their original connection because of the salt uplift.

For the working model of the structure of the salt dome, the results of the drillings permit the following conclusions: at the top of the salt dome all strata are capped because of subrosion (Fig. 3 and 5-7). The internal structure is characterized by inversion down to the level of ca. 600 m - 700 m; i.e., the Stassfurt rock salt, as the oldest strata series in the core, has covered the younger z3 and z4 layers in the boundary regions. The normally folded sequence of strata generally does not begin until a depth of ca. 600 m - 700 m is reached.

Most of the fold axes of minor folds dip relatively shallowly at a maximum angle of 30°. From this we can deduce that the major folds in the salt dome probably also exhibit a more or less shallow axial pitch. Documentation showing that overlapping folds are major folds which require steep-axial tectonics has not yet been found. The hypothesis which was already advanced rather early on in the course of the drilling program, namely that overlapping folds are probably lacking, was confirmed in the subsequent drilling operation.

The outline or geologic map (Fig. 3) of the top of the salt dome explains the research findings described. The map shows the boreholes which reached the saliniferous formation. Two structural elements are recognizable in the center of the salt dome: the uplift zones of Stassfurt rock salt, slightly shifted to the NW--the actual core zone and the 'main saddle' of the salt dome. In the NW it is bordered by the Stassfurt potash seam, gray salt pelite and main anhydrite, as well as z3 strata and probably also z4 strata. The second structural element is the inverted syncline adjacent to the core zone consisting of z3 and z4 layers. In the SE the downfold is bordered by overfolded Stassfurt rock salt from the core zone. The width of the inverted syncline is a function of its respective axial elevation or depth. The higher the axis protrudes, the wider the structure. The width of the core zone of Stassfurt rock salt also corresponds directly to these findings. The wider the inverted syncline is, the narrower the core zone becomes and vice versa.

With reference to three cross sections (Fig. 5-7), the structural outline of the salt dome is clarified. Because steep-axial tectonics probably do not exist at this salt dome level, these sections should provide a rather realistic picture of the salt dome.

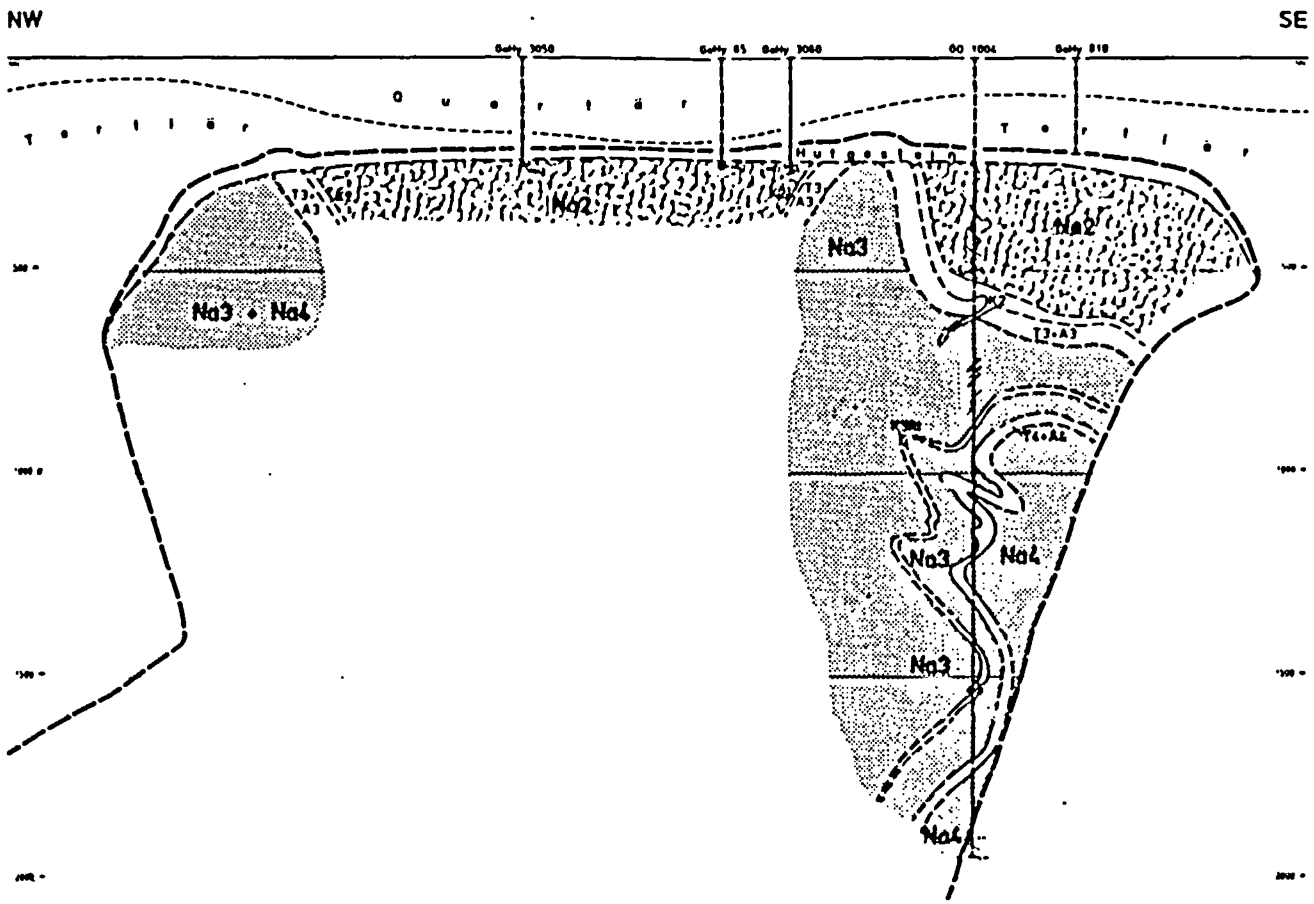


Fig. 5. Cross section through the Gorleben Salt Dome. Profile 1 from Fig. 3.

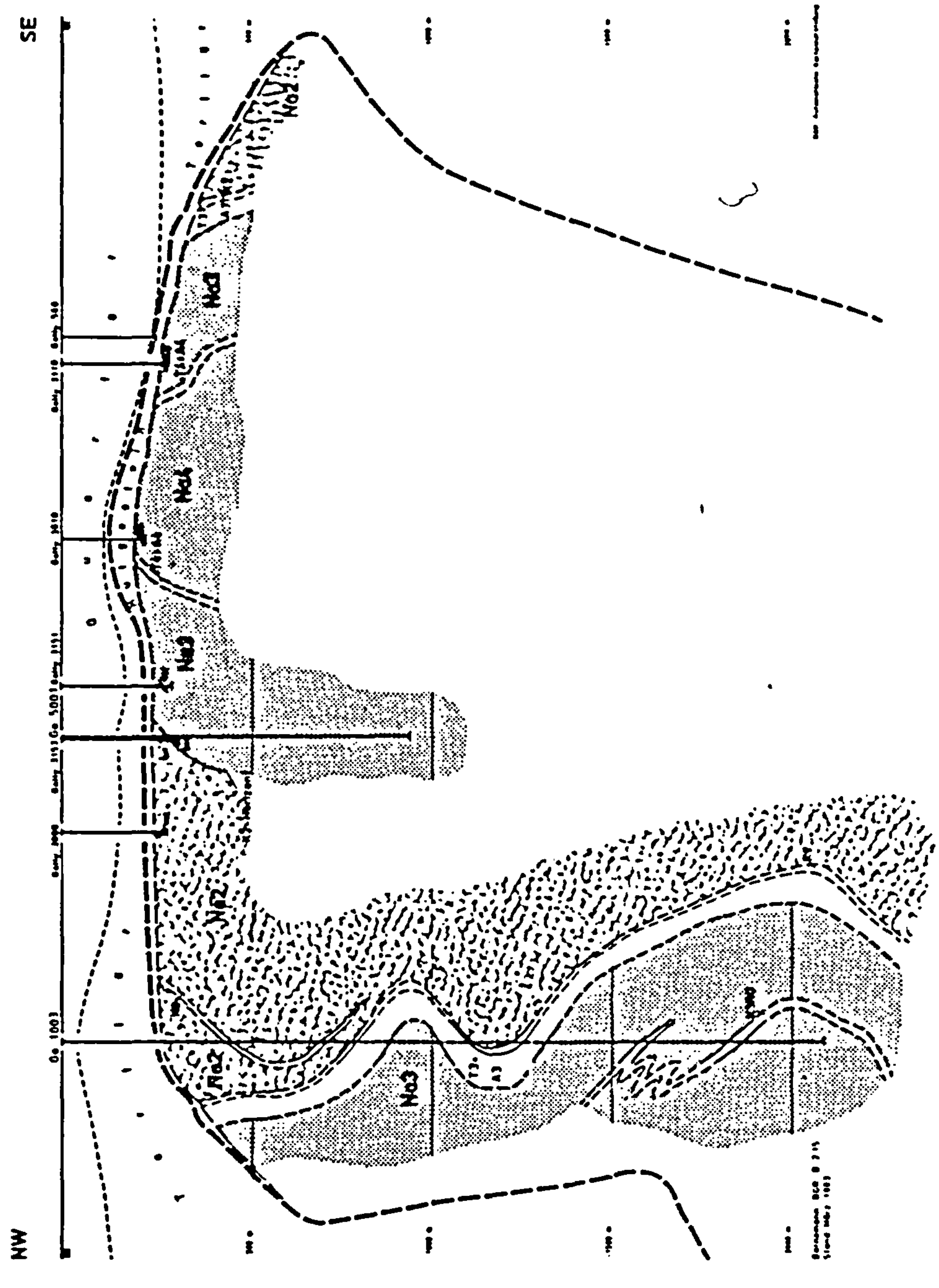


Fig. 6. Cross section through the Gorleben Salt Dome.
Profile 2 from Fig. 3.

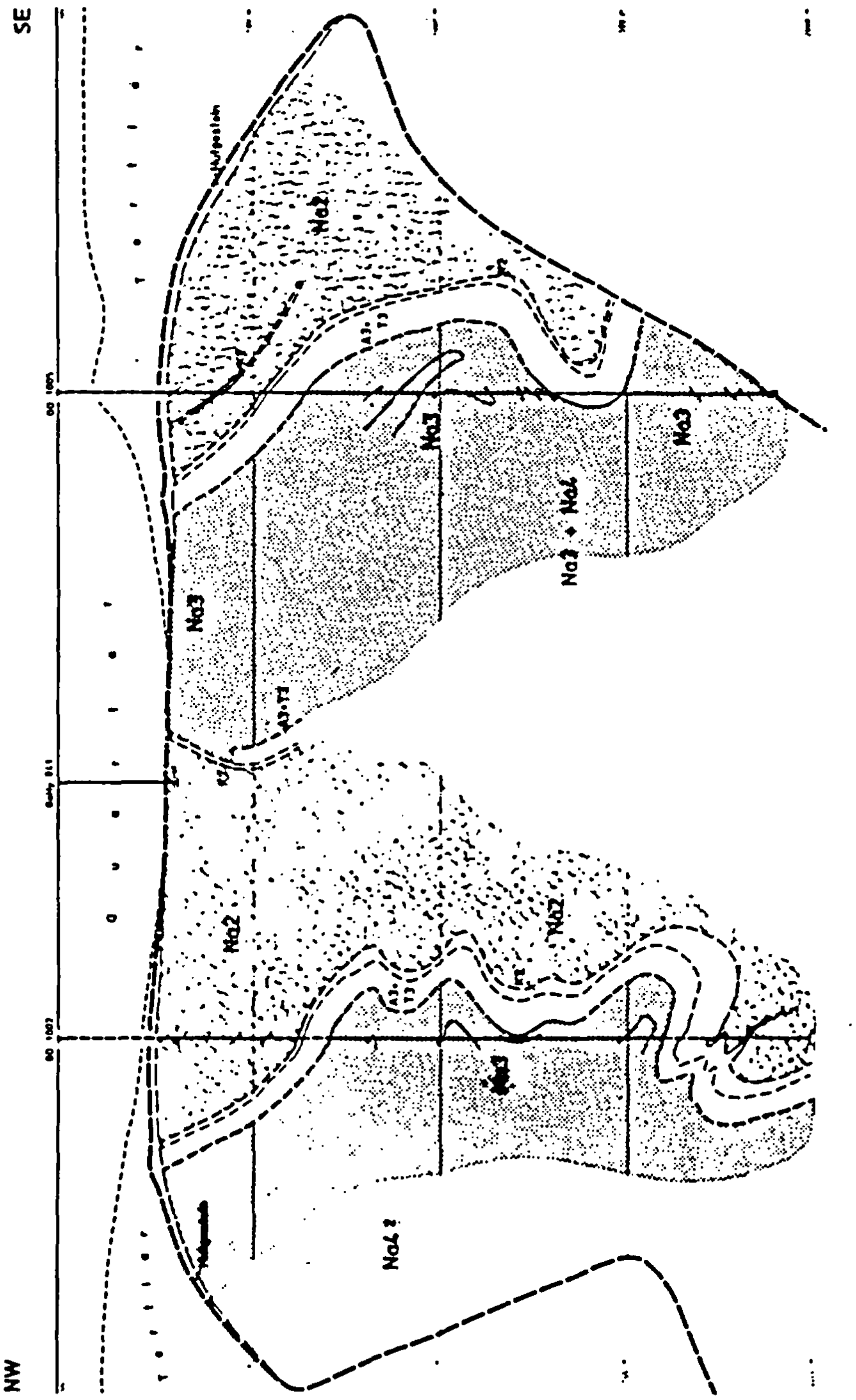


Fig. 7. Cross section through the Gorleben Salt Dome.
Profile 3 from Fig. 3.

Cross section 1 (Fig. 5) is based primarily on the results from deep borehole Go 1004, which intersected intensely folded z3 and z4 strata below Stassfurt rock salt. The boundary between the inverted syncline and the core zone is not yet known in detail. The salt surface borehole GoHy 3060 already encountered Stassfurt rock salt, however, so that the syncline can only be narrow in the area of the salt surface. Axially it is very deep at this point. The northwest limit of the core zone is projected and not proved here.

In cross section 2 (Fig. 6) the inverted downfold is very wide and is uplifted here to the greatest extent. The Aller rock salt is exposed at the top of the salt dome and has been detected by borehole GoHy 3010. The northwestern boundary between z2 and z3 was intersected in borehole GoHy 3153 and in the preliminary shaft borehold Go 5001, whereas the southwestern boundary is only projected. The deep borehole Go 1003 shows the highly folded NW flank of the core zone.

Cross section 3 (Fig. 7) is based primarily on the results of deep boreholes Go 1002 and Go 1005, which are both in intensely folded border regions. The northwestern boundary of the inverted syncline is projected and is based on the result of the salt surface drill hole GoHy 515. The drill hole Go 1005 bored through the flank of the salt dome shortly before the final depth was reached. Salt rocks of the Aller Series were not found; one can assume that they are folded into the core of the inverted syncline. In contrast to cross section 2, the inverted syncline plunges down steeply in cross section 3. The results of electromagnetic reflection measurements were taken into account in constructing the cross sections. This is especially true for the areas which are located at distances up to about 200 m from the deep boreholes.

To the east of cross section 3, in the area of the greatest transverse width of the salt dome, the most recent drilling results from the salt surface boreholes GoHy 1121 - GoHy 1181 show that the layout is somewhat more complicated here. Along with the primarily flank-parallel orientation of the fold axes in the area of the three cross sections described above, a second axial direction at right angles to the main direction appears to be more fully formed to the northeast. In addition, an essentially normal stratigraphic sequence was found in the boreholes, in contrast to the SW region, i.e. the boreholes intersected in each case the underlying formation.

Large areas of the salt dome have been left out of the cross sections. Projections extending further down would overinterpret the research results obtained to date.

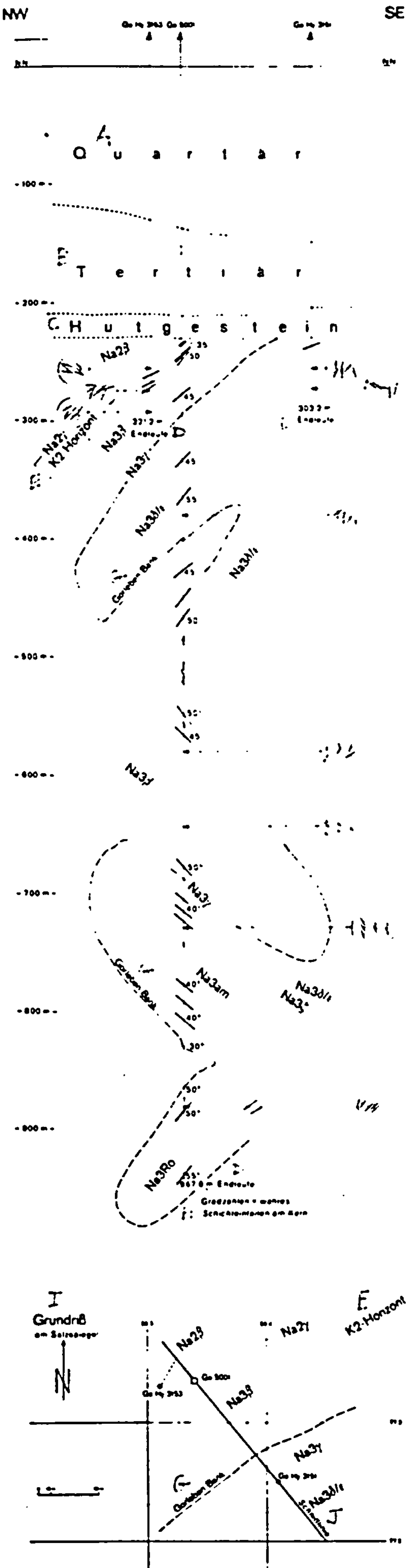
The salt surface boreholes GoHy 3151 - 3155 were located specifically for the purpose of preliminary exploration of the locations for the two preliminary shaft boreholes. What was sought was the boundary running between the inverted syncline containing Leine and Aller rock salt and the core zone containing Stassfurt rock salt (Fig. 6).

The shafts which will be sunk are to be located in strata of Leine rock salt over their entire length if possible for reasons of better stability. K2, T3 and A3 and the most recent Na3 and z4 strata should be avoided by the shaft structure if at all possible [6].

The results of the two preliminary shaft drillings Go 5001 and Go 5002 are now available (Fig. 8). As expected, the boreholes primarily intersected intensely folded Na3 strata, which are therefore repeated many times (primarily in the area of the strata from the Ronnenberg group). The higher Na3 strata, such as anhydrite band salt and swath salt, are below the planned shaft sumps. In the profile of the future shafts, strata which would be difficult to control were not encountered. From a geological standpoint, therefore, the sites investigated are suitable as shaft locations.

Figure 8. Stratigraphic sequence intersected by drilling in the prelimary shaft boreholes Go 5001 and Go 5002 [see next page]

Key:
A Quaternary
B Tertiary
C caprock
D final depth
E K2 horizon
F (hypothesized)
G Gorleben Bed
H even numbers = true bedding dip at core
I outline at salt surface
J intersection line


NW
SE
Quartär
Tertiär
Hutgestein
Na2β
K2 Horizont
Na3β
Na3γ
Na3δ/ε
Gorleben Bank
Na3am
Na3Ro
Endteufe
Gradzonen + wahres Schichteinfallen am Kern
Grundriß am Salzspiegel
K2-Horizont
Na2γ


NW
SE
Quartär
Tertiär
Hutgestein
A3
T3
Na2β
Na2γ
Na2K
K2
Na3β
Na3γ
K2 Horizont
Na3δ/ε
Gorleben Bank
Na3am
Endteufe
Gradzonen + wahres Schichteinfallen am Kern
Grundriß am Salzspiegel
K2-Horizont
Na3δ/ε

3.1.4 The Material Components of the Salt Dome

From the description of the strata found in the salt dome (Sec. 3.1.1) it is already clear that the rocks in the salt dome consist for the major part of rock salt. In addition, however, there are several other minerals or rocks as well as solutions and gases. In this section we will deal only with the solid constituents, whereas the gas inclusions will be treated in Section 3.1.6 and the solutions in 3.1.7.

The previous openings in the rock salt are not sufficient for carrying out accurate calculations of the mineral content. This can only take place after underground exploration.

Rough estimates of the mineral content in the Zechstein stratigraphic sequence are already possible, however: besides rock salt there are significant quantities of mudstone, anhydrite and carnallite rock. The average total thickness of all mudstones can be estimated at about 40 m, that of the anhydrite at about 75 m, and that of the carnallite rocks at about 20 m to 25 m. The thicknesses of the rock salt sequences are only partially known. If we begin with the general idea that the total thickness of the Zechstein amounted to 1000 m or somewhat more originally, then the proportion of rock salt in the sequence can be estimated at about 85% to 88%.

There are over 500 chemical analyses available of the rock salt series. They show that the rock salt consists up to about 96% of the mineral halite (mineral or rock salt). The remaining approximately 4% is composed of anhydrite, polyhalite, kieserite, argillaceous minerals and several additional salt minerals. The amount of anhydrite far exceeds that of any other mineral.

Of the potash salt seams, only the carnallitic Stassfurt seam is of any significance from a deposit standpoint, because only this seam occurs in the salt dome in wide distribution in a thickness which is necessary for the recovery of potash salts. A number of analyses shows that the average K_2O content is barely 6% and thus far below the minability limit.

3.1.5 Initial Estimate of Emplacement Areas

On the basis of the repository plans (see Chap. 5) an areal requirement of about 1.3 km^2 was determined for the wastes to be emplaced in chambers. The more highly heat-producing wastes to be emplaced in boreholes require an area of about 2.1 km^2. For all emplacement fields including the spaces between them, therefore, an area of approximately 3.4 km^2 is required.

According to initial estimates based on the drilling results, there is probably approximately 6 cm^2 of useful emplacement area available in Stassfurt rock salt (Na2) at a depth of 800 m and about 2.5 cm^2 emplacement area in the region of the lower Leine rock salt (Na3β - Na3ζ). These estimated areas can be verified in all probability, because the area to be explored in the salt dome will be about 18 km^2, according to the overall operating plan. There is therefore a ratio of explored area to estimated area to required area of 18 : 8.5 : 3.4 km^2. Although no capacity problems are expected for the planned mined repository on the basis of this initial estimate, proof cannot be provided until underground exploration is completed.

3.1.6 Hydrocarbons in the Salt Dome

The existence of hydrocarbons has been known for some time in the salt mining industry in many districts. This is also true of mines in several salt domes in Lower Saxony.

In the Gorleben Salt Dome there have been sporadic releases of liquid and gaseous hydrocarbons in boreholes Go 5001 and Go 5002. These liquid hydrocarbons have a condensate-like character, i.e. they contain primarily low-boiling components. Gaseous hydrocarbons have been associated with the condensates.

Samples of the gases were taken from the boreholes and analyzed in the laboratory as gas-air mixtures. Gas chromatographic analyses for determination of the composition of the hydrocarbons were carried out as well as isotopic analyses of methane, ethane and propane. The condensates have been examined for certain proportions of the low-boiling hydrocarbons and for the distribution of aromatics in the hydrocarbons.

The samples taken from the two boreholes at different times were very similar to one another, according to all investigative methods. Except for the different amount of air added, the gaseous and the liquid hydrocarbons have virtually the same composition. One can therefore assume with both deposits that they are hydrocarbons from the same formation process.

The methane of the gaseous hydrocarbons has a mean isotopic composition of

$$\delta^{13}C = -\ 45\ ^{o}/oo$$

$$\delta\ D = -\ 170\ ^{o}/oo$$

This isotopic composition of methane is characteristic for gases which are associated with liquid hydrocarbons. The mean isotopic composition for methane from Rotliegendes [New Red] gases from the environs of the Gorleben salt dome is

$$\delta^{13}C = -\ 24\ ^{o}/oo\ \text{to}\ -\ 20\ ^{o}/oo$$

$$\delta\ D = -\ 124\ ^{o}/oo\ \text{to}\ -\ 120\ ^{o}/oo$$

With respect to methane, therefore, the Rotliegendes gases are so different isotopically from the methane occurring in the boreholes that a derivation of the gaseous hydrocarbons in the salt dome from the Rotliegendes gases can be ruled out. This statement can be made with great certainty, since in the Wustrow-Gorleben region the variation in the Rotliegendes gases is precisely known.

In other areas of the North German Zechstein basin it is known that small fractions of condensate-like hydrocarbons accumulate with natural gases from reservoirs in Buntsandstein, Zechstein and Carboniferous formations. Therefore for the purpose of comparison with the liquid hydrocarbons from

Gorleben, tests of Zechstein condensates in one sample each from Gorleben and from the Emsland were made. The analysis of aromatics in one sample each from Gorleben and from Zechstein condensates showed clearly that the two sample groups can definitely be differentiated as regards their aromatic concentration distribution. Likewise, in both groups the so-called iso-heptane values are very clearly different. Other correlation parameters for the C_6 - C_7 hydrocarbons naturally show similarities, since we are dealing with low-boiling hydrocarbons. Here similarities naturally exist in all condensate-like hydrocarbons. The gaseous and the liquid hydrocarbons in the Zechstein salt of the Gorleben Salt Dome accordingly have no similarity on the basis of composition with hydrocarbons such as have been found to date in other Zechstein and Pre-Zechstein formations.

As mentioned briefly above, the gaseous hydrocarbons, especially methane, have an isotopic composition which is typical for natural gas, which occurs in association with oil in Mesozoic deposits in NW Germany. A derivation of the gases and condensates in the salt dome from Mesozoic oil deposits is, however, very improbable for several regional-geological reasons: seismic reflection profiles above the Gorleben Salt Dome indicate that the known potential oil reservoir rocks of the Upper Keuper, the Lias and the Dogger are not adjacent to the salt dome flanks but crop out at a considerable distance. Therefore a transfer of oil from such strata into the salt dome must be ruled out on the basis of geologic structure. The same is also true for the NW flank for the Lower Cretaceous strata, which do not begin until the Albian stage. Only on the SE flank do strata of the deeper Lower Cretaceous occur in the rim syncline of the salt dome. They are detected in borehole Go 1005, but do not contain any traces of oil or natural gas at this point either.

In summary, the studies show that the gases occurring in the salt dome cannot be derived from the pre-Zechstein formations below the salt dome. Instead, they were formed in the salt dome itself from condensates by means of cracking processes. The condensates also do not originate from the pre-Zechstein formations. A penetration of hydrocarbons into the salt dome from the outside from Mesozoic series is improbable. The condensates may have been formed by thermal transformation of the organic substance present in the salt dome itself or in the basal Zechstein strata.

3.1.7 Solutions

The chemical material components of the various evaporite deposits in Central and North Germany include solid material but secondarily also liquid and gaseous compounds and elements. From the formation and alteration processes in the salt rocks it is known that these solid, liquid and gaseous constituents of the evaporite bodies are in a genetic relationship with one another and therefore must not be analyzed in isolation.

Between a body of salt (salt beds in flat or steep stratification) and the adjacent rock or overburden there have been and still are periods of major and minor interactions. The result of such interactions, for example, are the clearly detectable mineral alterations and mass transports which took place above all during the deformation and folding of the salt rocks (salt dome formation). The initiating cause of mineral reactions was the formation of locally and chronologically limited paths between the surrounding rocks and the salt dome via which unsaturated aqueous solutions came in contact with the salt rocks (see in this regard also [7]). The proof of these processes, their physical-chemical formulation, and their geochemical interpretation today forms a part of the basic verified knowledge of modern salt deposit science.

Once brines are detected in evaporite bodies, one must ask how and when the solutions were formed and where they come from. In order to answer these questions one needs, among other things, information about the stratigraphic horizon of solution emergence and about the concentration, the chemical composition and the flow rates of the brines.

In Tab. 2 the salt solutions found in the four deep boreholes at Gorleben are described. The data included in the table are taken from [10] and from studies which were carried out by or under contract to DBE [11].

Table 2. Salt solutions in the salt dome exploratory boreholes Gorleben 1002 through 1005

A Bohrung	B Beobachteter 1. Zufluß	C Stratigraphie des Lösungsaustritts	D Teufe m	E Zuflußmenge m^3	F Datum der Probe	G Dichte g/cm^3	H Chemische Zusammensetzung I Verbindung	J Massenkonzentration g/dm^3	K Massenanteil %	L Stoffmengenanteil mol/kmol (H_2O)
Gorleben 1002	22.05.80	M Hauptanhydrit (A3), durchsetzt mit flockenartigen Carnallititeinschlüssen	wahrscheinlich 661,2	28,7 F von 22.05.80 G bis 28.02.83	21.10.81	1,280	NaCl	24,7	1,93	8,47
							KCl	28,6	2,23	7,67
							$MgCl_2$	306,9	24,0	64,6
							$CaCl_2$	22,1	1,73	4,0
							$CaSO_4$	0,44	0,03	0,06
							$CaCO_3$	0,49	0,04	0,1
							H_2O	896,8	70,0	1000
							Br	4,10	0,321	
							Li	0,042	0,0034	
Gorleben 1003	22.01.80	N Staßfurt- bzw. Älteres Steinsalz (Na2); der Zufluß kam aus der Hangendsalz (Na2)	431 -449	[illegible],6[illegible] F. Gesamtzufluß	24.01.80	1,312	NaCl	12,7	0,97	4,3
							KCl	6,7	0,51	1,8
							$MgCl_2$	383,7	29,2	80,2
							$MgSO_4$	10,1	0,77	1,7
							$CaSO_4$	2,4	0,18	0,35
							H_2O	896,4	68,4	1000
							Br	7,02	0,535	
							Li	0,066	0,0050	
Gorleben 1004	07.05.82[1]	O Hauptanhydrit (A3)	596,3 -626,8	< 1 geschätzt	11.05.82	1,263	NaCl	40,8	3,2	14,0
							KCl	35,9	2,8	9,7
							$MgCl_2$	286,5	22,7	60,5
							$CaCl_2$	3,5	0,28	0,63
							$CaSO_4$	2,2	0,17	0,32
							H_2O	894,1	70,9	1000
							Br	2,17	0,172	
							Li	0,023	0,0018	
Gorleben 1005	18.03.81[1]	O Hauptanhydrit (A3)	1421,1 -1475,3 1499,3 -1520,3	94,4 F von 18.03.81 G bis 18.01.82	23.02.82	1,353	NaCl	4,13	0,31	1,44
							KCl	1,42	0,10	0,39
							$MgCl_2$	438,9	32,4	94,1
							$CaCl_2$	29,9	2,21	5,5
							$CaSO_4$	0,07	0,005	0,01
							H_2O	876,6	65,0	1000
							Br	7,26	0,537	
							Li	0,193	0,0143	

Key:
- A borehole
- B 1st influx observed [day-month-year]
- C stratigraphy of solution emergence
- D depth
- E flow rate
- F date of sample [day-month-year]
- G density
- H chemical composition
- I compound
- J mass per unit volume
- K mass fraction
- L substance amount fraction
- M main anhydrite (A3), interspersed with flake-like carnallitite inclusions
- N Stassfurt or Older Rock Salt (Na2); inflow came from the overlying salt (Na2γ)

O main anhydrite (A3)
P from [day-month-year]
Q to [day-month-year]
R total inflow
S estimated

Notes to Table 2:

Boreholes 1002 and 1005: The total salt content and the chemical composition of the solutions remained virtually the same during the observation periods. The $CaCl_2$ component of the salt solutions can come perhaps only in part from the drilling fluid used [8].
Borehole 1002: Besides the influx mentioned above, solution inflow was also identified during ongoing tests in the depth zones 1009 m - 1013 m and 1610 m - 1645 m (ducts of main anhydrite). It was not possible to take samples because of the small amounts of solution.
Borehole 1003: The total salt content and the chemical composition of the solution remained practically constant during the observation period. By means of cementation and the installation of a tour to a depth of 550 m the influx point was sealed. No more solution influx was detected during further drilling operations.
Borehole 1004: The borehole was filled to the surface after the exporation work was completed.
Borehole 1005: During a test at the final depth zone of the borehold (1930.0 m) a small influx from the adjacent rock below the salt dome was detected under hydrostatic pressure but it was not great enough to be measured [9]. These borehole was sunk through the salt dome flank and was stopped in the wall rock at the final depth given above.

Preliminary shaft boreholes 5001 and 5002: no influx of solution was observed in the preliminary shaft boreholes.

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1) After conclusion of the drilling during test activities.

From a practical standpoint it proved advisable to distinguish between three groups of salt solutions or brines (Tab. 3, see also [12]). Group 1 includes solutions which originated in connection with the development, alteration and geologic situation of the salt deposit. Group 2 contains solutions the origin of which can be attributed directly or indirectly to mining activities. And Group 3 contains solutions which are formed during the processing of potash salts and get into the mine along with the backfill and/or as drilling fluids.

Table 3. Possibilities for the genesis and origin of salt solutions in potash and rock salt mines. From [12], p. 174.

Group 1	Geology, Deposit	Group 2	Mine	Group 3	Factory
1.1	surface and ground water	2.1	shaft solutions	3.1	hydraulic stowing solution
1.2	formation water	2.2	ventilation solutions	3.2	dry stowing solutions
1.3	metamorphic solutions	2.3	drilling solutions	3.3	solutions from crude salt processing
1.4	residual solutions from salt deposition basins ('primeval brines')	2.4	shaft sump		

In the Gorleben Salt Dome, groups 2 and 3 of Tab. 3 are not present because there has not yet been any mining nor specifically any salt mining in this salt body to date. The surface water, ground water and formation water of Group 1 indicates solutions which occur in the overburden and/or and wall rock of the salt dome. If such generally unsaturated water penetrates the salt deposits, it reacts primarily with the highly soluble minerals such as rock salt, sylvin and carnallite. In the process solutions are formed which differ in chemical composition from the water in the area surrounding the salt dome. From the chemistry of these solutions it is normally possible to determine whether they are remains of geologically old solutions in sealed reservoirs in the salt dome interior, so-called metamorphic solutions, or solutions which are presently in contact with the salt dome environment. Balance calculations show that the metamorphic solutions left the salt rock again in the geologic past for the major part [13]. In the case of the solutions found to date in the Gorleben deep boreholes it is necessary to investigate above all whether they involve surface water and formation water from the area adjoining the salt dome (wall rock, overlying rock) or whether they are the residue of geologically old metamorphic solutions.

The residue of metamorphic solutions, sometimes together with gases, form within the body of salt reservoirs that are currently sealed. The volumes of such solutions range from the order of magnitude of liters to an estimated 1000 m^3. Differences in the given volumes are possible. In order to prevent misconceptions we should point out that none of the types of solutions listed in Tab. 3 involve the microscopically small inclusions of solutions in salt crystals which are also frequently the topic of discussion.

The analyzed solutions from the Gorleben deep boreholes belong to two different types of saturated salt solutions (Fig. 9, 10): 1) solutions containing a high $MgCl_2$ content (1003, initially also 1002), 2) solutions containing a high $MgCl_2$ content with a $CaCl_2$ component (1002 beginning in September 1980, 1004 and 1005). Solutions with $CaCl_2$ components are also known from other bodies of salt in flat and steep stratification. Normally, however, the $MgCl_2$ solutions lacking a $CaCl_2$ component are predominant.

The reservoir rocks for the solutions from the Gorleben deep boreholes were identified as main anhydrite (1002, 1004, 1005) and in borehole Go 1003 the highest section of the Stassfurt rock salt directly below the Stassfurt potash salt seam. These reservoir rocks also correspond to observations made in other salt domes. In those cases the anhydrite horizons are also the preferred reservoir rocks for salt solutions, whereas the rock salt and potash salt strata are found to contain stored solutions less frequently.

A high $MgCl_2$ component is characteristic without exception for all four Gorleben solutions. Similar solution types have been found again and again in all salt deposit districts of Germany (Magdeburg-Halberstadt, Unstrut-Saale, South Harz, Werra-Fulda, South and North Hannover).

These solutions containing a high amount of $MgCl_2$ allow us to make the following basic statement: neither the high $MgCl_2$ fraction nor the $CaCl_2$ component can have gotten in the salt solutions by dissolution of the present reservoir rocks anhydrite ($CaSO_4$) and rock salt (NaCl).

Symbol	A Haupt-gruppe	B Massenanteil g/100 g (Lösung)
+	1	bis 0,1
Δ	2	> 0,1 bis 3,5
x	3	> 3,5 bis 14
*	4	> 14 bis 27
O	5	> 27

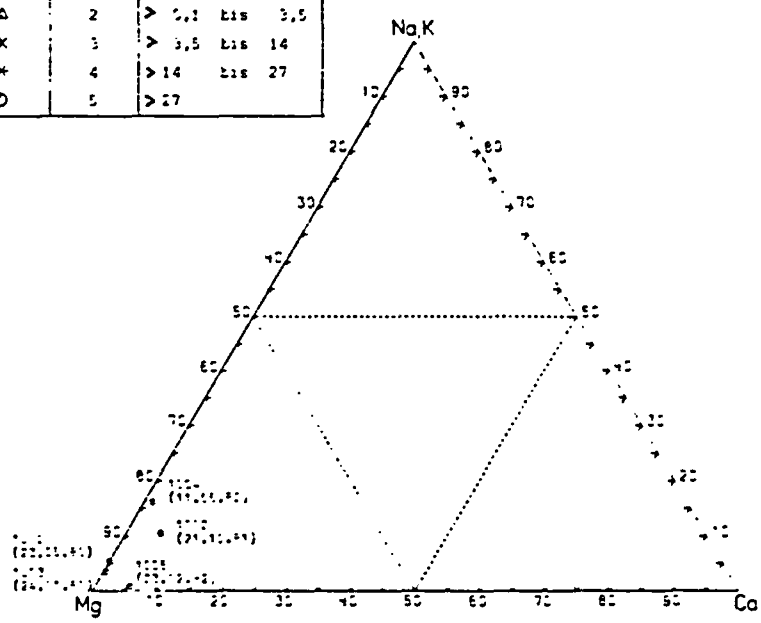

Fig. 9. Concentration of salt solutions
[Key: A = main group, B = mass fraction g/100 g (solution), bis = to]

Symbol	Unter-gruppe (A)	Stoffmengenanteil mol/kmol (H_2O) (B)
△	A	$NaCl$ > KCl, $MgCl_2$
+	B	KCl > $NaCl$, $MgCl_2$
✱	C	$MgCl_2$ > $NaCl$, KCl
○	D	$CaCl_2$ > C

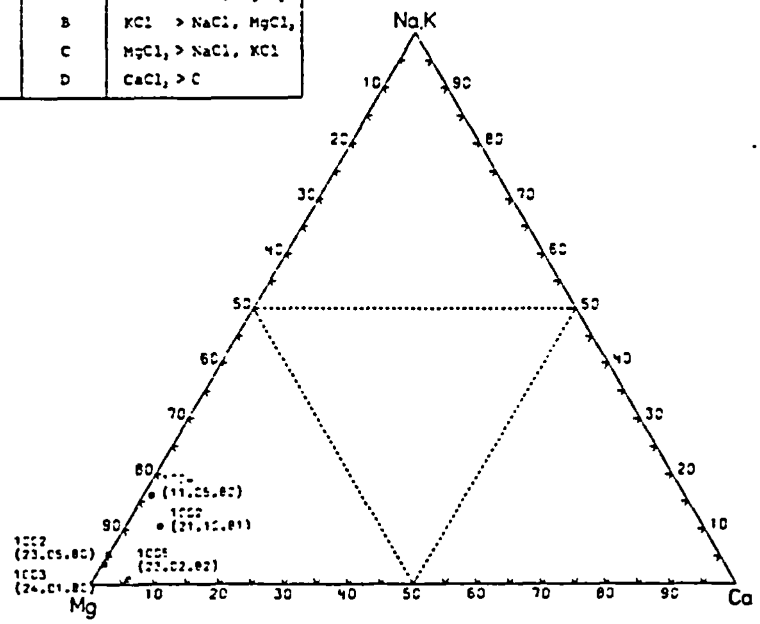

Fig. 10. Chemical composition of salt solutions
[Key: A = subgroup, B = percentage of substance amount]

According to present knowledge, there is only one rock within the Gorleben salt dome from which the $MgCl_2$ component could have passed into the Gorleben deep borehole solutions by reaction with unsaturated aqueous solutions. This is the rock carnallitite, which occurs in the Gorleben salt dome primarily in the Stassfurt potash seam and also in the potash seams of the Leine Series, which are only present in certain places. A potential supplier of $MgCl_2$ could also be the mineral bischofite ($MgCl_2 \cdot 6H_2O$), which has not yet been found at Gorleben. The $CaCl_2$ component can theoretically enter the solutions by dissolution of $CaCl_2$ minerals such as tachyhydrite ($CaMg_2Cl_6 \cdot 12H_2O$), by reactions with the carbonate components of the saliferous clay, or by sulfate reduction within the body of salt. Another possibility is the penetration of formation water already containing $CaCl_2$

from the wall rock into the strata of the salt dome at some unknown time in the geologic past.

The solutions confirm a fact that has been known for some time and is supported by observations of all Zechstein evaporite bodies, namely that the present reservoir rock of many salt solutions is not identical with the place of origin and the rock of origin of the solutions. Because the carnallitite strata from which the $MgCl_2$ component of the solutions stems are spatially separated from the present reservoir rocks, the solutions must have moved within the salt body from the place of origin via paths that cannot be precisely determined to the present reservoir rock. The solution paths are limited not only to anhydrite and saliferous clay horizons but they can also occur in rock salt strata. This statement is based on the secondary mineral formations found in anhydrite (e.g. boreholes 1002, 1003), saliferous clay, rock salt and in potash salt rocks. Absolute age determinations indicate that there are connections between solution movement and an intense deformation of the evaporite strata. One should emphasize in this connection the observation that solution influxes in a salt dome are not limited only to depth zones above 1000 m. In boreholes 1002 and 1005 solution emergence from the main anhydrite and the wall rock was also detected at depths between 1000 m and 1900 m. These findings are of importance for the interpretation of the evolutionary history of brine reservoirs and the flow movements of brines in the salt dome.

Of interest is the question regarding how rapidly or how slowly fracture deformations can arise and solution movements occur in salt bodies under specific conditions. Basic information is provided by the basaltic dikes which are interstratified with the Zechstein evaporites of the Werra region. There the opening of gaps up to more than 100 cm in width and the penetration of basaltic melts into the cavities can be considered as a process, for all practical purposes. A separation that can be interpreted chronologically between the gap formation in chloride rocks, on the one hand, and the penetration of basalt melts, on the other hand, can hardly be expected in a closed salt rock because of the physical properties of the evaporites. Based on these considerations, the formation of routing and the penetration of solutions into the routing system probably also largely coincides in salt domes. The secondary minerals (see above) which can frequently be observed today in such routes must have crystallized in a temperature gradient, since in sealed salt rock no evaporation of water takes place. The cooling of salt solutions is only possible if they pass from warmer salt dome regions (greater depths) into zones with lower temperatures (shallower depths). The detection of solution emergence in the Gorleben deep boreholes up to depths of about 2000 m provides interesting scientific evidence for such a mechanism. In salt domes 'linear' routing can have a width of several millimeters to centimeters. It therefore seems conceivable that, under the conditions of a deformation of the evaporite strata, horizontal and vertical solution movements over distances ranging between meters and hundreds of meters do not have to last several million years but can also take place in shorter periods. In this regard one might think of flow paths in the anhydrite, among other things, which has a jointing tendency.

The quantitative calculation of saliferous process sequences including element balance calculation for the secondary constituents Br and Li shows that the solutions from the deep boreholes are residues of metamorphic solutions which were formed during deformation of the salt rocks and the resulting mineral reactions and mass transport [14].

Measurements of the pressures to which the solutions were subjected and also their chemical composition permits the conclusion that there is no detectable routing at least at the present time between the wall rock and the brine reservoirs in the salt dome that have been investigated. Experience has shown that the consequence of this would be that in the course of time the $MgCl_2$ components and the total salt contents of the solutions flowing into the boreholes decrease, whereas the NaCl component increases. There were, however, no indications of any such development at the time of the investigations [14]. The emergence of solutions from the salt rock into the boreholes took place under pressures which were above the expected hydrostatic pressures [10]. This means that the solutions of the deep boreholes were located in reservoirs sealed by secondary mineral formation and plastic deformation, under high pressures. When these reservoirs are opened by drilling or mining, the solutions exit under pressure and are usually exhausted after a period of time, according to experience with other salt domes. If connections exist or are formed, on the other hand, between the emergence points under ground and surface water, then the hydrostatic pressures of the flow system are measured at the solution influx points [10].

On the basis of the present state of exploration by means of deep boreholes and taking into account data collected in other salt domes, we can hypothesize that solution reservoirs in the Gorleben Salt Dome occur in limited areas (anhydrite, secondarily also chloride rocks) of the rock body. Therefore in Gorleben as in other flat and steep bedded salt bodies we must reckon with the fact that brine reservoirs will be encountered during underground mining operations and that these will then run out. It must also be kept in mind that after the outflow of an initially limited solution reservoir it is possible that presently sealed routing to the wall rock and the overlying rock can be reopened. In such a case the danger of additional solution influxes could not be ruled out.

Potash and rock salt mining in Zechstein salts proves that brine reservoirs do not necessarily make underground mining impossible. The problem of salt solutions can in most cases be recognized early, evaluated and also controlled because of the foundation of experience acquired over a period of 120 years. All previous observations indicate that when other salt domes are explored, solutions will be encountered in salt rock by deep drilling and underground mining.

The brine reservoirs that presently exist in the salt rock become significant in connection with the emplacement of highly heat-producing radioactive wastes. With another deformation of the salt rocks it might happen that former paths that are now sealed could open again. This, however, would create the preconditions for a new mobilization of the brines which are currently sealed in the salt body and for possible brine movements between evaporite bodies and the wall rock or overlying rock.

3.1.8 Oil and Natural Gas Deposits Outside the Salt Dome

In the environs of the Gorleben Salt Dome there are several formations containing porous rocks that are possible locations for the storage of hydrocarbons (oil or natural gas).

The deepest rocks investigated belong to the Rotliegendes [New Red Sandstone] Age. The borehole designated as Gorleben Z 1 struck a gas-bearing sandstone at a depth of 3649 m [15]. The inflowing gas was not combustible. More than 90% of it consists of nitrogen [16]. In the same borehole traces of petroleum were found in a thin layer within the Werra anhydrite. Tests did not show any inflow, however. The sandstone horizons of the Bunter [Sandstone] lifted up on the NW flank of the salt dome did not show any traces of hydrocarbons.

Other reservoir rocks are found in Upper Keuper [Upper Triassic], Lias [Lower Jurassic] and Dogger [Middle Jurassic] formations. These strata do not occur at locations immediately adjacent to the salt dome. In the environs they have been investigated a number of times by means of drilling operations, but no hydrocarbons have been found. Reservoir rocks from the Upper Jurassic to Lower Cretaceous time periods can also be expected finally in the rim syncline on the SE flank of the salt dome. The borehole designated as Go 1005 intersected these strata without encountering hydrocarbons. Several oil wells drilled in the general vicinity were intended to investigate these strata in structurally favorable positions. None of them yielded oil.

There is no reliable information regarding any gas deposit near Lenzen (north of the Elbe River). However, what is involved here is apparently not a gas deposit, for no gas deposit is given for this location in the appropriate documents of the GDR [East Germany] [17].

3.2 The Overburden

3.2.1 The Geology of the Overburden

3.2.1.1 Stratigraphic Sequence

Except for sporadic relics of Cretaceous formations, the overburden of the Gorleben Salt Dome consists of sediments from the Tertiary and Quaternary periods. They have been described in detail in the interim reports on the hydrogeological investigation program [18-21]. In the following a short summary description of the Tertiary and Quarternary stratigraphic sequence will be given.

Tertiary

An overview of the Tertiary stratigraphy and the type and former range of Tertiary sediments is shown in Fig. 11.

Paleocene and Older Sediments

The oldest sediments that can be detected above the salt dome stem from the period extending from the Upper Cretaceous to the Paleocene. They have been found in the course of drilling in small thicknesses (3 m - 4 m) in karst caves of the caprock or immediately on top of the cap. The limestone and marlstone of the Cretaceous period are found preferentially on the edge of the salt dome roof and occur in the greatest thicknesses yet found by drilling in these areas. Millimeter-thin, gray layers of tuffites occur approximately at the boundary between Paleocene and Lower Eocene sediments.

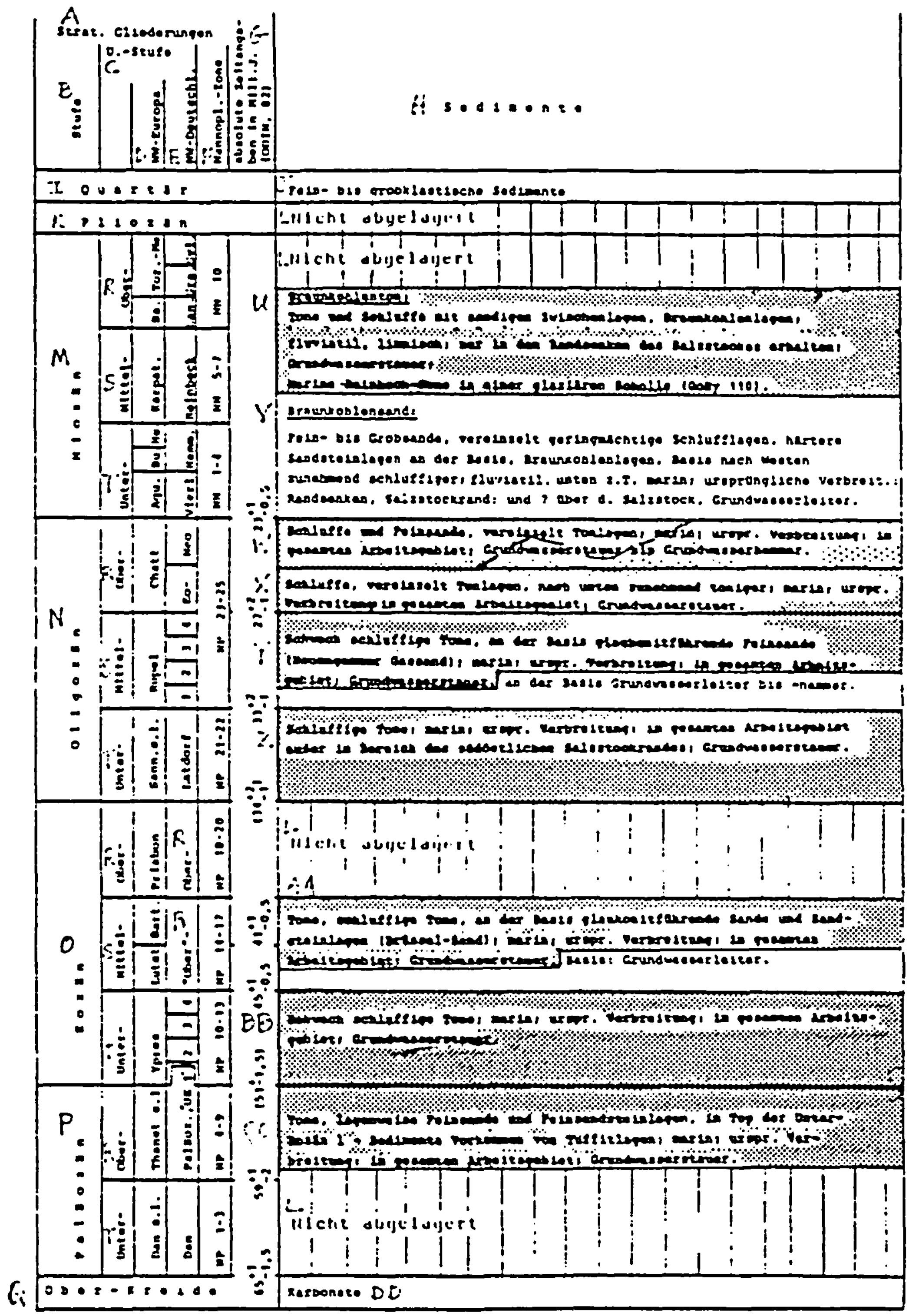

Fig. 11. Overview diagram of the Tertiary stratigraphy and associated sediments in the Gorleben area [see key next page]

Key to Fig. 11:

A stratigraphic divisions
B stage
C substage
D NW Europe
E NW Germany
F nannoplankton zone
G absolute times in million years
H sediments
I Quaternary
J finely to coarsely clastic sediments
K Pliocene
L not deposited
M Miocene
N Oligocene
O Eocene
P Paleocene
Q Upper Cretaceous
R Upper
S Middle
T Lower
U Brown-Coal Clay:
Clays and silts with sandy interlayers, brown-coal layers, fluvial, limnic; preserved only in the rim synclines of the salt dome; aquicludes.
Marine [...]* in a glacial block ([...]* 110)
V Brown-Coal Sand:
Fine to coarse sands, scattered thin silt layers, harder sandstone layers at the base, brown-coal layers, base increasingly siltier to the west; fluvial, at the bottom partly marine; original range:
rim synclines, salt dome edge; and ? above the salt dome, aquifers.
W Silts and fine sands, scattered clay layers; [...]*; original range: in the entire area under investigation; aquicludes to ground-water inhibitors.
X Silts, scattered clay layers, increasingly more argillaceous toward the bottom; marine; orig. range in entire area under investigation; aquicludes.
Y Slightly silty clays, at the base glauconite-bearing fine sands ([...]* gas sand); marine; orig. range: in the entire area under investigation; aquicludes; at the base, aquifers to ground-water inhibitors
Z Silty clays; marine; orig. range: in entire area under investigation except in the area of the southeastern salt dome rim; aquicludes.
AA Clays, silty clays, at the base glauconite-bearing sands and sandstone layers (Brussels sand); marine; orig. range: in entire area under investigation; aquicludes; base: aquifers.
BB Slightly silty clays; marine; orig. range: in entire area under investigation; aquicludes.
CC Clays, by layers fine sands and fine sandstone layers, at the top of Lower Eocene 1 - sediments deposits of tuffite layers; marine; orig. range: in entire area under investigation; aquicludes.
DD carbonates

aquifers
aquitards
aquifuges

* Illegible in translator's copy of original--Translator's Note

Eocene

Clays or silty clays were generally deposited in the Eocene, interstratified with sandy, partially solidified strata approximately 8 m to 20 m thick ('Brussels sandstone'). The sandy layers are aquifers of low yield.

The sediments are Lower and Middle Eocene in age. Upper Eocene strata were not deposited in the area under investigation.

Oligocene

The sediments of the Lower and Middle Oligocene consists predominantly of clays with varying proportions of silt. Occasionally there is a greater lime content, sometimes in the form of calcareous concretions. Fine-sand layers and silty fine sands--frequently highly glauconitic--are typical for the Middle Oligocene base. Above the Middle Oligocene are clays and silts of the Upper Oligocene, which are replaced by silty fine sands.

Miocene

Characteristic of the lower Miocene in the area under investigation are the non-calcareous, highly humic, terrestrial brown-coal sands. They contain in some places brown-coal seams up to 15 m thick.

At the beginning of the Miocene the area under investigation was broken down into two interlocking facies areas. In the eastern and southeastern sections fine sands were deposited. They contain up to five more or less easily detectable sandstone layers. The boreholes in the western regions, on the other hand, show a more silty Miocene base, and no more solid sandstone layers can be found.

Above the brown-coal sand are deposited clays and silts with thin brown-coal seams from the Middle Miocene. The brown-coal clays are dissected by fine sand sections. Above the brown-coal clays follow fine to medium sands. Interstratified with them are larger brown-coal-bearing silt and clay groups.

In the borehole designated as GoHy 110, silts and fine sands about 43 m thick were found which, according to micropaleontological studies, represent a marine Reinbek facies. This deposit, however, is a block that drifted because of advancing glacier ice, because a Quaternary till or boulder clay was found at the base of the silt.

Younger Tertiary sediments (Upper Miocene and Pliocene) in definite autochthonous stratification have not been found in the area under investigation.

The structural-geological conditions of the Tertiary strata in the Gorleben area correspond to the conditions that are customarily observed in the region of a salt dome. The subsidence of the strata which took place in the subsoil next to the salt dome because of salt migration during the aftermovements in the Tertiary was more pronounced in the northwestern rim syncline that in the southeast (see Fig. 4 in Sec. 3.1).

Halokinetically caused disturbances of the overlying strata on the salt dome with definite amounts of fill have been found in only a few places on the northwestern salt dome shoulder, on the central part of the southeast salt dome shoulder and in the area of the two preliminary shaft boreholes Go 5001 and Go 5002. The primarily argillaceous Tertiary strata have absorbed the stress largely without fracture. Microtectonic studies [20] show that the stress on the Tertiary strata above the salt dome increases with depth. Up to about 15 m above the caprock there is a region in which the strata are intensively broken by joints, small faults and slickensides.

Bedding disturbances which were caused by the continental glaciers of the ice ages are described in the final report entitled 'Quartärgeologische Gesamtinterpretation Gorleben' ['Overall Quaternary Geological Interpretation for Gorleben'] written by Prof. Duphorn's team [4].

Quaternary

Figure 12 gives an overview of the Quaternary sediments in the Gorleben area and their stratigraphic order.

Pre-Elsterian Age

The sediments of the Pre-Elsterian Age consists primarily of fine to middle sands in which scattered silt layers are interstratified. The occurrence of the strata is limited to an area above the central and southwest part of the salt dome, where they were deposited in a former subrosion depression (Fig. 13).

Elsterian Ice Age

The sequence consisting of till, glaciofluvial sands and basin deposits (Lauenburg clay complex) has its greatest thickness within the Gorleben channel. Characteristic of the channel zone --primarily in the upper zone of the filling--are thick clays and silts (Lauenburg clay complex) of the Elsterian Ice Age, which in other parts of the area under investigation were not deposited or were eroded during subsequent ice ages.

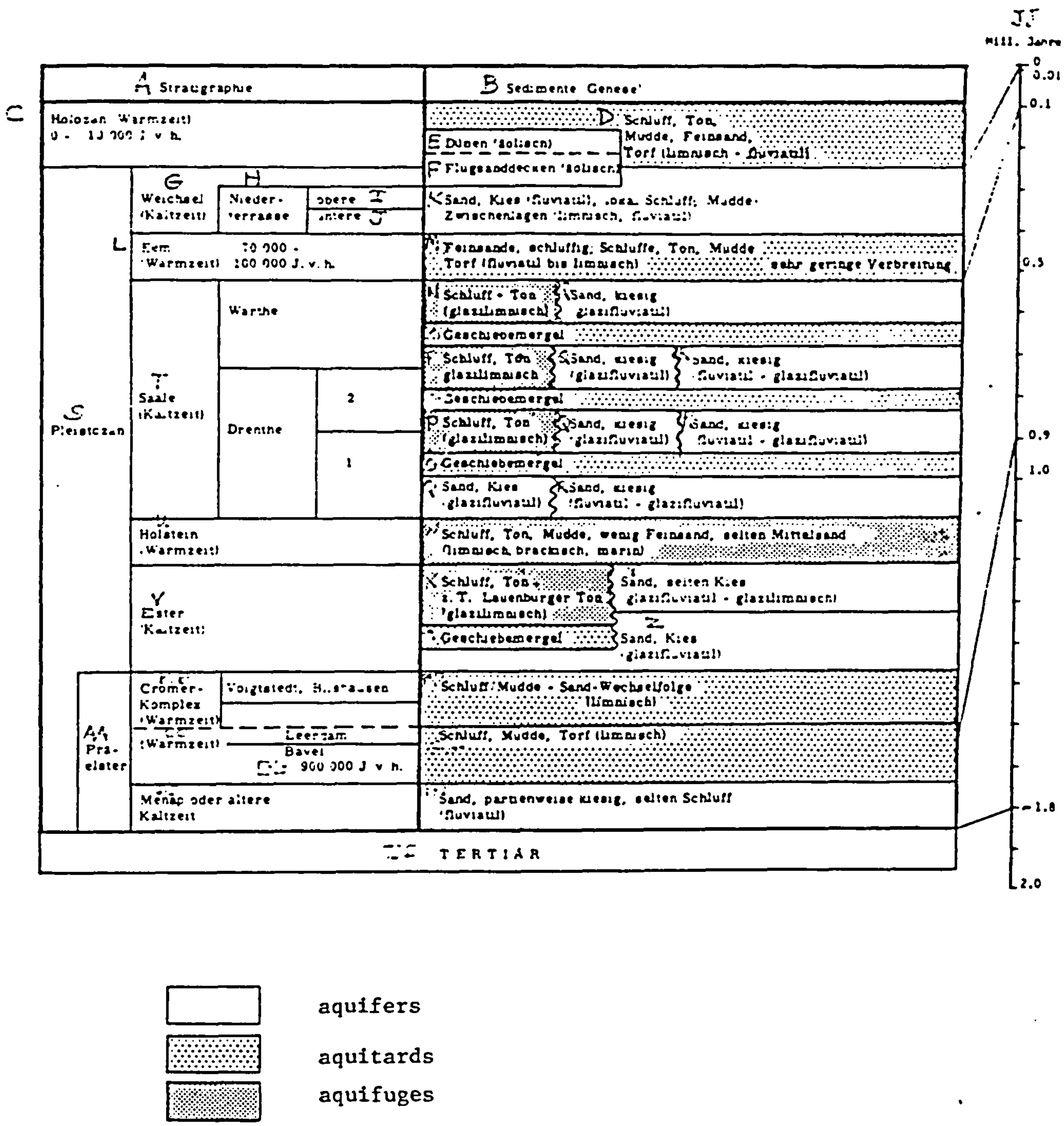

Fig. 12. Overview diagram of Quaternary stratigraphy and associated sediments in the Gorleben area [see next page for key]

Key to Fig. 12:

A stratigraphy
B sediments (genesis)
C Holocene (interglacial episode), 0 - 10,000 yrs before the present
D Silt, clay, mud, fine sand, peat (limnic-fluvial)
E dunes (eolian)
F flying sand (eolian)
G Weichsel (ice age)
H lower terrace
I upper
J lower
K Sand, gravel (fluvial), locally silt, mud interlayers (limnic, fluvial)
L Eemian (interglacial episode)
M Fine sands, silty; silts, clay, mud, peat (fluvial to limnic)
very limited range
N Silt + clay (glaciolimnic)
O till
P silt, clay (glaciolimnic)
Q sand, gravelly (glaciofluvial)
R sand, gravelly (fluvial-glaciofluvial)
S Pleistocene
T Saale (ice age)
U Holstein (interglacial episode)
V Esterian (ice age)
W Silt, clay, mud, little fine sand, rarely medium-grained sand
(limnic, brackish, marine)
X Silt, clay and sometimes Lauenburg clay (glaciolimnic)
Y Sand, rarely gravel (glaciofluvial-glaciolimnic)
Z Sand, gravel (glaciofluvial)
AA Pre-Elsterian (ice age)
BB Cromer Complex (interglacial episode)
CC (interglacial episode)
DD Menap Drift [ice age] or older ice age
EE 900,000 years before the present
FF Siltymud - sand alternating sequence (limnic)
GG Silt, mud, peat (limnic)
HH Sand, in parts gravelly, rarely silt (fluvial)
II Tertiary
JJ million years

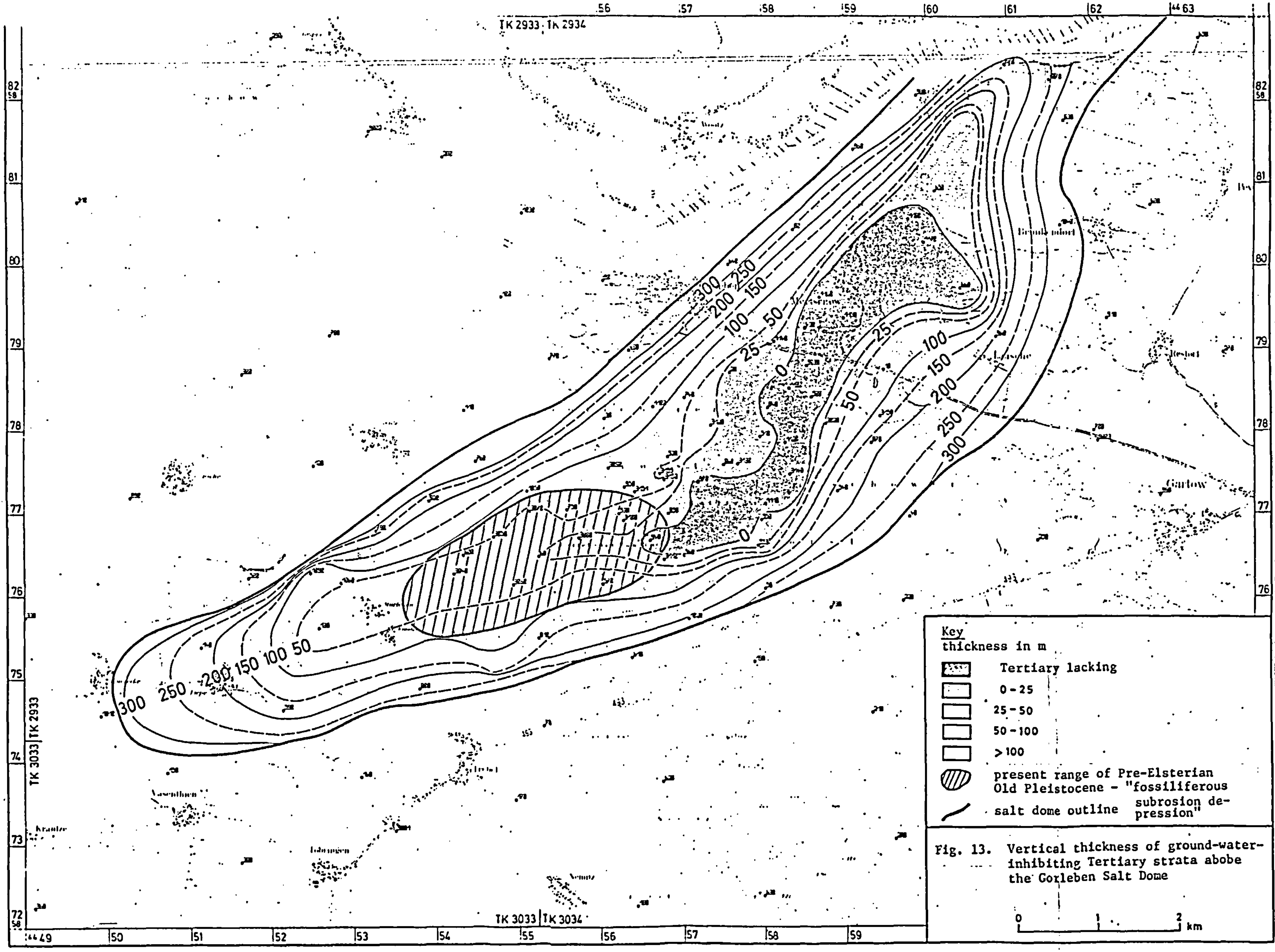

Fig. 13. Vertical thickness of ground-water-inhibiting Tertiary strata abobe the Gorleben Salt Dome

Holstein Interval

The clays, silts and silty fine sands of the Holstein interglacial episode were deposited in a brackish-marine or limnic-fluvial milieu. They fill in cavities which were present at the end of the Elsterian ice age and can therefore be found primarily in areas of the Gorleben channel, sometimes also far to the south of the salt dome.

Clays from the Holstein Interval which lie as isolated blocks in glaciofluvial sands or at the base of tills have been detected in different places. Far-reaching compression and imbrication, as can be observed in the region of the push moraines in the Höhbeck area, where flakes of clays from the Holstein Interval, glaciofluvial sands and boulder clays are mixed with one another, is probable over large areas of the region.

Saale Ice Age

Special Quaternary geological studies showed that during the Saale period three different tills were deposited in the Gorleben area. The two older tills belong to the Drenthe stage, whereas the younger one belongs to the Warthe stage.

Thick tills from both stages are found above the salt dome. Together with Elsterian tills, they can reach thicknesses there of up to 150 m.

Eemian Interglacial Stage

Autochthonous sediments from the Eemian interglacial episode have only been found to date in borehole GoHy 620 to the south of the salt dome. They are 3 m thick deposits formed of fine sand or silt.

Weichsel Ice Age

Deposits from the Weichsel Ice Age are present as the upper stratum in almost the entire area under investigation and consist of gravels and sands (lower and upper sections of lower terrace).

The most important stratigraphic members for the reconstruction of the salt dome development in the Quaternary are the deposits of a subrosion depression from the Lower Quaternary (Pre-Elsterian period) more or less in the Gorleben Tannen area, the filling of a deep cut in the overburden of the salt dome during the Elsterian Ice Age ('Gorleben channel'), and deposits of an arm of the sea from the interglacial period before last ('Holstein clay').

The results of the extensive Quaternary geological studies made by Prof. Duphorn's team [4], which were carried out in conjunction with BGR and Dr. Pickel's office, can be summarized by the following statements:

- The overlying strata above the salt dome are heterogeneous in structure; correlation of the strata is sometimes difficult and only possible locally with high expenditures for drilling and sample-processing operations. Geometric diagrams of the stratigraphic sequence are only suitable after a great deal of schematization for model calculations of ground-water movement (see Sec. 3.2.3). Fig. 14 shows the course of the hydrogeologic sections (Fig. 15 and 16) through the overlying strata.

- The sedimentary filling of a fossiliferous subrosion depression from the Lower Pleistocene (about 900,000 to 500,000 years before the present) is more or less preserved above the central portion of the salt dome (see Fig. 12, 13). The contact between these strata and the caprock, which was intersected at one point by drilling (GoHy 904), is now 239 m below sea level. Limited chronologically (from 900,000 years to 700,000 years before the present) and locally (GoHy904), the leach rate was as high as 0.3 mm/a.

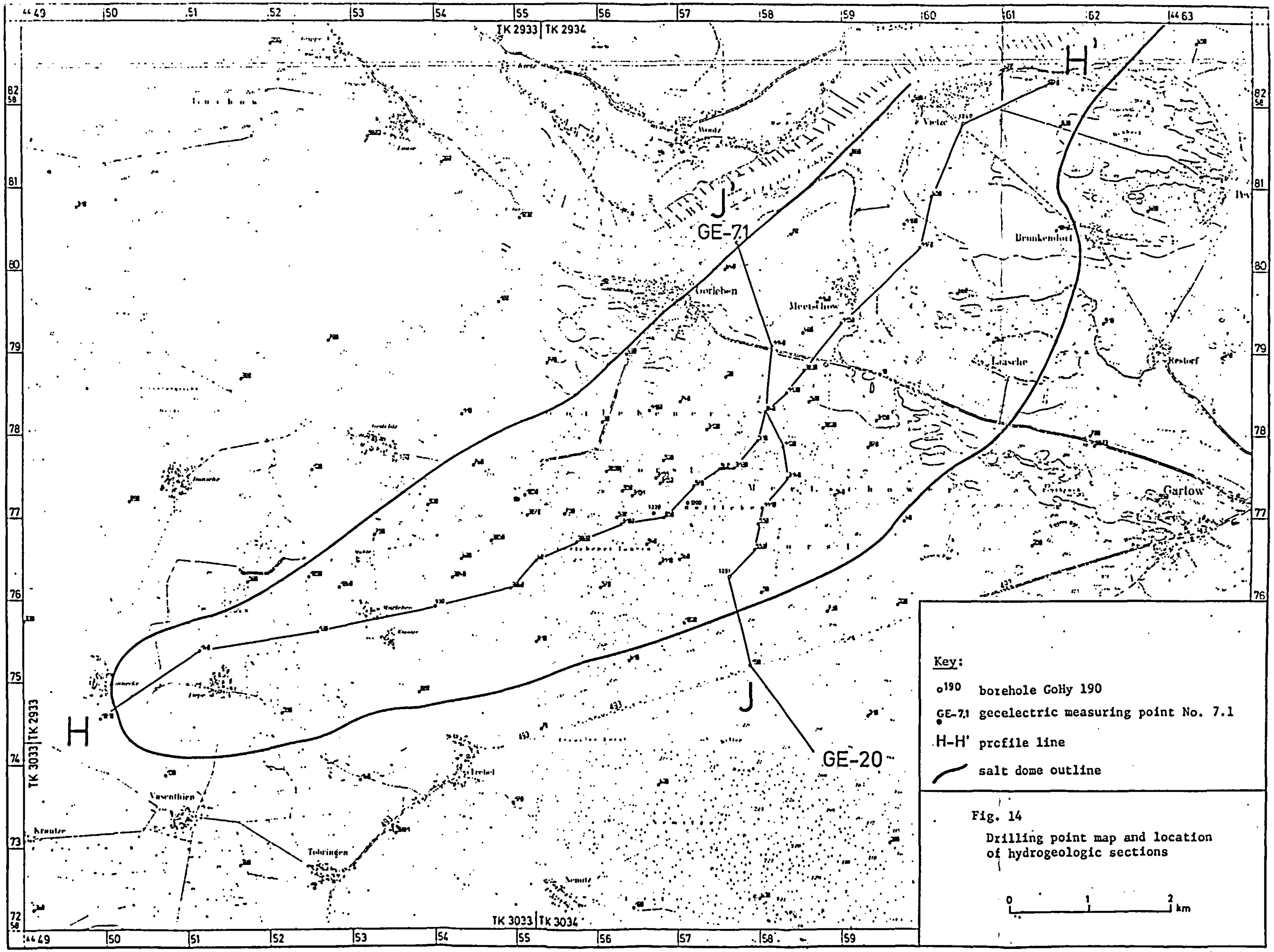

Fig. 14
Drilling point map and location of hydrogeologic sections

Abb. 14

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[Schematic Profile J-J']

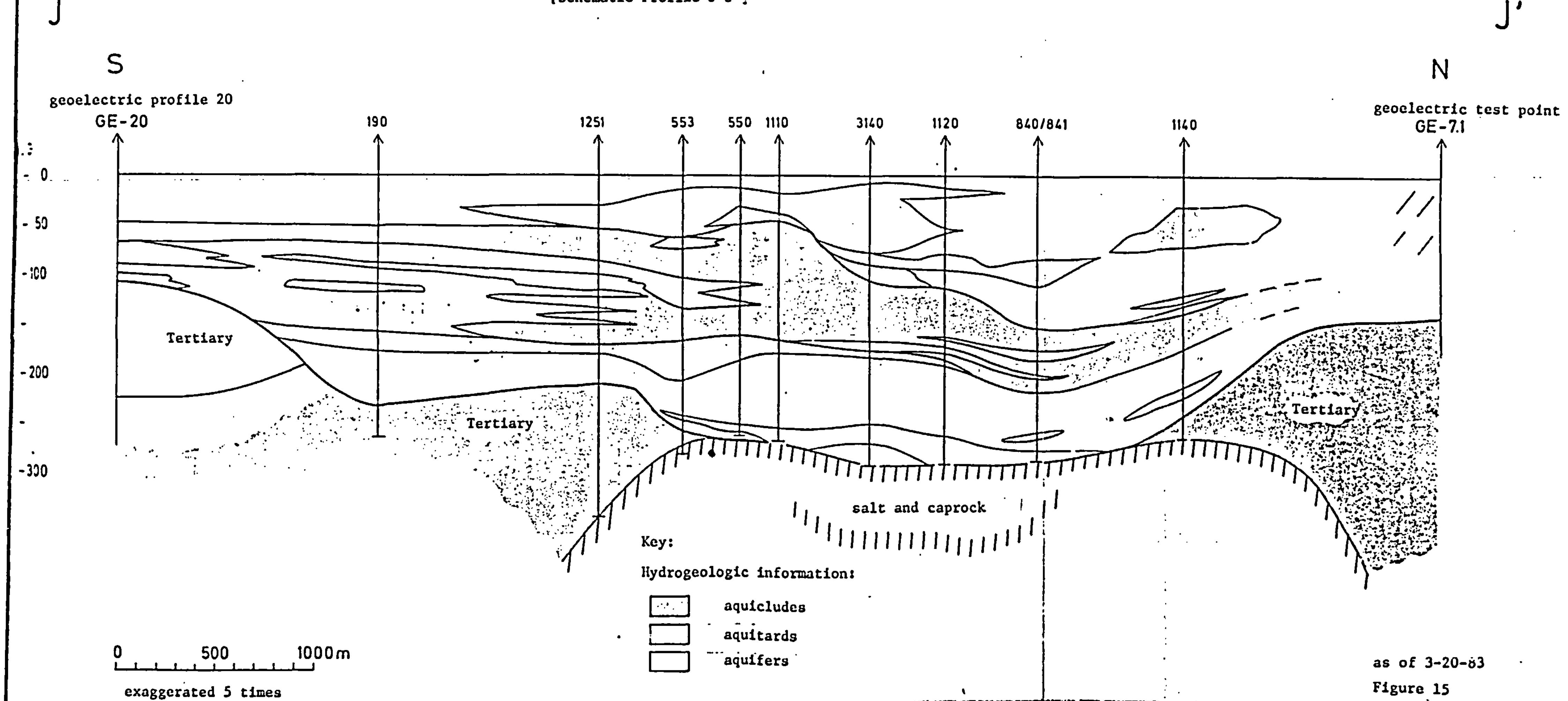

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Figure 15

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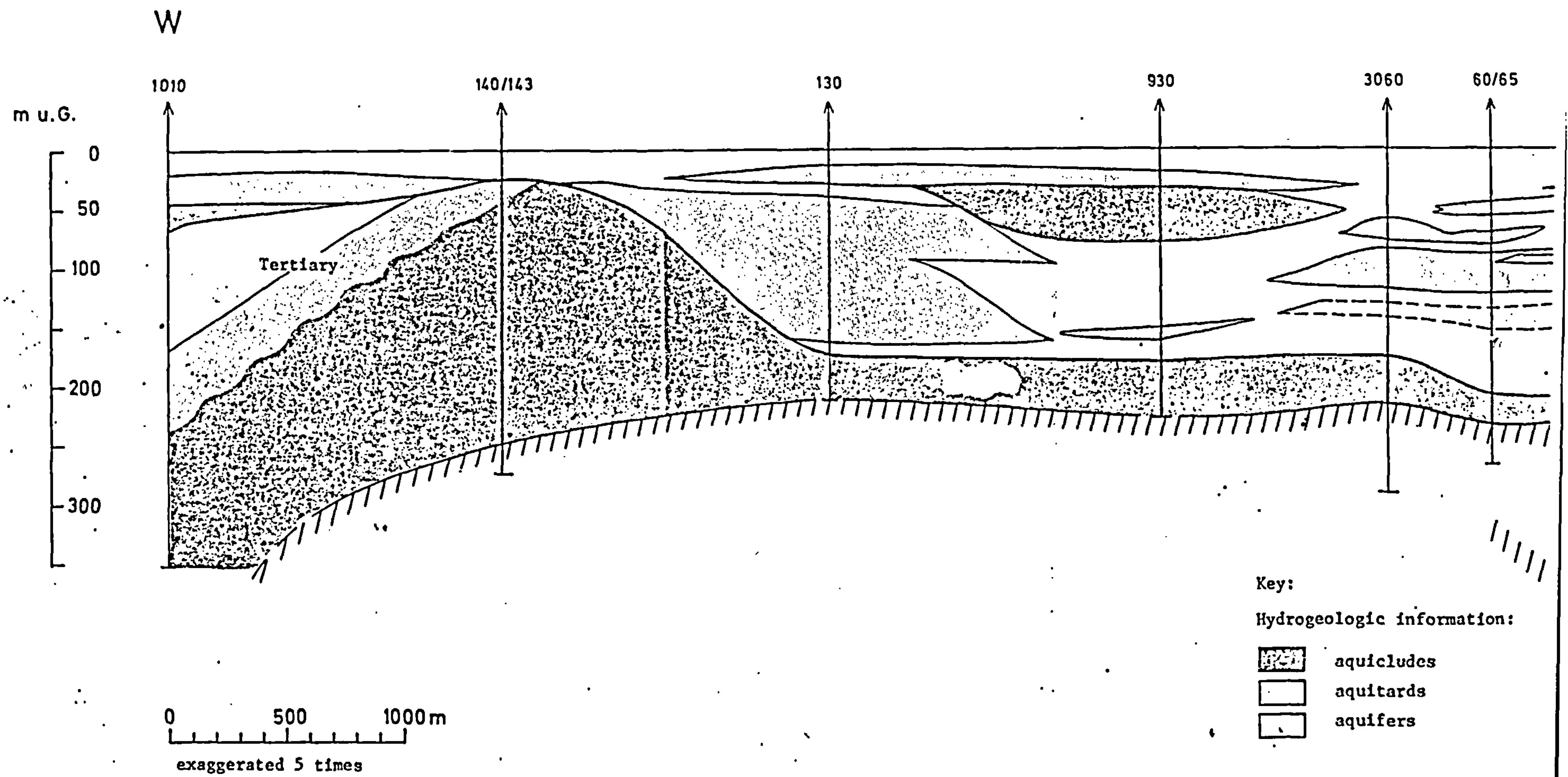

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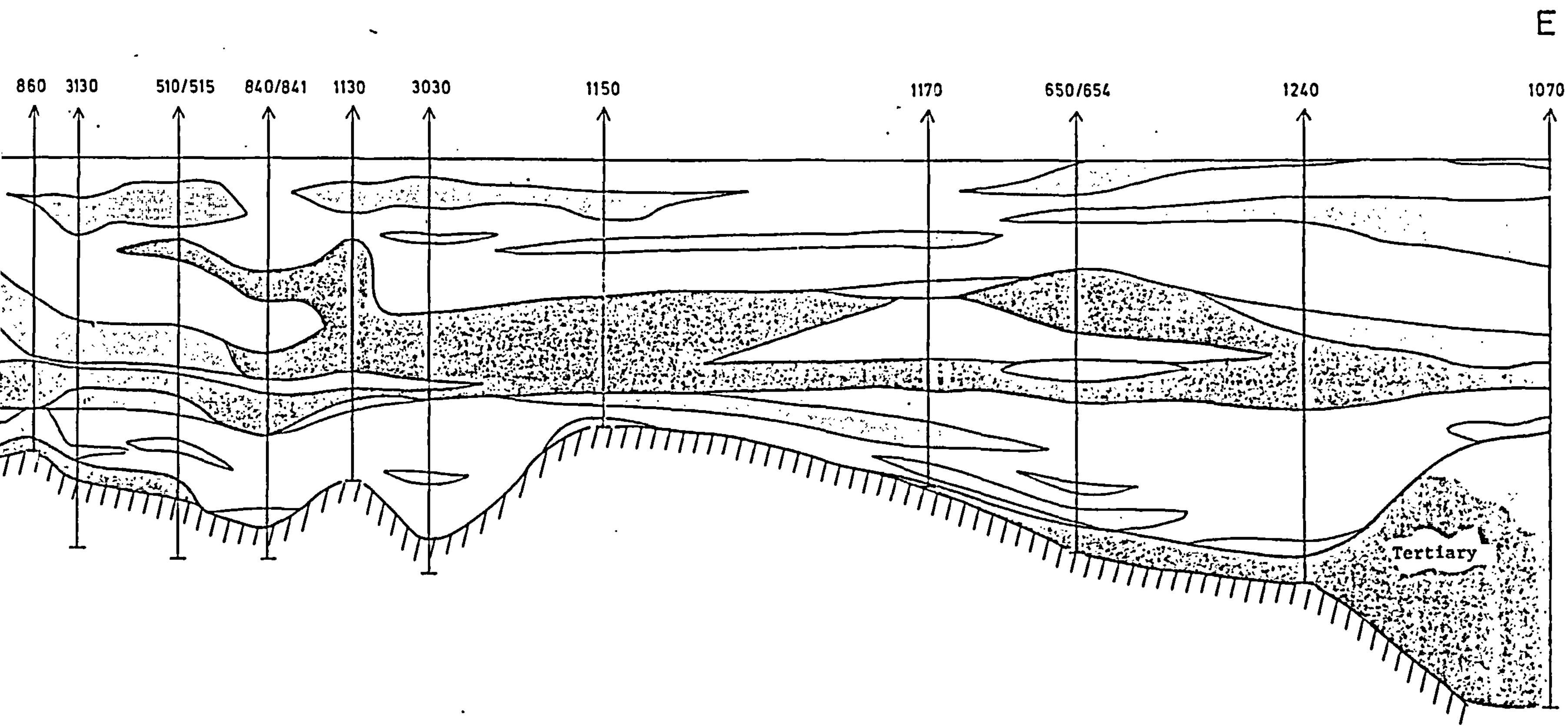

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Figur

- The northeast half of the salt dome, more or less, is covered by a glacial channel or dorr from the Elsterian Ice Age, which has in some places cleared away the older overlying layers down to the caprock or the salt rock.

  A similar, smaller channel that is not as deep lies above the western portion of the salt dome. The 'salt surface' (the top of the salt plug) in the area of the Gorleben channel is about 50 m deeper than in the other parts of the salt dome.

- No hollow subrosion form from any period later than the Warthe Stage (ca. 150,000 years ago) has been detected.

Specific details about the most recent geologic history of the area and the present ground-water movement will be obtained through further exploratory operations in 1983. These will include a core hole drilled into the Lower Quaternary sediments of the fossiliferous subrosion depression, by means of which the duration and the amount of the subrosion at that time can be studied, as well as exploratory boreholes and measuring stations in the vicinity of Gorleben, where the present transport of dissolved salt in the subsurface ground water is to be determined.

3.2.1.2 The Evolutionary History of the Salt Dome in the Tertiary and Quaternary Periods

The Gorleben Salt Dome had passed through the diapiric phase in the period from the Malm to the Lower Cretaceous epochs and had broken through the (Triassic and Jurassic) overburden to the surface (see Sec. 3.1). The wedge-shaped bases of the salt dome that still remained provided slower salt aftermovements in the subsequent history of the salt dome, which gradually died out. The base on the southeast side has been largely consumed since the end of the Tertiary.

After an uplift period in the Upper Cretaceous and at the beginning of the Tertiary, the area around Gorleben containing the salt dome has been subsiding further since the Upper Paleocene (North German Tertiary basin). Except for briefer periods of uplift and subsidence of the earth's crust, which were superimposed on this general trend and which led to large-area stratigraphic gaps, small-area effects of salt migration in the underlying area also influenced the deposition of Tertiary strata. In this way thicker strata were deposited next to the salt dome than above it, where they may even be missing completely. Thus in an area to the south of Gedelitz there are no Paleocene deposits at all, and the sedimentation on the caprock, which at that time lay on the surface of the ocean floor, does not begin until the beginning of the Lower Eocene epochs 2-3.

Likewise, rocks from the Upper Eocene were also not deposited on the salt dome. In the area above the southeast uplift zone this stratigraphic gap extends from the later Middle Eocene to the Lower Oligocene. The continued uplift of the salt dome had therefore led to the formation of a submarine swell or sill and as a consequence to lesser thicknesses, sedimentation gaps, and in places to a local facies.

In the further development the movements of the salt dome caused uparching and expansion of the overlying Tertiary strata, which were then largely eroded above the central area of the salt dome. At the end of the Tertiary the upper edge of the capping rocks in the central region of the salt dome was several tens of meters below the surface, and in some places the caprock reached the surface.

The uplift of the salt dome, averaged over the entire Tertiary period (from 65 to 2 million years ago), was about 0.01 mm to 0.02 mm per year according to present knowledge [18].

The Quaternary (beginning about 2 million years ago and extending up to the present) is a very short time period when measured geologically. In spite of the high resolution, aftermovements of the salt dome are too small to be confirmed for this period using Quaternary stratigraphy. This is also due among other things to the fact that the oldest deposits in the Quaternary outside the salt dome are less than 500,000 years old, about 50 times younger than the youngest Tertiary strata preserved here.

For example, Quaternary geologic evidence of halokinesis from the last approximately 1 million years is not known. Continuous salt movements which approximately correspond in rate to the movements in the Tertiary cannot be assumed, however. The visible changes in the shape of the salt dome are limited to salt leaching at the surface in the Lower Quaternary period, during the Elsterian Ice Age, and possibly in the Saale Ice Age.

Thus the traces of the glaciations which covered the salt dome and left behind deposits--a total of four--are that much more striking.

When the first glaciation advanced ('Elsterian Ice Age'), the salt dome had a substantially higher position with respect to the earth's surface than it does today. The ice and its melt water cleared away the overlying strata and parts of the caprock in the area of the 'Gorleben channel' and filled up the hollow again with sand and till, over which then a widespread clay stratum ('Lauenburg clay') was deposited. Compaction drill holes in the area of the channel have revealed a stratified relief of the channel base, but without anomalous local overdeepening (Fig. 17).

During the subsequent interval of deglaciation ('Holstein Interglacial Episode') the sea level rose so that a fjord-like landscape resulted in which marine and limnic clays were deposited in the region of the old channel. The depth of the ocean inlet at that time, which also extended to the area of present-day Höhbeck, is not exactly known.

The recooling period led to three consecutive glaciations ('Saale Ice Age'), between which there were no interglacial episodes with demonstrable forestation. The deposits of the previous periods, especially the late marine and limnic deposits, were covered over by the glacier, compressed, and pushed together, for example in the Höhbeck area. The subsurface depth of the compression or swell of 100 m to 150 m is almost twice as great as the elevation with which the Höhbeck today protrudes above the region. These severe glacial swells are one reason why the ice age strata are difficult to correlate.

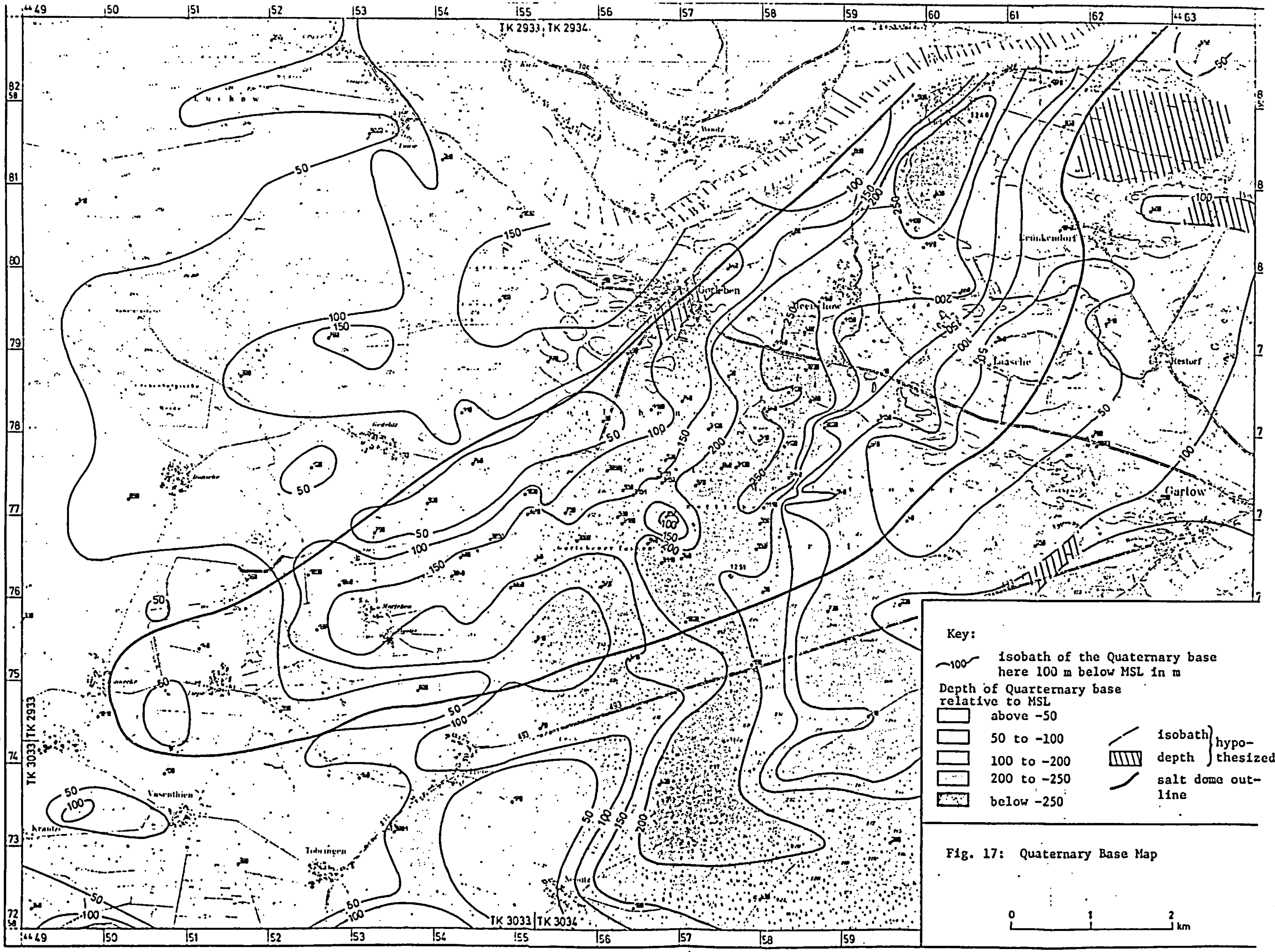


Fig. 17: Quaternary Base Map

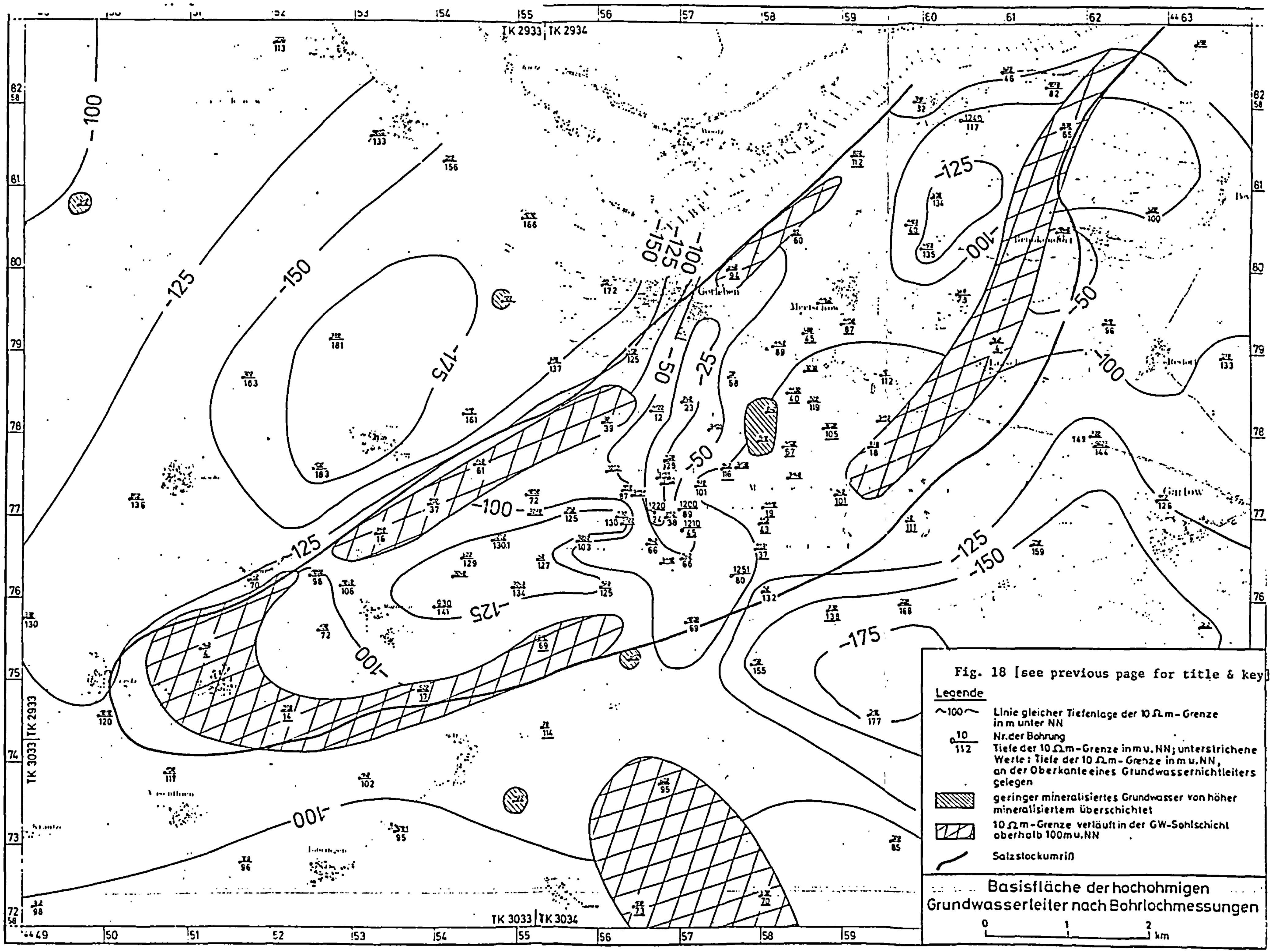


Fig. 18 [see previous page for title & key]

The third and last of these glaciations ('Warthe Stage') has left only superficial traces on the Höhbeck.

No deposits over the salt dome from the last interglacial episode ('Eemian') have been found. We can conclude from this that no more particular subrosion activity took place in this period.

The subsequent, last nordic glaciation to date ('Weichsel Ice Age') did not reach the Gorleben area with its glaciers. The evidence of this period is the cover of sand deposits from the primeval Elbe River, which are spread rather homogeneously over the area. It has not been possible through careful determination of the undersurface of these strata to detect any uplift in the salt dome since the deposition of the Lower Terrace (a maximum of 70,000 years ago) [4].

3.2.1.3 Initial Assessment of the Overburden with Regard to the Barrier Function for Potentially Contaminated Ground Water

The sediments of the Lower Tertiary can be viewed in their totality as beds that are impermeable to ground water (aquicludes). They are present in sufficient thickness in the rim synclines and on the boundaries of the salt dome so that they can retain over a long term any potentially contaminated water stemming from the salt dome. Above the center of the salt dome, however, no Tertiary strata have survived, or if so, only with thicknesses of less than 100 m (Fig. 13).

In the primarily argillaceous Lower Tertiary strata, three different sandy members are present which are slightly aquiferous. They have no significance for ground-water circulation, since the stratigraphic sequence in which they are embedded plunges deep down into the rim syncline. They have therefore no hydraulic connection with the local ground-water recharge areas. The water contained in them can be referred to as deep ground water. It is not very effective for leaching because of its high salt content, and its movement is very limited.

The present range of the older Quaternary sediments of a fossiliferous subrosion depression above the salt dome (Fig. 13) shows that approximately 50 m thick, argillaceous Tertiary sediments are not sufficient to prevent subrosion completely either locally or chronologically. The same is also true of the caprock, although in the majority of boreholes a firm contact between caprock and salt rock was found.

Of the Quarternary strata which are also spread above the salt dome it is primarily the Lauenburg clay complex which is considered an aquiclude. It is widespread in the Gorleben channel and generally also covers those areas in which the Tertiary strata are lacking completely or partially. It consists essentially of clays and silts, but also contains some thick interbeds of fine sands (cf. profile H-H' in Fig. 16; for example, between GoHy 850 and GoHy 860; near GoHy 1170). In the numeric ground-water model, therefore, permeable spots are introduced in this interlayer that can bring about water and mass transport. Pump tests and additional exploratory work will be able to determine more precisely these vertical routing paths.

In summary we can say that the argillaceous sediments occurring above the central areas of the Gorleben Salt Dome do not have the thickness and continuous range necessary to enable them to hold back potentially contaminated ground water from the biosphere on a permanent basis.

3.2.2 Hydrogeology

3.2.2.1 The Ground-Water System

The Quaternary and Tertiary stratigraphic sequence covering the Gorleben Salt Dome and in its environs (see Sec. 3.2.1.1) forms an aquifer system up to 280 m thick. In between the aquifers are embedded aquifuges and aquitards in an irregular form that is not always continuous vertically and horizontally but which frequently permits a rough division into an upper and a lower main ground-water storey (multiaquifer formation). The general sequence of aquifers and less permeable strata in the Gorleben area is shown in Fig. 11 and 12.

The most important aquifers in the area under investigation are the Miocene brown-coal sands (primarily fine-grained to medium-grained sands) and fluvial and glaciofluvial sands and gravels from different stages of the Quaternary (Pre-Elsterian, Elsterian, Saale, Weichsel).

The distribution of the water-bearing horizons and the hydraulic relationships is very different in the various subzones of the region. According to the hydrogeologic structure, four subzones can be delimited: rim synclines and adjacent areas outside the salt dome, ring wall, inner salt dome area, and Gorleben channel.

The rim synclines accompany the salt dome on the sides and extend in a NE-SE direction. The Tertiary sediments are more thickly developed in them and are at a greater depth than those of the same age on the salt dome. Important aquifers are the 'brown-coal sands' of the Miocene and the sands and gravels of the Elsterian Ice Age. The two aquifers are usually separated by water-impermeable clays and silts of the Middle Miocene and sometimes by water-retarding tills of the Esterian Ice Age. The base of the ground-water system is formed here by the clays and silts of the Oligocene at depths ranging between 150 m and 250 m below MSL.

The ring wall sits on the marginal areas of the salt dome and consists primarily of clays and silts of the Tertiary which are usually close to the surface and thus severely retard the movement of the ground water in the deeper stories at right angles to the salt dome. In the region of the Gorleben Channel (see below) the ring wall has been eroded so that here there is contact between the aquifers of the rim synclines and those on the salt dome in some places at least.

The inner salt dome, which is not included by the Gorleben Channel, forms its own hydraulic system in the southwest and central part of the salt dome. Directly above the salt dome lie thin argillaceous strata of the Lower Tertiary, some of which exhibit disturbed stratification. Above them are aquiferous sands of the Pre-Elsterian and Elsterian periods. The ground water in this lower storey is largely held in by the ring wall as in a bowl and is mineralized. It is generally separated from the uppermost ground-water storey by thick tills and silts.

The Gorleben Channel, which runs virtually NS, was cut during the Elsterian Ice Age to a maximum depth today of 290 m below MSL. The deepest ground-water storey of sands from the Elsterian period is built up in the channel. Contact with the overlying aquiferous sediments of the Upper Quaternary is largely but not completely prevented by thinly spread Lauenburg clay and/or till.

The channel cuts through the southern ring wall more or less to the west of Rondel and leaves the salt dome at its northern boundary near Vietze. The extent to which the northern ring wall also has a shallow opening near Gorleben will be determined by additional exploratory drilling.

3.2.2.2 The Characteristics of the Ground Water

The ground water in the overlying strata in the Gorleben area contains different amounts of dissolved substances. In general the salt concentration increases downward from the ground-water table, but the depth at which a certain concentration is reached differs greatly (see Fig. 18). There are two zones in the area under investigation--one each to the north and to the south of the salt dome--in which fresh water extends beneath the salt dome to surprising depths, and there are zones in which salty water comes close to the surface, principally to the south of Gorleben. At some points it happens that briny water, controlled by specific pressure conditions and flow paths, spreads over an interbed of low permeability under which fresher water is present ('overlapping').

From the distribution of fresh water and brine in the area under investigation it is found that the major portion of the salt content of the ground water above the Gorleben Salt Dome and in its immediate vicinity stems from the salt dome itself, but that other sources are present in the broader surrounding area such as the Siemen salt dome.

In lowland areas, for example in the area of the Lucie Nature Reserve, briny ground water is discharged into the streams [22].

<u>Figure 18</u>. Basal face of the high-resistivity aquifers based on borehole measurements [see next page]

Key:

~ 100 ~	line of equal depth of the 10 Ω m limit in m below MSL
10	borehole no.
112	depth of the 10 Ω m limit in m below MSL; underlined values: depth of the 10 Ω m limit in m below MSL, located at the upper edge of an aquifuge
	slightly mineralized ground water overlain by more highly mineralized ground water
	10 Ω m limit runs in the lower confining bed above 100 m below MSL
	salt dome outline

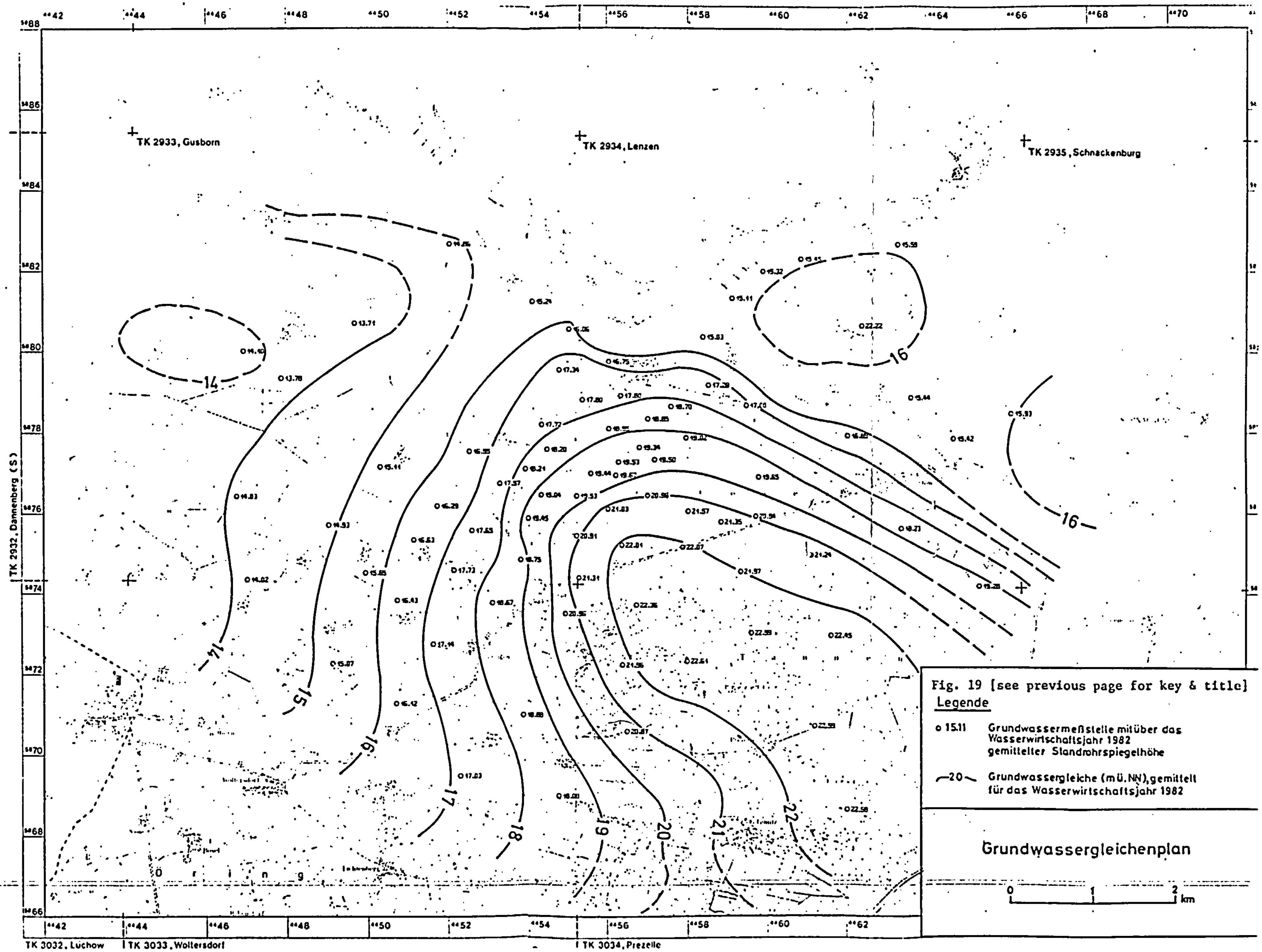


Fig. 19 [see previous page for key & title]

Water samples taken at selected ground-water measuring stations have been analyzed for concentrations of oxygen, hydrogen and carbon isotopes. Preliminary results show that the ground waters in the area of the Gorleben salt dome can be divided into two groups:

1) ground water which was formed under climatic conditions corresponding more or less to current conditions, with ages up to about 12,000 years (C-14 model age),
2) ground water, the Delta O 18 and Delta H 2 values of which indicate formation in a cooler and/or more humid climatic period, with C-14 model ages of more than 12,000 years.

A stratification based on depth is generally found from the younger to older ground waters, whereby the water age increases in a downward direction.

According to these analytical results we can assume that the older ground waters were formed during or at the end of the last ice age. The younger ground waters close to the surface were probably formed postglacially.

The isotopic tests are not yet completed, because the sampling conditions for a number of analyzed samples were unsatisfactory and repeat samplings must be made.

In addition, the results even of perfect samples can only give hints about the formation age of the ground water, but no definite figures. For example, the basic hydrochemical assumptions of the C-14 dating method are still under discussion, and the concentrations of heavy stable isotopes are only loosely correlated with the formation climate, in which case many other factors besides temperature play a role.

3.2.2.3 <u>Ground-Water Movements</u>

Fig. 19 shows the water-level contours of the averaged gage ground-water levels of the uppermost ground-water storey in the water resources year

1982. From this we can derive qualitative data on ground-water movement, primarily for the subsurface zones:

A topographically relatively highly elevated, continuous zone in the southeast portion of the area under investigation (Gartower Tannen and Prezeller Forst) emerges as the ground-water recharge area.

From here the ground water close to the surface flows to the NE, N and W with a maximum gradient of 1.5 p.m. to the lower lying areas and receiving streams, i.e. the Elbe and Seege lowlands and the adjacent lowlying areas extending to Löcknitz in the north and to the northwest the area of the Lucie Canal and the Dannenberger Landgraben. In high-water periods the Elbe feeds into the uppermost aquifer in its immediate vicinity, but during the longer lasting normal and low-water periods it is a receiving stream for the ground water, as are the other surface waters. In the NE of the salt dome area the Höbeck forms an independent ground-water recharge area. The ground-water regenerated here is utilized by the Höbeck Waterworks (see Sec. 3.2.2.4).

The flow rates of the ground water close to the surface are in the order of magnitude of 10 m/yr to 50 m/yr according to hydraulic estimates (speeds of filtration).

In the same order of magnitude are the results of direct flow measurements using the single-borehole method as obtained by the Gesellschaft für Strahlen- und Umweltforschung (GSF) [Company for Radiation Protection and Environmental Research].

<u>Figure 19</u>. Contour map of the water table [see next page]

Key:

o 15.11 ground-water measuring station with gage ground-water level averaged over the water resources year 1982

~ 20 ~ ground-water contour (m below MSL), averaged for the water resources year 1982

It is much more difficult to make any definite statements about the movement of the deeper ground water. Different estimates are described in Sec. 3.2.3.

In general the fresh water close to the surface, which flows relatively rapidly, is underlain by briny ground water (cf. 3.2.2.2), which moves at a lower rate. Hydraulic model calculations yield flow rates in the order of magnitude of 1 m/yr to 10 m/yr (speeds of filtration), which agree well with the results of flow measurements with the single-borehole method taken by GSF even in the deep aquifer (see Fig. 20, 22 and 25). The results indicate measurable flow of the deeper briny ground water in a generally northern direction. Radiometric age determinations and isotopic analyses indicate that the deeper briny ground water was essentially formed during the last ice age more than 12,000 years ago.

3.2.2.4 Ground-Water Utilization

In the area under investigation, which is rural in nature, the ground water is used for the drinking water supply and as industrial water (for livestock and irrigation).

Only some of the communities are connected to the public water supply system. In a large number of communities water is supplied from private wells from the local uppermost aquifer (see Fig. 21). The most important waterworks in the area is the Höhbeck Waterworks near Vietze, which supplies water chiefly to the communities in the lowland area of the Elbe Valley. Its approved water delivery rate is 0.44 million m^3/yr, for a water protection area (Zone III) about 2.5 km^2 in size.

In the northwest of the map section is the Quickborn Waterworks, which is only of local significance, however--delivery below 0.1 million m^3/yr--and does not belong to the runoff area under investigation.

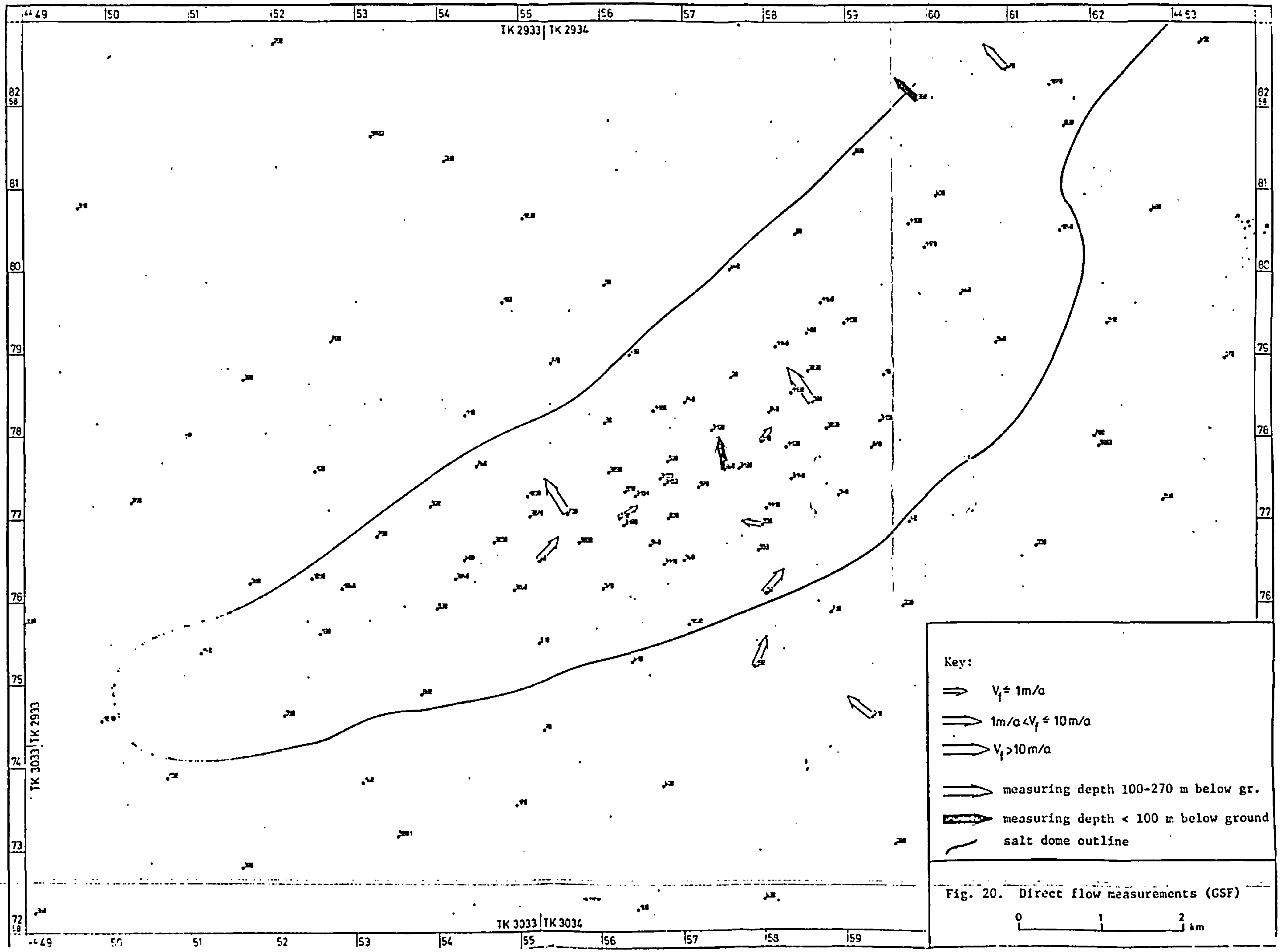
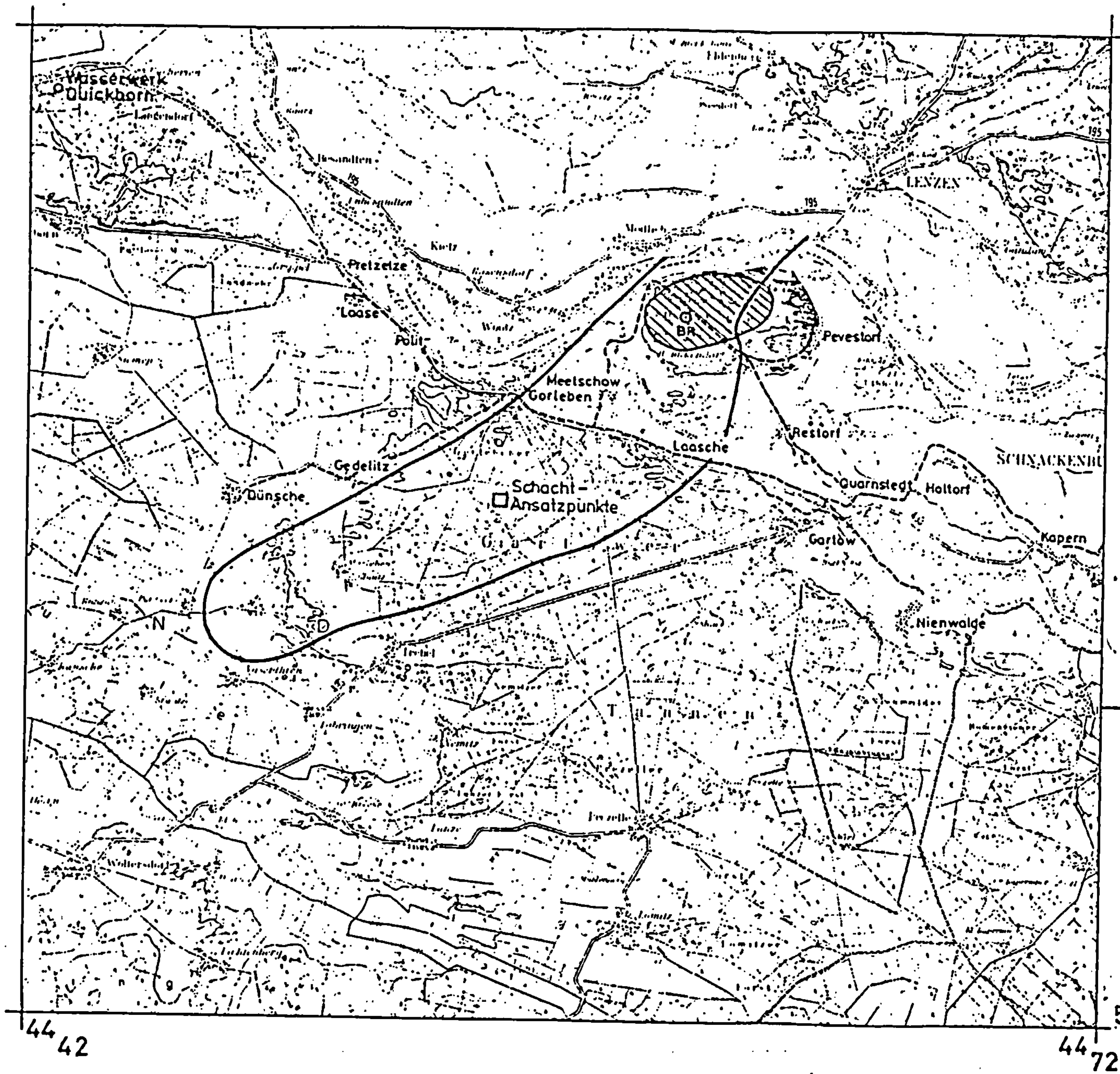


Fig. 20. Direct flow measurements (GSF)



Key:

protected zone (Zone III) Wasserwerk Höbeck [Höhbeck Waterworks]

BR delivery wells

water line to below NW 300

Dünsche connected municipal system for Dünsche

zone of planned shafts

References: Arbeitskarte öffentliche Wasserversorgung / Blatt CC 3126 Hamburg Ost, Stand 1976

Hydrogeologisches Gutachten Wasserwerk Höhbeck Archiv, NLfB, Nr. 941

Ground-Water Utilization

0 1 2 3 4 5 km

Fig. 21

With the primarily sandy soils of the area, field irrigation can bring about definite yield increases, so that the requirement for irrigation water can rise in the future. The areas to the north and the south of the Gorleben Salt Dome with deep-reaching fresh water (see Fig. 18) contain ground-water supplies which have been largely unused to date.

3.2.2.5 Possible Future Changes in the Ground-Water System and the Consequences

A ground-water system is determined by the geometry of the aquifers and the distribution of power water pressure and density, which is established on the basis of the recharge of ground water and the permeability distribution. While the permeability of existing aquifers can no longer change substantially, changes in climate and erosion or reformation of strata in the future can affect the ground-water system.

The trend to be read from the geologic history of the area, namely that newer and newer layers will be deposited over the older ones, would result in a thickening of aquiferous strata and, given identical ground-water recharging, a gradual slowing down of the ground-water flow in the lower layers. However, it is also conceivable that the deep ground-water flow will be intensified in the geologic future. Because of climatic changes in the direction of a cooler and more humid climate than today, the recharge of ground water would be increased. In conjunction with a possible lowering of the receiving stream base; this would lead to greater differences in ground-water potential. Such an increase in the gradient is, however, limited by the existing land form, so that in the area between the salt dome and the northern receiving stream a maximum local increase in the present value from 1.5 p.m. to 2.5 p.m. appears possible. Accordingly, the computed values for the ground-water flow rates at the different depths could change. Similarly, intensive tapping of ground water, for example by a waterworks, would result in an increase in ground-water runoff. This would remain locally limited in its consequences, however, and would hardly have an effect on the deeper ground-water runoff.

A reduction in the ground-water flow rate observed today is likewise possible, and would be especially more probable if the general receiving stream level would rise for natural reasons or because present drainage measures would cease and if as a result the lowland area would again become swampy all year round. A possible ice age in the distant future which would result in the formation of a permafrost, would sharply reduce or even completely stop the ground-water runoff.

The ground-water flow rates which can be observed today in the different ground-water stories may consequently increase by a factor of about 1.5 or drop to zero in the geologic future. The same is true of the transport of dissolved substances from the salt dome through the ground-water system to the biosphere (for more details see Sec. 3.2.3).

The situation is different with respect to the long-term leaching of the salt dome by the ground water. If leachable salt dome sections come in contact with flowing ground water, the possible extent of dissolution is usually much greater than the makeup supply: a subrosion depression will be formed on the surface which will remain active until leaching deeps pace with the salt uplift through a lowering of the contact area and a reduction in the transport force of the ground water with greater depth. Thus the long-term leaching of the salt dome is controlled primarily by the slow uplift movement of the salt dome itself, and only the fluctuations in leaching rate, which last only a brief time, will be caused by exogenetic processes.

3.2.3 Calculations of Ground-Water Movement and Salt Transport in the Ground Water

The Gartower Tannen area between the Elbe, Seege and Lucie rivers is 5 m to 15 m above the surrounding lowlands. In the formations underlying the flat topographic rise the ground-water table arches upward (Fig. 19). Its shape only changes slightly [18 and 19]. The reason is the following: the recharge of ground water from precipitation balances out the runoff of groundwater, which follows more or less the ground-water level gradient and is directed towards the valley plains (flood plain). We speak of a dynamic equilibrium between recharge and runoff. This equilibrium determines the shape and extent of the ground-water arching.

The ground-water runoff penetrates deeply into the sedimentary rocks. As measurements show, it is detectable down to levels only a short distance above the salt dome at depths of 200 m to 250 m (Fig. 25) [19]. In places where ground water was found directly above the salt dome, it is saline [18].

The following questions are being researched:

1. What path does the ground water take from the selected receiving points at depths above the salt dome to the terrain surface and how long does it travel?

2. Do the data on ground-water movement give indications of the recent subrosion on the salt dome?

Data on these areas will be required for the treatment of scenarios involving the transport of radioactive substances (Sec. 6.4).

The following factors, among others, will be used to determine ground-water movement:
- recharge of ground-water
- the geologic structure of the area
- the permeability values and porosities for members of geologic strata
- the ground-water surface
- the pore water pressure
- the electric conductivity, chemical composition and density of the ground water
- the temperature of the ground water
- ground-water flow rates measured in the borehole
- age determinations from isotopic analyses of water samples.

The source of data on these subjects and the processing of measurements are described in sections 3.2.1 and 3.2.2. Most of the studies based on this information that deal with the movement of the ground water are documented [18-20, 23-27]. The most important of the results obtained to date are treated here.

A numerical model is used to calculate ground-water movement in the area under investigation [20].

The geologic body bounded by the model edge, which includes near the bottom the Quaternary and the sands of the Miocene, is divided into geohydraulically homogeneous zones in accordance with the geology found there. 380 areas lie in a horizontal plane. There are 15 horizontal planes lying one above the other. Each area is assigned an average permeability in accordance with the type and amount of sediments contained in it. The hydraulic interfaces between adjacent areas can be calculated from this information. The total system can be imagined as a complicated network. It is mathematically formulated and entered into a large computer.

The flow law for water of constant density (fresh water) can also be mathematically formulated for this grid. The resulting system of differential equations can be solved numerically if the boundary conditions are given. The boundary conditions given are data on the recharge of ground water at the grid points which represent the ground-water surface. In the model the gage water level is calculated at each grid point. Since average annual values are used for the recharge of ground water, the calculated values must also be evaluated as such.

The quality of the model is checked by comparing calculated and measured values. For example, the ground-water surface calculated using the model follows the observed surface on the whole, although it does not arch upward to the same degree [20]. The model calibration work is not yet completed. Data which are incorporated in the model are changed in the research within the limits of uncertainty in order to obtain the best possible overall fit between the model and natural conditions.

Fig. 22 shows a model result. The horizontal components of the ground-water flow are represented according to size and direction at a depth of about 190 m below MSL.

In Fig. 23 the areas for the recharge of ground water from precipitation on the elevations (infiltration) and the areas for the exit of ground water in the lowland districts (exfiltration) are shown.

The model is used to calculate flow paths which extend from receiving points that lie in the channel. Fig. 24 shows an elevation and side elevation of the flow paths. The flow paths which begin at these receiving points cross under the Elbe. They end north of the Elbe in the Elbe Plain. The travel times are 600 years and 1170 years. Two additional flow paths not shown in the figures that begin further to the west below the salt dome run to the west and end in the Lucie and Jeetzel plains. The ground-water travel times are 1320 years and 3700 years.

The ground-water system reaches its greatest depth in the channel at a point directly on the salt dome. The lowermost section of the aquifer bears highly saline water [19, 27]. The density differences between brine and fresh water affect the ground-water dynamics. The model described above does not take these influences into account and therefore does not correctly reproduce the flow rates in the saline water.

From the spatial distribution of the salt concentrations, however, conclusions can be drawn regarding the ground-water flow in the saline deep water. Data on ground-water density are plotted in Fig. 25 in a section along the Quarternary channel. The salt content of the water and therefore the density increase with depth. The sharpest increase takes place in a density gradient layer about 25 m thick at a depth of approximately 190 m below mean sea level. The areas of equal density rise slightly to the north, i.e. in the freshwater runoff direction.

From the angle of inclination of these areas and the density increase with depth we can determine within certain limits the flow rates in the saline water body.

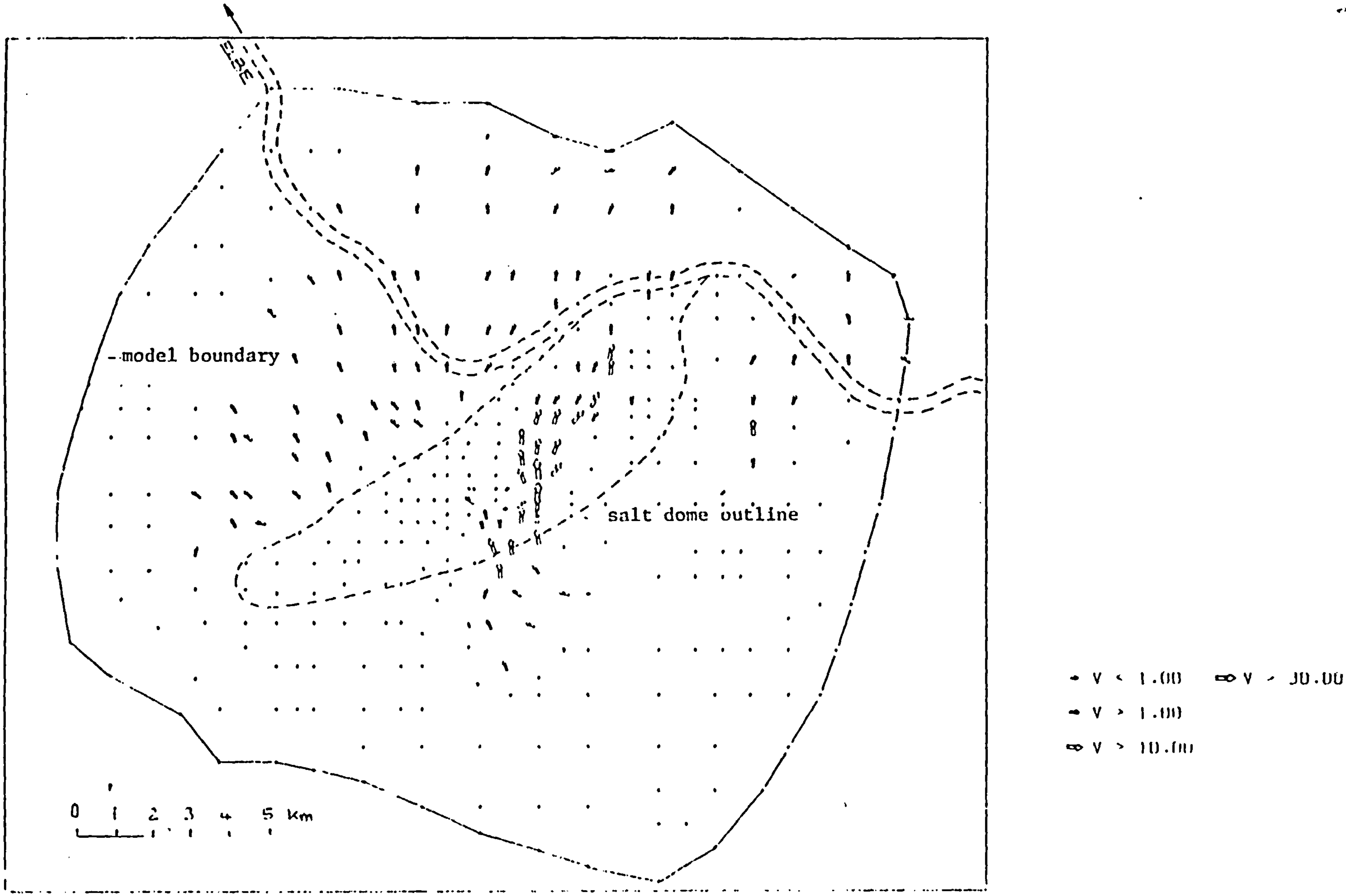


Figure 22. Calculated ground-water runoff amounts (filtration speed v in m^3/m^2 yr) at a depth of 190 below MSL.

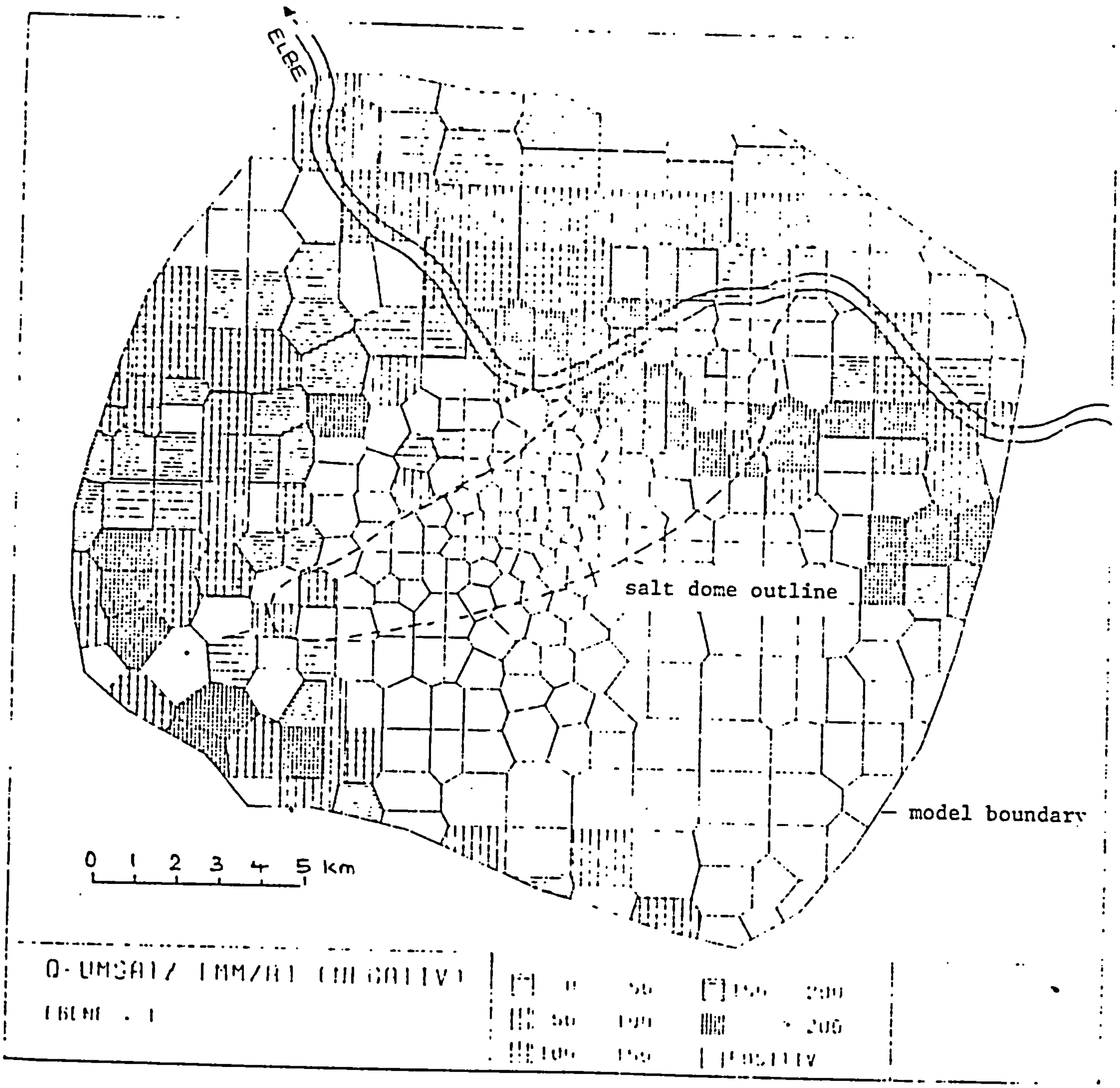


Figure 23. Exfiltration areas

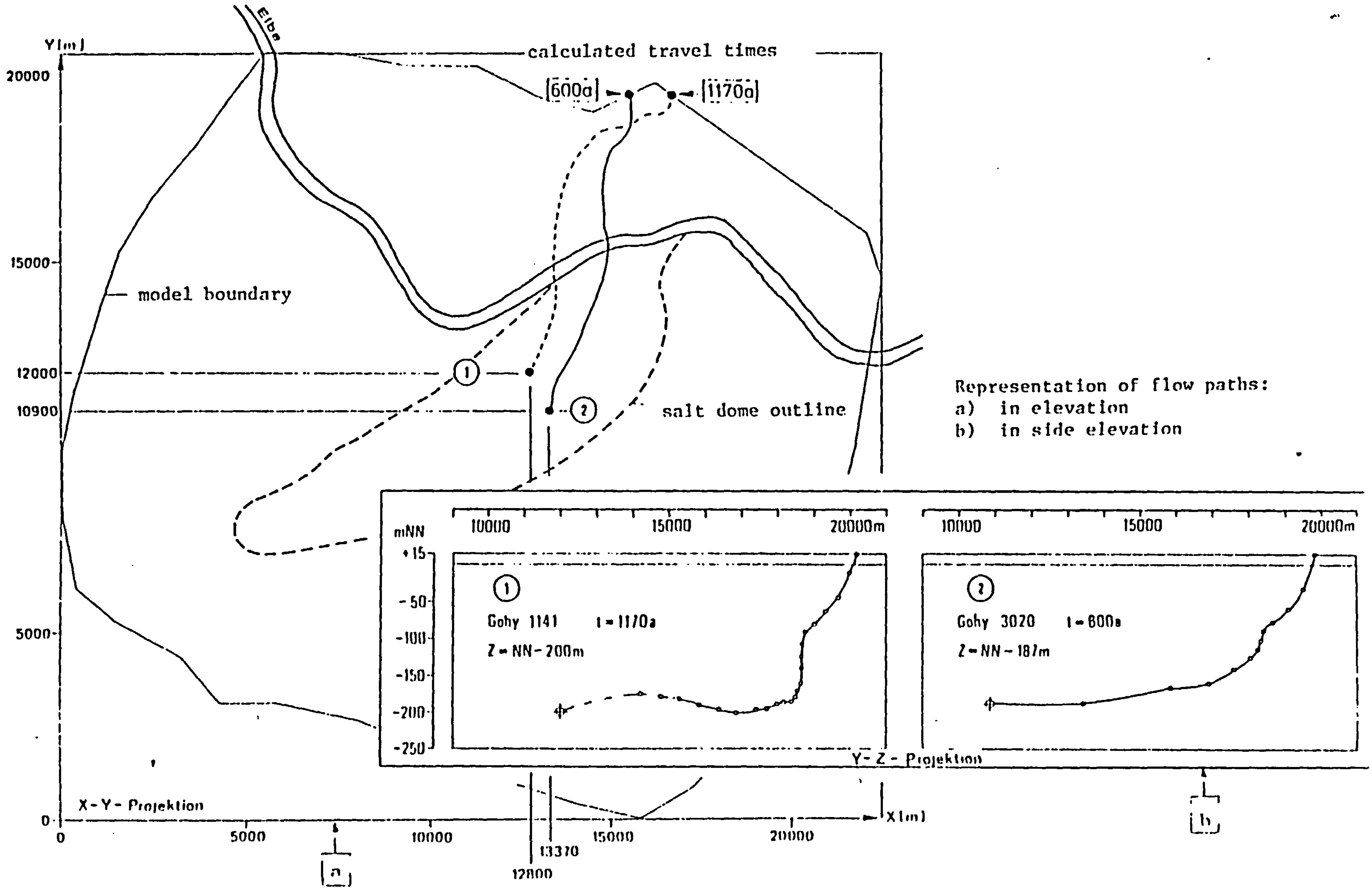


Figure 24. Calculated flow paths and travel times for two different receiving points

For this purpose the following assumptions are made:

- The permeability in the part of the channel filled with salt water is constant (here $3 \cdot 10^{-4}$ m/s) and
- the horizontal pressure gradient is constant above the salt water body.

One obtains a runoff volume of 4 m^3/m^2 to 5 m^3/m^2 yr for the less saline water above the gradient layer and continuously decreasing runoff volumes in the gradient layer with increasing salt content with depth (Fig. 25).

The runoff amounts were measured directly at six points in the saline water [20]. With one exception, these values measured in boreholes agree well with the calculated values (Fig. 25).

There is also agreement between the pressure gradients in the less saline water directly above the gradient layer (Fig. 25) and the mean pressure gradient which the freshwater model yields for this depth [20].

From the flow field and the salt concentrations one can estimate the transport of salt out of the channel. It follows from the runoff data on the righthand edge of Fig. 25 and from the cross-sectional area for the cut in the salt dome ring wall, through which the saline water runs off to the north. According to the observations listed, salt quantities Q on the order of 3,000 m^3/yr to 12,000 m^3/yr are removed.

It is not possible to deduce a recent subrosion rate q from this data until one knows that the ground-water system is in dynamic equilibrium as regards salt transport and until one knows with sufficient accuracy the leaching surface area F, which is about 10 km^2. The mean recent subrosion rate would then be $q = Q/F$. A rate calculated in this way must not be extrapolated over geologic periods, since the leach rate is subject to fluctuations over time and is probably lower at other times than at the present (see Sec. 3.2.2).

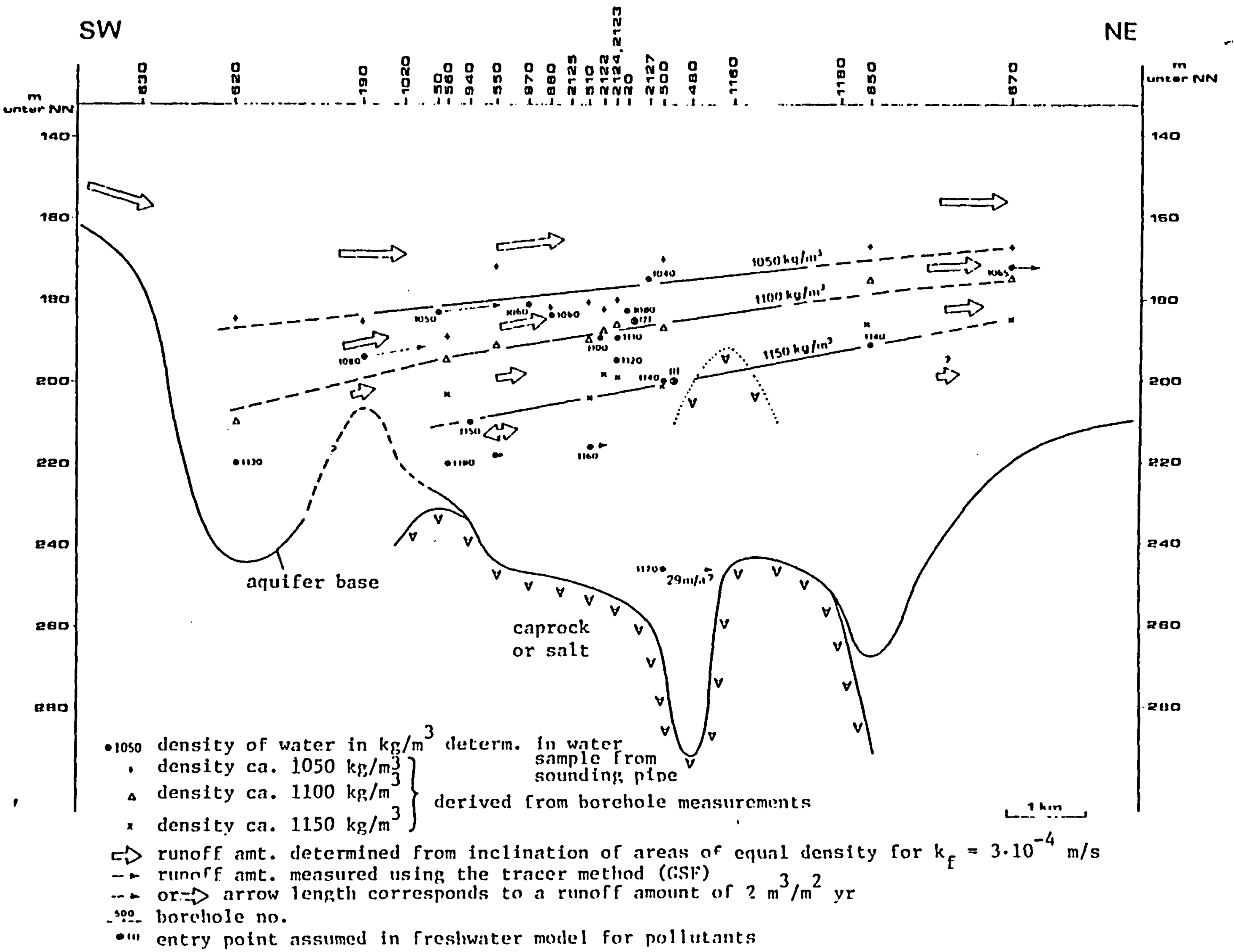


Fig. 25. Density and flow of saline water on the floor of the channel

The results given above are preliminary in nature. They will be verified by further tests.

These include:

- pump tests,
- direct pressure measurements in the ground water,
- additional density determinations of water samples,
- isotopic measurements,
- additional direct flow measurements.

4. Mining Facilities for Exploration of the Gorleben Salt Dome

In contrast to a mine which is designed for the quickest possible recovery of mineral reserves, this mine will be used for the geological exploration of the internal structure of the salt dome and is intended to provide a detailed, flat opening at the depth zone ranging from 700 m to 850 m (not yet finally established). At the position of depth to be investigated, tunnels will be excavated in the direction of the longitudinal axis of the salt dome up to several kilometers in length and from there primarily horizontal core holes will be drilled to the salt dome flanks and to the center of the salt dome, as well as boreholes up to 300 m into the underlying formations of the mine floor. The areas between the individual core holes will be investigated using geophysical test methods [28].

In order to attain this goal, the mine--consisting of surface facilities, shafts 1 and 2, and the underground workings--will be constructed from the center of the Gorleben Salt Dome. The selected shaft locations have been investigated in detail by means of preliminary shaft boreholes (Gorleben 5001 and 5002). The results support the selection of the shaft sites (Fig. 1), which are on the grounds of the Deutsche Gesellschaft zur Wiederaufarbeitung von Kernbrennstoffen mbH (DWK) [German Company for Nuclear Fuel Reprocessing] in the boundary area referred to as 'Gorlebener Genossenschaftsforst' ['Gorleben Cooperative Forest']. The mean terrain elevation in the shaft areas is + 23.5 m MSL. The ground-water levels have a gage level there of + 19.5 m MSL. For safety reasons (century flood) the measured ground-water level is increased theoretically by one meter and considered to be the 'maximum ground-water level.' Because of this and because of the requirement that the air drifts be connected to the shaft cellar without contact with the ground water, the upper edge of the pit bank of Shaft 1 is at + 25.6 m MSL and that of shaft 2 + 27.7 m MSL. A dirt fill on the shaft sites is therefore necessary before the sinking operations can begin.

After the fill operations, the supply and waste system lines and the power supply cables are laid and the necessary roads, paths and parking lots built. Then construction work begins on the buildings required during shaft sinking operations, including interior furnishings and equipment (office, administration building, workshops, lounge and dressing rooms, etc.).

Because of the fact that the overlying strata are water-bearing and because of their lack of stability, the two shafts must be sunk using the freeze sinking process. Once the shaft site is secured about four freezing boreholes and up to three temperature measuring holes are drilled into the salt rock for this purpose, in order to create a freezing zone having a diameter of 15 m to 16 m. After the freezing holes are completed, they are connected to the respective freezing system and the overburden is frozen. This operation is now beginning for Shaft 2. Shaft 1 will follow with a time delay of approximately half a year.

During the preliminary freezing phase the sinking equipment required for each shaft (sinking frame, hoist, electr. power supply, etc.) is installed by the shaft building contractor. The sinking frame for Shaft 1 is provided by the owner as a part of the later shaft tower. The sinking hoist system for Shaft 2 erected by the shaft contractor will be taken over by the owner after the sinking operations are completed for use as an auxiliary system.

Both shafts will have an inside diameter of 7.5 m and will be sunk and lined in the same way, so that at this point we only need to describe one shaft as an example.

After the frost body is created in the overburden and the shaft sinking facilities are set up (sinking frame, hoist, handling devices, etc.), the shaft sinking operations begin. The frozen rock is mechanically loosened through pick work, loaded by a clamshell loader into the skip, and transported in it to the surface. The overburden debris on the surface is used partly for fill in construction of the surface facilities, and the excess is dumped, along with the caprock and salt rock debris.

During sinking operations in the freezing shaft section a preliminary lining is installed as protection against rock slides. After the shaft is completed, it assumes the function of the outer lining.

After the ice wall is intersected and sinking is continued to a depth of about 70 m to 80 m beneath the top of the salt dome, the sinking operations are interrupted and a completely watertight, final lining is installed for permanent protection of this part of the shaft. It consists of a reinforced concrete cylinder that is seated on a foundation poured in the salt rock and has an outer, tightly welded sheet metal jacket, which is separated from the preliminary lining (see above) by a lubricating layer of asphalt (Fig. 26).

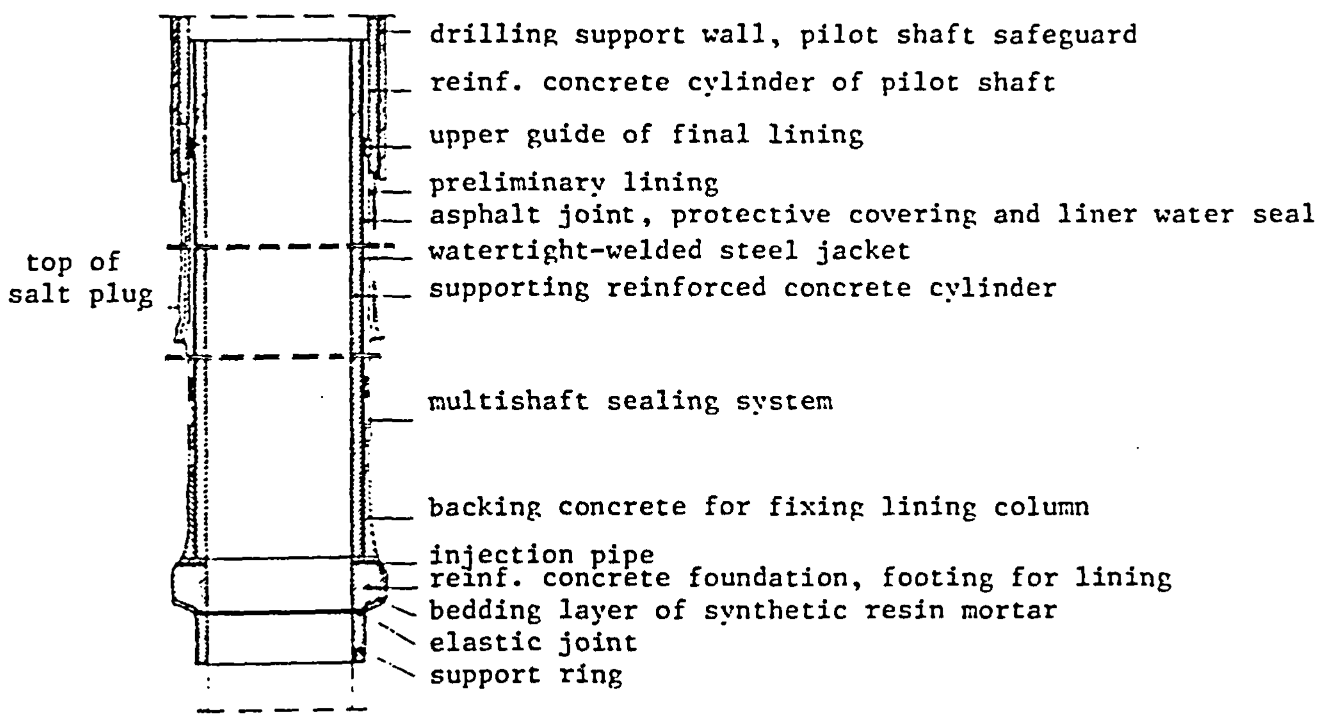


Fig. 26. Shaft lining diagram

With installation of the final lining, the water-bearing overburden strata that are not stable for shaft construction purposes and the transition to the salt rock are secured, and the ice wall no longer needs to be maintained. The freezing systems are turned off and the frozen overburden thaws naturally. The freezing and temperature-measuring holes are filled with cement after the area has thawed.

The shaft, which has now reached the salt rock, is sunk further to the final depth by means of drilling and blasting operations in the core zone and cutting operations in the boundary zones. This part of the shaft remains without lining, if possible.

After the landings are excavated at the exploration level, a connecting tunnel to Shaft 1 is excavated, beginning from Shaft 2, and after prior exploration through core holes. When Shaft 1 is reached and after sinking is completed, Shaft 1 is converted into a man shaft and hoisting shaft. During this conversion phase the first underground core holes for geologic exploration and determination of the tunnel excavation directions will be carried out from Shaft 2, the mine workings close to the shaft will be excavated (bunker tunnels for Shaft 1, rooms for infrastructure, etc.), and the equipment required for mining operations, including mining machinery, will be transported underground.

With the initiation of operation in Shaft 1 as a man and hoisting shaft, the excavation of the exploration tunnels will also begin. These will be 6 m wide and at least 3 m high and will be excavated mechanically by road-heading machines. The direction and length of the tunnel sections will be investigated by core holes and established after geological evaluation before they are excavated.

As the tunnels are excavated, drilling stations will be constructed every 50 m approximately, from which horizontal core holes up to 1000 m in length will be drilled to the salt dome flanks and to the core of the salt dome.

The tunnels and core holes will cover a length of strike of about 9.4 km and a width across the strike of 1.85 km in the western exploration region of the salt dome and 2.0 km in the eastern section (Fig. 27), whereby the mine field will be divided into nine exploration regions.

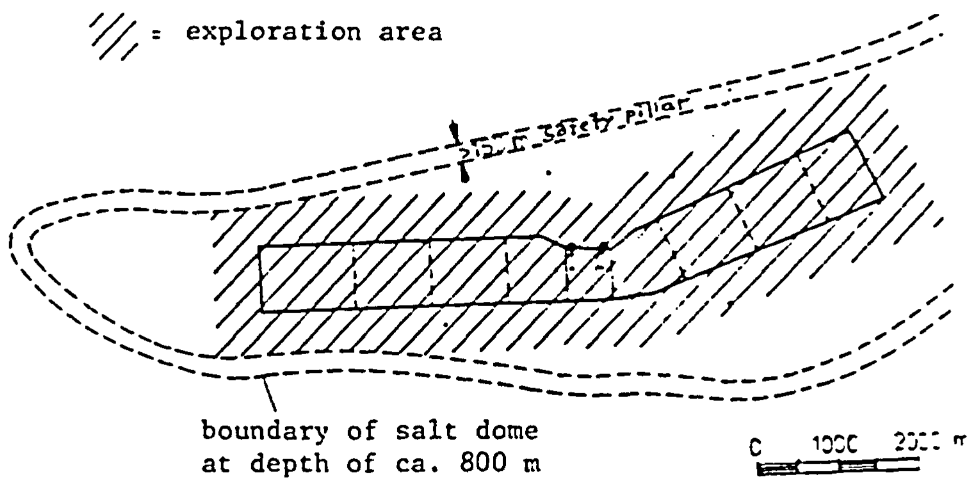


Fig. 27. Underground exploration. Exploration zone.

A total of about 52,000 m of preliminary drill holes are necessary for excavation of the planned tunnel network 26,000 m in length. Another approximately 50,000 m of exploration boreholes are necessary for exploration of the salt dome flanks and core. Including the creation of the underground infrastructure spaces, about 570,000 m^3 or 1.2 million tons of salt debris must be transported to the surface.

For efficient and timely implementation of this task, appropriate equipment and buildings must be constructed on the surface.

In contrast to Shaft 2, where—as already mentioned—the shaft sinking plant ceases operation for the period of underground exploration, the partially errected headframe for shaft 1 is completed after the sinking word has ended, and the machine parts for the haulage plant are mounted. Specifically planned is the installation of a six-cable Koepe tower hoist, a winding system consisting of a skip bucket with a useful load of 25 t, and a hoisting cage for man-hoisting and material transport, loading and unloading equipment, and an auxiliary hoisting system.

In addition to the buildings already constructed and utilized in the shaft sinking phase (dressing room and lounge building, warehouse, parts shop, transformer station, tank store, gatehouse, information center), the shaft hall, the final workshop, the structure connecting shaft hall with dressing rooms, and the dump conveyor belt system will be constructed in the area of Shaft 1 for operation of the mine (Fig. 28).

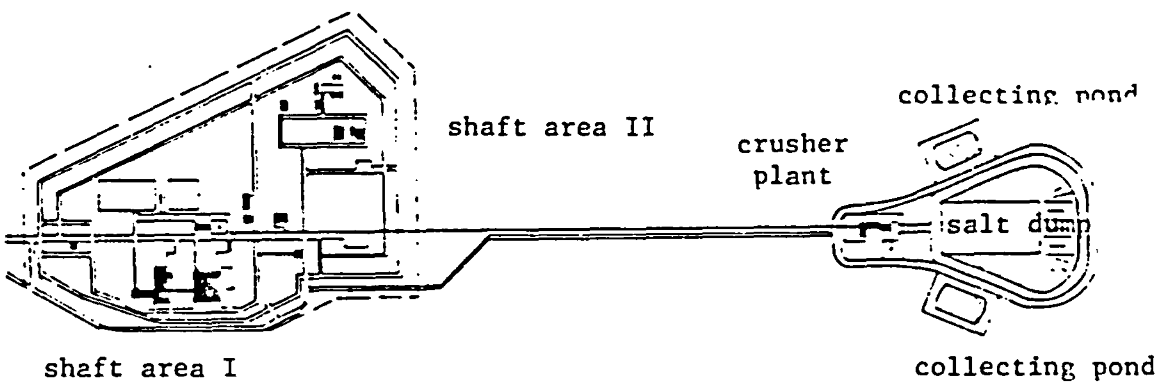


Fig. 28. Underground exploration. Surface facilities for exploration phase.

The dump itself is located outside the mining complex in the southeast section of the Gorleben Cooperative Forest on DWK grounds.

The soil beds located at the dump site and the relatively high ground-water level require sealing measures. The dump underlayer is therefore sealed with a layer of watertight and compacted material provided with an external gradient. A system of ditches surrounds the dump and is also sealed, and on the side of the dumped salt it is secured against possible slippage by a protective dam. This ditch system conducts any dump water that accumulates to two catch basins. An earth wall is constructed in front of the dump as an outer containment dam, covered with topsoil, and planted with trees and bushes.

In the area of Shaft 2 the air drift and the building for the mine fans and the diffusers is constructed during the shaft sinking phase (Fig. 28). When the underground connecting tunnel hits Shaft 1 the ventilation system (Shaft 1 = downcast, Shaft 2 = upcast shaft) will be completed, the air volume of which will be ca. 20,000 m^3/min in the full operating phase of the mine. The air volumes required by the mining operation in the development phases will be generated by two main mine fans installed in the mine ventilation building above ground. The air volume requirement at any given time will be controlled by fan blade adjustments or by changes in the number of fan blades. The noise emissions will be reduced to permissible values by the series-connected diffusers.

5. The Final Repository

The mined repository planned for the Gorleben site is intended to accept radioactive wastes of different origins. Since exploration of the site is not yet completed and since the interior of the salt dome in particular is only incompletely known, the bases for the design of a final repository in a salt dome were developed on the basis of a model plan. This model plan could not take into account the actual conditions in the salt dome and must be adapted in the future to the results of underground exploration. The later mine workings can differ substantially from the model plans. The location of the individual emplacement fields, which must possibly be divided over different suitable areas, can vary greatly both as regards their orientation in the salt dome and their configuration. The fundamental planning information developed in the course of the model planning phase for the repository will be retained, however.

The site-independent plans for the mined repository were initially based on the idea of an integrated waste management center and were made by Konsortium Planung Endlager (KPE) [Repository Planning Consortium] under contract to PTB [29]. They take into account only reprocessing wastes. Because of the change from the NEZ [waste management center] to the integrated waste management concept, the KPE plans were revised and presented in a collection of preliminary plan verification documents for the plan entitled 'Radioactive Waste Repository - Salt Mine (Gorleben)' [30]. Incorporated in these plans are not only wastes from the reprocessing of nuclear fuels, but also radioactive wastes from nuclear power plants, industry, research and medicine.

5.1 Mine Facilities

The mined repository consists of the surface facilities and the mine workings with the shafts.

The most important surface installations include:
-- acceptance hall for receiving radioactive waste containers from railroad

cars and trucks,

-- transfer station for inspecting the arriving waste containers and for combining them for transport underground,
-- receiving store as time buffer for the waste containers until they are transported underground,
-- shaft hall 1 with associated equipment,
-- shaft hall 2 with associated equipment,
-- structural facilities for the mine ventilation system,
-- administrative building and building with dressing rooms and lounge area for employees,
-- workshops,
-- warehouse and
-- salt dump.

The mine workings consists of the following:

-- Shaft 1, downcast shaft:
  shaft for salt transport, men hoisting and material transport,
-- Shaft 2, upcast shaft:
  shaft for transport of radioactive waste containers and for occasional transport of machine parts,
-- central field with shafts 1 and 2, the landing station and the auxiliary mine rooms,
-- wings A and B which are used for the emplacement of the different types of waste:
  wing A with the emplacement fields for the dump method ['Versturz-technik' (VT)], stack method ['Stapeltechnik' (ST)] and lowering method ['Absenktechnik' (AT)]
  wing B with the emplacement fields for the borehole method ['Bohrloch-technik' (BT)].

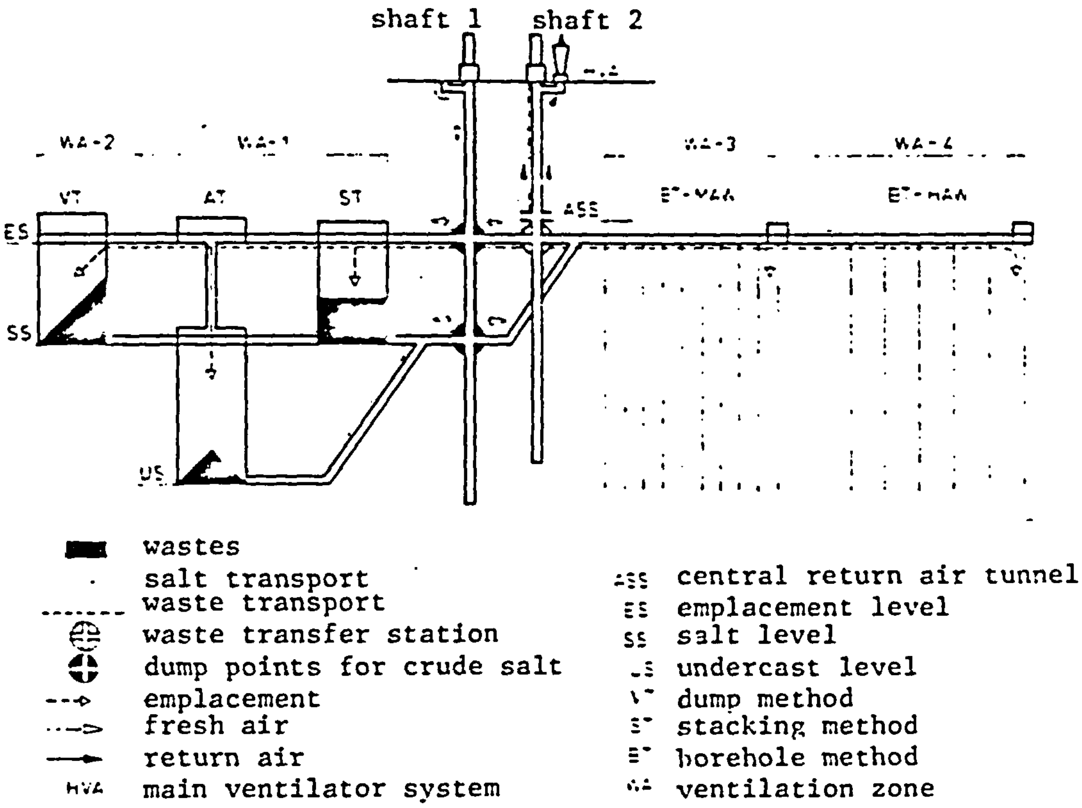


Fig. 29. Diagram of the mine workings and the transport paths.

The mine workings are arranged on two levels:

-- the emplacement level, which is used for the transport of the radioactive wastes from Shaft 2 to the emplacement rooms, for the transport of backfill, and for removal to Shaft 1 of a portion of the salt obtained during excavation of the emplacement rooms.
   All the charging tunnels in Wing B are also excavated on this level, and from them the emplacement boreholes are drilled.

-- The salt level, on which the principal amounts of salt from the excavation of the emplacement chambers in Wing A are transported to Shaft 1.

In addition, an undercut level is required for excavation of the AT chambers and for removal of the salt accumulated in the process.

The emplacement fields are divided into four ventilation sections. The dimensions of the model mine workings and the volumes of waste to be emplaced are shown in Fig. 30 and Table 4.

The wastes are emplaced in double shift operation.

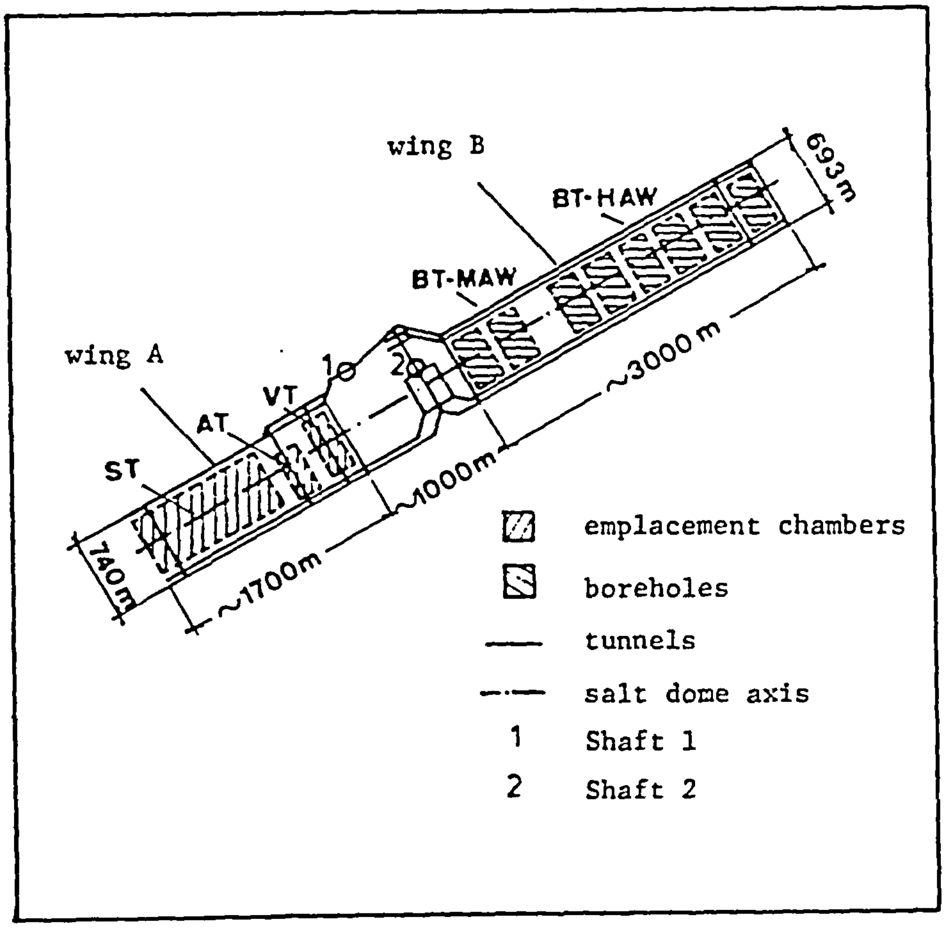


Fig. 30. Mine workings (model)

Table 4. Dimensions of the model mine and the wastes to be emplaced

Total length of the mine workings	5700 m
Length of the central field	1000 m
Width of the central field	900 m
Length of Wing A	1700 m
Width of Wing A	740 m
Length of Wing B	3000 m
Width of Wing B	693 m
Depth of the emplacement level (relative to pithead)	830 m
Depth of salt level (relative to pithead)	846.5 m
Depth of undercut level (relative to pithead)	875 m
Min. distance of the mine workings from the salt dome flanks	200 m
Min. distance of the mine workings from the top of the salt plug	300 m
Distance of the shafts from one another	500 m
Safety pillars for the shafts (diameter)	300 m
Distance between the emplacement fields in Wing A	100 m
Distance between the borehole fields in Wing B	270 m
Minimum distance between the last filled emplacement rooms and the shafts	300 m

Emplacement period: 50 years based on radioactive wastes from the operation of nuclear power plants and from the reprocessing of spent fuel elements for the generation of electric work totalling 2,500 GW per year and of ca. 50% of the waste volume accumulating annually from research, medicine and industry in casks of 200 to 400 liters.

In the design of the mined repository, the following planning principles are considered:

- In the configuration of the mine workings minimum safety clearances of 200 m from the salt dome rim and 300 m from the overburden are observed. A safety pillar 300 m in diameter is provided around each shaft, and no emplacement can take place in this area.

- The emplacement conditions are developed on the basis of waste data. The volumes, weights, nuclide concentrations and compositions of the waste containers determine the size and divisions of the mine workings, the hoisting capacities, hoisting equipment, ventilation requirements, etc.

- The downcast shaft is intended for man hoisting, material transport and salt transport, and the upcast shaft for the transport of waste containers.

- The design of the mine workings and the emplacement fields takes into account relevant experience acquired in salt mining. The excavation of the mine workings and the creation of the emplacement rooms shall be done using the methods, equipment and machinery that correspond to the state of the art.

- Before excavation of the emplacement chambers and borehole charging tunnels, development drifts will be excavated.

- The main tunnels shall have sufficiently large cross sections (25 m^2 - 30 m^2) because of the trackless operation of the heavy transport cars and the ventilation system. Large curve radii shall be observed. Sloped tunnels will be excavated with a maximum inclination of 7%.

- The mine ventilation system shall be operated such that all operating mine workings are supplied with fresh air.
  The ventilation system is designed for the most highly occupied layer and the installed power of the diesel vehicles. Emplacement fields are assigned to the ventilation sections.

- The different waste types shall be spatially separated from one another. The division into ventilation sections undertaken for safety reasons also corresponds to this separation of emplacement fields. For underground transport the separation of salt transport from emplacement transport is assumed.

- The emplacement of wastes in the emplacement fields shall take place in a retreating fashion from the boundaries of the emplacement fields in the direction of the shafts. The emplacement rooms shall be separated from the operating mine workings after they are filled and sealed.

- In accordance with the separation of salt transport operations from the emplacement transport and in accordance with the mine ventilation system, the mined repository will be divided into a conventional area (e.g. development and preparatory work) and a non-conventional section (e.g. transport and emplacement of radioactive wastes). The division affects basically the entire mine workings, the technical and organizational areas with their functional procedures, and the equipment used with their respective sites (operation points).

5.2 Radioactive Substances

Radioactive wastes are produced during the operation of nuclear facilities (for example nuclear power plants, reprocessing plants, and fuel fabrication plants) and the handling of radioactive substances (research, medicine, pharmaceutical industry). The wastes scheduled for emplacement were determined and combined with respect to origin, waste type and conditioning, and their radionuclide composition was given. All data are preliminary in nature.

For model plans of the mine (see Sec. 5.1), the radionuclide inventories of the wastes from the operation of nuclear power plants and from the reprocessing of spent fuel elements for the generation of electric work of 2,500 GW/yr and of wastes from research centers and state collection points over a period of 50 years were totalled.

When the activity inventory for the filled repository is totalled, the decay of radionuclides, the buildup of relevant decay products and the afterproduction of radionuclides by spontaneous fission is taken into account. Tables 5 to 10 give not only the activity inventories to be deposited per year, per borehole or chamber and per emplacement field, but also the cumulative inventory of the repository.

Table 5. Vitrified fission product concentrate. Emplacement in boreholes, 250 containers per borehole, 1760 containers per year. (A = nuclide, B = activity per year, C = activity per borehole, D = activity after 50 yrs.)

A Nuklid	B Aktivität pro Jahr Bq/a	C Aktivität pro Bohrloch Bq	D Aktivität nach 50 Jahren Bq
Sr-90	$3,6 \cdot 10^{18}$	$5,0 \cdot 10^{17}$	$1,1 \cdot 10^{20}$
Zr-93	$1,0 \cdot 10^{14}$	$1,5 \cdot 10^{13}$	$5,2 \cdot 10^{15}$
Tc-99	$7,8 \cdot 10^{14}$	$1,1 \cdot 10^{14}$	$4,1 \cdot 10^{16}$
Ru-106	$3,3 \cdot 10^{16}$	$4,7 \cdot 10^{15}$	$8,9 \cdot 10^{16}$
Sb-125	$4,1 \cdot 10^{16}$	$5,5 \cdot 10^{15}$	$1,9 \cdot 10^{16}$
Cs-134	$5,2 \cdot 10^{17}$	$7,0 \cdot 10^{16}$	$2,0 \cdot 10^{18}$
Cs-135	$1,4 \cdot 10^{13}$	$2,1 \cdot 10^{12}$	$7,0 \cdot 10^{14}$
Cs-137	$4,8 \cdot 10^{18}$	$7,0 \cdot 10^{17}$	$1,6 \cdot 10^{20}$
Ce-144	$9,3 \cdot 10^{15}$	$1,3 \cdot 10^{15}$	$2,2 \cdot 10^{16}$
Pm-147	$4,1 \cdot 10^{17}$	$5,5 \cdot 10^{16}$	$1,9 \cdot 10^{18}$
Sm-151	$6,3 \cdot 10^{16}$	$9,0 \cdot 10^{15}$	$2,6 \cdot 10^{18}$
Eu-154	$2,7 \cdot 10^{17}$	$3,7 \cdot 10^{16}$	$4,6 \cdot 10^{18}$
U-234	-	-	$2,7 \cdot 10^{12}$
U-237	-	-	$5,2 \cdot 10^{12}$
Pu-238	$7,8 \cdot 10^{14}$	$1,1 \cdot 10^{14}$	$3,3 \cdot 10^{16}$
Pu-239	$6,7 \cdot 10^{13}$	$9,5 \cdot 10^{12}$	$3,4 \cdot 10^{15}$
Pu-240	$2,0 \cdot 10^{14}$	$2,8 \cdot 10^{13}$	$9,6 \cdot 10^{15}$
Pu-241	$1,4 \cdot 10^{16}$	$2,1 \cdot 10^{15}$	$2,6 \cdot 10^{17}$
Pu-242	$3,3 \cdot 10^{11}$	$4,7 \cdot 10^{10}$	$1,6 \cdot 10^{13}$
Am-241	$3,0 \cdot 10^{16}$	$4,3 \cdot 10^{15}$	$1,4 \cdot 10^{18}$
Am-242m	$4,4 \cdot 10^{14}$	$6,5 \cdot 10^{13}$	$1,9 \cdot 10^{16}$
Am-243	$1,2 \cdot 10^{15}$	$1,7 \cdot 10^{14}$	$5,6 \cdot 10^{16}$
Cm-242	$3,5 \cdot 10^{14}$	$5,0 \cdot 10^{13}$	$1,2 \cdot 10^{16}$
Cm-243	$1,8 \cdot 10^{14}$	$2,6 \cdot 10^{13}$	$5,9 \cdot 10^{15}$
Cm-244	$1,2 \cdot 10^{17}$	$1,7 \cdot 10^{16}$	$2,2 \cdot 10^{18}$
Cm-245	$2,5 \cdot 10^{13}$	$3,5 \cdot 10^{12}$	$1,2 \cdot 10^{15}$
Cm-246	$5,2 \cdot 10^{12}$	$7,0 \cdot 10^{11}$	$2,6 \cdot 10^{14}$
$\Sigma\ \alpha$	$1,5 \cdot 10^{17}$	$2,2 \cdot 10^{16}$	$3,8 \cdot 10^{16}$
$\Sigma\ \beta/\gamma$	$9,6 \cdot 10^{18}$	$1,4 \cdot 10^{18}$	$2,9 \cdot 10^{20}$

[Translator's Note: Commas should be read as decimal points in the following tables.]

<u>Table 6</u>. Cemented hulls, structural parts, feed sludge, core components. Emplacement in boreholes, 273 containers per borehole, 4331 containers per year. (A = nuclide, B = activity per year, C = activity per borehole, D = activity after 50 years.)

A Nuklid	B Aktivität pro Jahr Bq/a	C Aktivität pro Bohrloch Bq	D Aktivität nach 50 Jahren Bq
H-3	$2,3\cdot10^{16}$	$1,5\cdot10^{15}$	$5,2\cdot10^{17}$
Mn-54	$2,3\cdot10^{16}$	$1,5\cdot10^{15}$	$4,1\cdot10^{16}$
Fe-55	$1,1\cdot10^{18}$	$7,0\cdot10^{16}$	$5,2\cdot10^{18}$
Co-60	$8,1\cdot10^{17}$	$5,0\cdot10^{16}$	$7,6\cdot10^{18}$
Ni-63	$1,5\cdot10^{17}$	$9,5\cdot10^{15}$	$6,7\cdot10^{18}$
Sr-90	$4,4\cdot10^{16}$	$2,8\cdot10^{15}$	$1,5\cdot10^{18}$
Zr-93	$5,6\cdot10^{11}$	$3,5\cdot10^{10}$	$2,7\cdot10^{13}$
Tc-99	$9,3\cdot10^{13}$	$6,0\cdot10^{12}$	$4,8\cdot10^{15}$
Ru-106	$7,8\cdot10^{17}$	$4,8\cdot10^{16}$	$2,9\cdot10^{18}$
Sb-125	$1,3\cdot10^{15}$	$8,0\cdot10^{13}$	$8,5\cdot10^{15}$
Cs-134	$4,1\cdot10^{16}$	$2,6\cdot10^{15}$	$5,9\cdot10^{16}$
Cs-135	$9,3\cdot10^{10}$	$6,0\cdot10^{9}$	$4,4\cdot10^{12}$
Cs-137	$6,3\cdot10^{16}$	$3,9\cdot10^{15}$	$2,1\cdot10^{18}$
Ce-144	$2,4\cdot10^{16}$	$1,5\cdot10^{15}$	$1,4\cdot10^{18}$
Pm-147	$2,1\cdot10^{16}$	$1,3\cdot10^{15}$	$2,7\cdot10^{18}$
Sm-151	$7,4\cdot10^{14}$	$4,7\cdot10^{13}$	$3,3\cdot10^{16}$
Eu-152	$2,5\cdot10^{13}$	$1,6\cdot10^{12}$	$4,6\cdot10^{13}$
Eu-154	$3,7\cdot10^{15}$	$2,4\cdot10^{14}$	$7,0\cdot10^{16}$
Eu-155	$7,4\cdot10^{14}$	$4,7\cdot10^{13}$	$1,0\cdot10^{16}$
Ta-182	$3,3\cdot10^{15}$	$2,1\cdot10^{14}$	$2,4\cdot10^{15}$
U-234	-	-	$3,4\cdot10^{12}$
U-237	-	-	$1,0\cdot10^{13}$
Pu-238	$9,6\cdot10^{14}$	$6,0\cdot10^{13}$	$4,1\cdot10^{16}$
Pu-239	$9,6\cdot10^{13}$	$6,0\cdot10^{12}$	$4,4\cdot10^{15}$
Pu-240	$1,4\cdot10^{14}$	$9,0\cdot10^{12}$	$7,0\cdot10^{15}$
Pu-241	$2,8\cdot10^{16}$	$1,8\cdot10^{15}$	$6,7\cdot10^{17}$
Pu-242	$4,4\cdot10^{11}$	$2,8\cdot10^{10}$	$2,3\cdot10^{13}$
Am-241	$3,6\cdot10^{14}$	$2,2\cdot10^{13}$	$1,7\cdot10^{15}$
Am-242m	$2,8\cdot10^{12}$	$1,8\cdot10^{11}$	$1,3\cdot10^{14}$
Am-243	$7,4\cdot10^{12}$	$4,7\cdot10^{11}$	$3,7\cdot10^{14}$
Cm-242	$1,1\cdot10^{14}$	$7,0\cdot10^{12}$	$8,1\cdot10^{13}$
Cm-243	$1,2\cdot10^{12}$	$8,0\cdot10^{10}$	$4,1\cdot10^{13}$
Cm-244	$1,6\cdot10^{15}$	$5,5\cdot10^{13}$	$3,2\cdot10^{16}$
Cm-245	$1,5\cdot10^{11}$	$9,5\cdot10^{9}$	$7,8\cdot10^{12}$
Cm-246	$3,4\cdot10^{10}$	$2,1\cdot10^{9}$	$1,7\cdot10^{12}$
$\Sigma\ \alpha$	$3,3\cdot10^{15}$	$1,7\cdot10^{14}$	$1,0\cdot10^{17}$
$\Sigma\ \beta/\gamma$	$3,1\cdot10^{18}$	$2,0\cdot10^{17}$	$3,2\cdot10^{19}$

Table 7. Cemented powdered and spherical resins, filter cartridges, filters, aqueous concentrates. Emplacement in drop chambers [for lowering method], 6400 containers per chamber, 12,464 containers per year. (A = nuclide, B = activity per year, C = activity per chamber, D = activity after 50 years.)

A Nuklid	B Aktivität pro Jahr Bq/a	C Aktivität pro Kammer Bq	D Aktivität nach 50 Jahren Bq
H-3	$2,3 \cdot 10^{12}$	$1,2 \cdot 10^{12}$	$5,2 \cdot 10^{13}$
Co-60	$2,3 \cdot 10^{14}$	$1,2 \cdot 10^{14}$	$2,1 \cdot 10^{16}$
Sr-90	$2,2 \cdot 10^{15}$	$1,1 \cdot 10^{15}$	$7,8 \cdot 10^{16}$
Zr-93	$2,1 \cdot 10^{13}$	$1,1 \cdot 10^{13}$	$1,1 \cdot 10^{15}$
Ru-106	$1,0 \cdot 10^{16}$	$5,0 \cdot 10^{15}$	$2,2 \cdot 10^{17}$
Sb-125	$1,2 \cdot 10^{15}$	$6,0 \cdot 10^{14}$	$1,3 \cdot 10^{16}$
J-129	$2,1 \cdot 10^{12}$	$1,1 \cdot 10^{12}$	$1,0 \cdot 10^{14}$
Cs-134	$2,0 \cdot 10^{15}$	$1,0 \cdot 10^{15}$	$9,3 \cdot 10^{15}$
Cs-137	$3,7 \cdot 10^{15}$	$1,9 \cdot 10^{15}$	$1,3 \cdot 10^{17}$
Ce-144	$7,0 \cdot 10^{15}$	$3,5 \cdot 10^{15}$	$1,0 \cdot 10^{16}$
Pm-147	$2,3 \cdot 10^{15}$	$1,2 \cdot 10^{15}$	$1,8 \cdot 10^{16}$
Eu-154	$2,0 \cdot 10^{14}$	$1,0 \cdot 10^{14}$	$3,5 \cdot 10^{15}$
Eu-155	$5,2 \cdot 10^{13}$	$2,6 \cdot 10^{13}$	$5,2 \cdot 10^{14}$
U-234	-	-	$2,9 \cdot 10^{10}$
U-237	-	-	$3,2 \cdot 10^{11}$
Pu-238	$8,1 \cdot 10^{12}$	$4,1 \cdot 10^{12}$	$3,5 \cdot 10^{14}$
Pu-239	$3,0 \cdot 10^{12}$	$1,5 \cdot 10^{12}$	$4,1 \cdot 10^{16}$
Pu-240	$4,8 \cdot 10^{12}$	$2,4 \cdot 10^{12}$	$2,2 \cdot 10^{14}$
Pu-241	$8,9 \cdot 10^{14}$	$4,5 \cdot 10^{14}$	$2,2 \cdot 10^{16}$
Pu-242	$1,4 \cdot 10^{10}$	$7,0 \cdot 10^{9}$	$7,0 \cdot 10^{11}$
Am-241	$7,0 \cdot 10^{14}$	$3,5 \cdot 10^{14}$	$3,6 \cdot 10^{16}$
Am-242m	$1,0 \cdot 10^{13}$	$5,0 \cdot 10^{12}$	$4,4 \cdot 10^{14}$
Am-243	$3,0 \cdot 10^{13}$	$1,5 \cdot 10^{13}$	$1,5 \cdot 10^{15}$
Cm-242	-	-	$2.8 \cdot 10^{14}$
Cm-244	$1,1 \cdot 10^{12}$	$5,5 \cdot 10^{11}$	$5,2 \cdot 10^{13}$
$\Sigma\ \alpha$	$7,5 \cdot 10^{14}$	$3,8 \cdot 10^{14}$	$7,9 \cdot 10^{16}$
$\Sigma\ \beta/\gamma$	$3,0 \cdot 10^{16}$	$1,5 \cdot 10^{16}$	$5,3 \cdot 10^{17}$

Table 8. Wastes in lost concrete shielding. Emplacement in stack chambers, max. 12,500 containers per chamber, 8,900 containers per year. (A = nuclide, B = activity per year, C = activity per chamber, D = activity after 50 years.)

Nuklid	Aktivität pro Jahr Bq/a	Aktivität pro Kammer Bq	Aktivität nach 50 Jahren Bq
H-3	$1{,}5 \cdot 10^{12}$	$2{,}2 \cdot 10^{12}$	$2{,}5 \cdot 10^{13}$
Na-22	$3{,}1 \cdot 10^{11}$	$4{,}4 \cdot 10^{11}$	$1{,}3 \cdot 10^{12}$
Mn-54	$2{,}4 \cdot 10^{12}$	$3{,}7 \cdot 10^{12}$	$4{,}1 \cdot 10^{12}$
Co-57	$4{,}4 \cdot 10^{11}$	$6{,}7 \cdot 10^{11}$	$7{,}0 \cdot 10^{11}$
Co-60	$6{,}7 \cdot 10^{14}$	$1{,}0 \cdot 10^{15}$	$6{,}7 \cdot 10^{15}$
Sr-90	$8{,}1 \cdot 10^{13}$	$1{,}2 \cdot 10^{14}$	$2{,}7 \cdot 10^{15}$
Ru-106	$1{,}2 \cdot 10^{14}$	$2{,}0 \cdot 10^{14}$	$2{,}7 \cdot 10^{14}$
Sb-125	$5{,}9 \cdot 10^{11}$	$8{,}9 \cdot 10^{11}$	$2{,}7 \cdot 10^{12}$
J-129	$1{,}1 \cdot 10^{10}$	$1{,}7 \cdot 10^{10}$	$5{,}9 \cdot 10^{11}$
Cs-134	$2{,}2 \cdot 10^{14}$	$3{,}3 \cdot 10^{14}$	$8{,}5 \cdot 10^{14}$
Cs-137	$1{,}1 \cdot 10^{15}$	$1{,}7 \cdot 10^{15}$	$3{,}7 \cdot 10^{16}$
Ce-144	$1{,}3 \cdot 10^{13}$	$1{,}9 \cdot 10^{13}$	$2{,}1 \cdot 10^{13}$
Pu-238	$1{,}4 \cdot 10^{9}$	$2{,}1 \cdot 10^{9}$	$6{,}3 \cdot 10^{10}$
Pu-239	$2{,}0 \cdot 10^{8}$	$3{,}1 \cdot 10^{8}$	$9{,}6 \cdot 10^{9}$
Pu-240	$3{,}1 \cdot 10^{8}$	$4{,}4 \cdot 10^{8}$	$1{,}5 \cdot 10^{10}$
Am-241	$2{,}7 \cdot 10^{8}$	$4{,}1 \cdot 10^{8}$	$1{,}3 \cdot 10^{10}$
Cm-242	$9{,}3 \cdot 10^{8}$	$1{,}4 \cdot 10^{9}$	$9{,}3 \cdot 10^{8}$
Cm-244	$1{,}4 \cdot 10^{9}$	$2{,}1 \cdot 10^{9}$	$2{,}7 \cdot 10^{10}$
$\Sigma\ \alpha$	$4{,}2 \cdot 10^{9}$	$6{,}3 \cdot 10^{9}$	$1{,}2 \cdot 10^{11}$
$\Sigma\ \beta/\gamma$	$2{,}3 \cdot 10^{15}$	$3{,}4 \cdot 10^{15}$	$4{,}8 \cdot 10^{16}$

Table 9. Wastes in drums (200 to 400 liters). Emplacement in dump chambers, number of containers per chamber 18,500, 18,500 containers per year. (A = nuclide, B = activity per year, C = activity per chamber, D = activity after 50 years.)

A Nuklid	B Aktivität pro Jahr Bq/a	C Aktivität pro Kammer Bq	D Aktivität nach 50 Jahren Bq
H-3	$4{,}9 \cdot 10^{12}$	$4{,}9 \cdot 10^{12}$	$8{,}4 \cdot 10^{13}$
C-14	$3{,}3 \cdot 10^{12}$	$3{,}3 \cdot 10^{12}$	$1{,}7 \cdot 10^{14}$
Sc-46	$3{,}0 \cdot 10^{9}$	$3{,}0 \cdot 10^{9}$	$3{,}0 \cdot 10^{9}$
Mn-54	$2{,}9 \cdot 10^{11}$	$2{,}9 \cdot 10^{11}$	$4{,}4 \cdot 10^{11}$
Co-57	$1{,}2 \cdot 10^{12}$	$1{,}2 \cdot 10^{12}$	$3{,}7 \cdot 10^{13}$
Co-60	$1{,}2 \cdot 10^{13}$	$1{,}2 \cdot 10^{13}$	$1{,}3 \cdot 10^{14}$
Zn-65	$4{,}4 \cdot 10^{9}$	$4{,}4 \cdot 10^{9}$	$6{,}7 \cdot 10^{9}$
Sr-90	$7{,}0 \cdot 10^{12}$	$7{,}0 \cdot 10^{12}$	$1{,}3 \cdot 10^{14}$
Ru-106	$8{,}9 \cdot 10^{12}$	$8{,}9 \cdot 10^{12}$	$8{,}9 \cdot 10^{12}$
Sb-125	$6{,}7 \cdot 10^{10}$	$6{,}7 \cdot 10^{10}$	$3{,}0 \cdot 10^{11}$
J-129	$7{,}0 \cdot 10^{6}$	$7{,}0 \cdot 10^{6}$	$3{,}7 \cdot 10^{8}$
Cs-134	$1{,}1 \cdot 10^{13}$	$1{,}1 \cdot 10^{13}$	$3{,}9 \cdot 10^{13}$
Cs-137	$2{,}7 \cdot 10^{13}$	$2{,}7 \cdot 10^{13}$	$9{,}6 \cdot 10^{14}$
Ce-144	$8{,}1 \cdot 10^{12}$	$8{,}1 \cdot 10^{12}$	$1{,}5 \cdot 10^{13}$
Eu-154	$3{,}9 \cdot 10^{9}$	$3{,}0 \cdot 10^{9}$	$3{,}7 \cdot 10^{10}$
Ra-226	$3{,}7 \cdot 10^{10}$	$3{,}7 \cdot 10^{10}$	$1{,}9 \cdot 10^{12}$
U-234	-	-	$6{,}7 \cdot 10^{12}$
U-237	-	-	$1{,}9 \cdot 10^{12}$
Pu-238	$1{,}8 \cdot 10^{15}$	$1{,}8 \cdot 10^{15}$	$7{,}8 \cdot 10^{16}$
Pu-239	$1{,}7 \cdot 10^{14}$	$1{,}7 \cdot 10^{14}$	$8{,}5 \cdot 10^{15}$
Pu-240	$2{,}7 \cdot 10^{14}$	$2{,}7 \cdot 10^{14}$	$1{,}3 \cdot 10^{16}$
Pu-241	$5{,}2 \cdot 10^{16}$	$5{,}2 \cdot 10^{16}$	$1{,}2 \cdot 10^{18}$
Pu-242	$8{,}5 \cdot 10^{11}$	$8{,}5 \cdot 10^{11}$	$4{,}1 \cdot 10^{13}$
Am-241	-	-	$5{,}6 \cdot 10^{16}$
Cm-242	$2{,}3 \cdot 10^{7}$	$2{,}3 \cdot 10^{7}$	$1{,}6 \cdot 10^{7}$
Cm-244	$4{,}1 \cdot 10^{7}$	$4{,}1 \cdot 10^{7}$	$1{,}8 \cdot 10^{9}$
$\Sigma\ \alpha$	$2{,}2 \cdot 10^{15}$	$2{,}2 \cdot 10^{15}$	$1{,}6 \cdot 10^{17}$
$\Sigma\ \beta/\gamma$	$5{,}2 \cdot 10^{16}$	$5{,}2 \cdot 10^{16}$	$1{,}2 \cdot 10^{18}$

Table 10. Cumulative activity inventory of the final repository after 50 years of operation.

* Nuclides are not included in Tables 5-9.

(A = nuclide, B = activity.)

Nuklid	Aktivität Bq	Nuklid	Aktivität Bq
H-3	$5{,}2 \cdot 10^{17}$	Sm-151	$2{,}8 \cdot 10^{16}$
C-14	$1{,}7 \cdot 10^{14}$	Eu-152	$4{,}8 \cdot 10^{13}$
Na-22	$1{,}3 \cdot 10^{12}$	Eu-154	$4{,}8 \cdot 10^{16}$
Sc-46	$3{,}0 \cdot 10^{9}$	Eu-155	$1{,}0 \cdot 10^{16}$
Mn-54	$4{,}1 \cdot 10^{16}$	Ta-182	$2{,}4 \cdot 10^{15}$
Fe-55	$5{,}2 \cdot 10^{18}$	Rn-222	$1{,}9 \cdot 10^{12}$
Co-57	$3{,}7 \cdot 10^{13}$	Ra-226	$1{,}9 \cdot 10^{12}$
Ni-59*	$1{,}7 \cdot 10^{16}$	U-234	$1{,}3 \cdot 10^{13}$
Co-60	$7{,}8 \cdot 10^{18}$	U-236*	$1{,}0 \cdot 10^{13}$
Zn-65	$6{,}7 \cdot 10^{9}$	U-237	$3{,}4 \cdot 10^{13}$
Ni-63	$6{,}7 \cdot 10^{18}$	Np-237*	$1{,}2 \cdot 10^{15}$
Se-79*	$1{,}3 \cdot 10^{15}$	U-238*	$1{,}1 \cdot 10^{13}$
Kr-85	$1{,}1 \cdot 10^{10}$	Pu-238	$1{,}5 \cdot 10^{17}$
Sr-90	$1{,}1 \cdot 10^{20}$	Pu-239	$5{,}6 \cdot 10^{16}$
Zr-93	$6{,}3 \cdot 10^{15}$	Pu-240	$3{,}0 \cdot 10^{16}$
Mo-93*	$5{,}2 \cdot 10^{13}$	Pu-241	$2{,}2 \cdot 10^{18}$
Nb-94*	$3{,}3 \cdot 10^{15}$	Pu-242	$8{,}1 \cdot 10^{13}$
Tc-99	$4{,}4 \cdot 10^{16}$	Am-241	$1{,}6 \cdot 10^{16}$
Ru-106	$3{,}2 \cdot 10^{18}$	Am-242m	$1{,}9 \cdot 10^{16}$
Pd-107*	$3{,}6 \cdot 10^{14}$	Am-243	$5{,}9 \cdot 10^{16}$
Sb-125	$2{,}1 \cdot 10^{17}$	Cm-242	$1{,}3 \cdot 10^{16}$
J-129	$1{,}0 \cdot 10^{14}$	Cm-243	$5{,}9 \cdot 10^{15}$
J-131	$3{,}5 \cdot 10^{11}$	Cm-244	$2{,}3 \cdot 10^{18}$
Xe-133	$5{,}9 \cdot 10^{11}$	Cm-245	$1{,}2 \cdot 10^{15}$
Cs-134	$2{,}1 \cdot 10^{16}$	Cm-246	$2{,}6 \cdot 10^{14}$
Cs-135	$7{,}0 \cdot 10^{14}$		
Cs-137	$1{,}6 \cdot 10^{20}$		
Ce-144	$1{,}4 \cdot 10^{18}$		
Pm-147	$4{,}8 \cdot 10^{18}$		
		Σ a	$4{,}1 \cdot 10^{18}$
		Σ a/γ	$3{,}2 \cdot 10^{20}$

6. Safety Analyses

The final isolation of radioactive wastes is intended to guarantee the protection of society and the environment from damage from the ionizing radiation of these wastes over the long term. The protective goals of the operation of a final repository are given by the German Atomic Energy Law, the Radiation Protection Ordinance and other regulations. In the period after decommissioning of the repository (post-operation phase) the individual doses which result as a consequence of radionuclide transport processes from the sealed repository to the biosphere (which processes cannot be completely ruled out) should not exceed the values given in Para. 45 of the Radiation Protection Ordinance [1].

For the repository system--composed of the total geologic situation, the mine and the wastes--barriers such as the waste form and the waste packaging, the backfill of chambers and tunnels, sealing structures such as chamber, borehole and shaft seals, dams, the repository formation, and the overlying and adjacent rock must prevent an excessive release of radioactive substances into the biosphere if at all humanly possible in order to achieve the protective goals. This is true both of the operation period of a facility and for its post-operation phase. Site-specific safety analyses, which also include treatment of accidents, must provide proof of the attainment of protective goals. These safety analyses must be carried out using scientific methods, whereby sequences of events in the total system must be simulated by appropriate models on the basis of sufficiently conservative assumptions.

For the post-operation phase, therefore, a possible water intrusion extending as far as the emplaced material must be assumed, the spread of radioactive substances with the water in the remaining cavities of the repository and through the repository formation and the overlying and adjacent rock into the biosphere must be modelled, and the potential radiation exposure to the biosphere determined (see Sec. 6.4). The processes taking place in situ in the case of such an event are complex, and it is only possible to quantify them after results of underground exploration of the salt dome and of ongoing R+D research and tests are available. One repository-specific peculiarity results from the long time periods (see Sec. 3.2.3, 6.1.2, 6.2) over which the safety analyses can extend. In this respect changes in subsystems must be analyzed (see Sec. 3.2.2.5, 6.2.2).

6.1 The Integrity of the Repository

The safety of the mined repository depends to a decisive extent on the stability of the salt rock. Rock salt has the characteristic property that it reduces stress peaks through creep deformation. This long-term deformation capability leads to the closure of open cavities. At higher temperatures, which are established in the case of the final isolation of highly radioactive wastes due to the release of radioactive decay heat, the deformation capability of the salt rocks is increased.

The first step in avoiding accidents is the safe design of mine areas and of the entire mine workings. For evaluation of the operation safety and the post-operation phase, preliminary studies are necessary which can be divided into 1) salt mechanics tests in the laboratory and in situ and 2) stress calculations which take into account geologic conditions and the geometry of the planned cavities.

6.1.1 Salt Mechanical Laboratory Tests

The laboratory tests which are necessary for determining the material parameters are divided into creep and strength tests.

In creep tests the rock salt is subjected essentially to a constant load, and in strength tests it is loaded at a constant strain rate.

The test results for rock salt in general and for the rock salt from the Gorleben Salt Dome in particular are summarized below [31-36].

Maximum Absorbable Bearing Force
(Limit Load-Carrying Capacity)

The limit load-carrying capacity is necessary for estimating safety clearances between cavities.

It is the maximum possible absorbable stress or bearing force of the rock salt under investigation and varies depending on composition and impurities.

As extensive mechanical tests have shown, the bearing strength of rock salt increases with a rising strain rate until it reaches a limit value. It is established at a strain rate of $\dot{\varepsilon} \geqslant 10^{-4}$ (s^{-1}). Higher strain rates do not generate significantly greater bearing force.

As an example of several test series, the results of the investigation of line salt from borehole Go 1004 (Gorleben) are reproduced below.

Table 11. Thermomechanical characteristics of rock salt and bases for calculation [commas should be read as decimal points--Transl. Note]

Density	ρ = 2163 (kg/m³) bei 20 °C
Temperature-dependent density	ρ = 2237−0,254·T (kg/m³) T (K)
Acceleration due to gravity	b = 9,81 (m/s²)
Modulus of deformation of release of load and reloading	E_S = 25 000 (MPa)
Dynamic elasticity modulus	E_D = 36 000 (MPa)
Contraction in area for wave propagation	ν = 0,27
Uniaxial compressive strength	σ_D = 25 (MPa)
Modulus of consolidation (as numerical value)	$E_T = (1/10)\cdot E_S$ (MPa)
Steady-state creep rate	$\epsilon_{eff} = A\cdot e^{-\frac{Q}{R\cdot T}}\cdot\frac{\sigma_{eff}}{Q^*}$ (1/d) T (K)
Normalization value	σ^* = 1
Structural factor	A = 0,18 (d^{-1})
Activation energy	Q = 54 (kJ/mol)
Stress exponent	n = 5
Universal gas constant	R = $8,3143\cdot 10^{-3}$ (kJ/(K·mol))
Temperature	T(K) = T(°C)+273,2
Thermal conductivity	$\lambda_T = 6,1/(1+4,5\cdot 10^{-3}\cdot T)$ T (°C) (W/m·K)
Linear coefficient of expansion	$\alpha_L = 4\cdot 10^{-5}$ (K^{-1})
Specific heat at 20°C (equivalent to 293 K)	c_p = 0,88 (kJ/kg·K)

Specific heat as a function of temperature	$c_p = 0{,}81+0{,}00023\cdot T$ $T\,(K)$	(kJ/kg·K)
Specific heat per volume unit at 20°C	$c_p\cdot\rho = 1{,}90\cdot 10^3$	(kJ/m³·K)
Molar mass	$M_{NaCl} = 58{,}4$	(kg/mol)

Density of Saturated Salt Solutions:

NaCl	$\rho_{-} = 1\ 200\ (kg/m^3)$
Q-solution	$Q_L = 1\ 300\ (kg/m^3)$

Mechanical Formulas:

Effective stress

$$\sigma_{eff} = \sqrt{\frac{3}{2}\, S_{ij}\cdot S_{ij}} = \sigma_1 - \sigma_3 \quad (MPa)$$

$$\text{for } \sigma_2 = \sigma_3$$

Mean stress

$$\sigma_m = \frac{1}{3}\, I_\sigma$$

__Table 12__. Laboratory tests of the limit load-bearing capacity of line salt from borehole Go 1004

		A					
		$\sigma_1 - \sigma_3$ [MPa] maximale Werte					
		" $\dot{s}$ (mm/min ≙ $\frac{mm}{...}$) weggeregelt ," $\dot{\varepsilon}$ (1/d) dehnungsgeregelt					
Kern Nr	σ_3 [MPa]	" 1,152 · 10[illegible]	5.76 · 10[illegible]	5.76 10^{-3}	5.76 10^{-2}	5.76 10^{-1}	5.76 10^{0}
		" 1,123 10[illegible]	8.64 10[illegible]	8.64 10^{-3}	8.64 10^{-2}	8.64 10^{-1}	8.64 10^{0}
269	0					(26)	
272		9	9	24	32	34	27
271	5					(50)	
264			19			52	
259		20	24	31	48	70	77
268	10					(59)	
260		26	22	29	45	67	78
270	15					(58)	
261		21	22	32	49	66	85
266	20					(66)	
262		(22)	(25)	(29)	(53)	(77)	(81)
265	30					(62)	
263		(17)	(19)	(32)	47	73	90

Key: A maximal values
B displacement-controlled
C strain [or elongation]-controlled

This bearing force as defined above is a function of the general pressure of the rock (intermediate principal stress) and can be described mathematically as follows for a rock salt (Na3) from borehole Gorleben 1002:

$$\sigma_{eff} = \frac{\sigma_m + c}{a + b\ (\sigma_m + c)} \quad \text{for} \quad \dot{\varepsilon} > 5{,}76\ (1/d)$$

$$\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)\ /\ 3 \qquad \text{intermediate principal stress}$$

$$\left.\begin{array}{lll} a = 0{,}19 & - \\ b = 0{,}012 & MPa^{-1} \\ c = 0{,}65 & MPa \end{array}\right\} \quad \text{structural parameters}$$

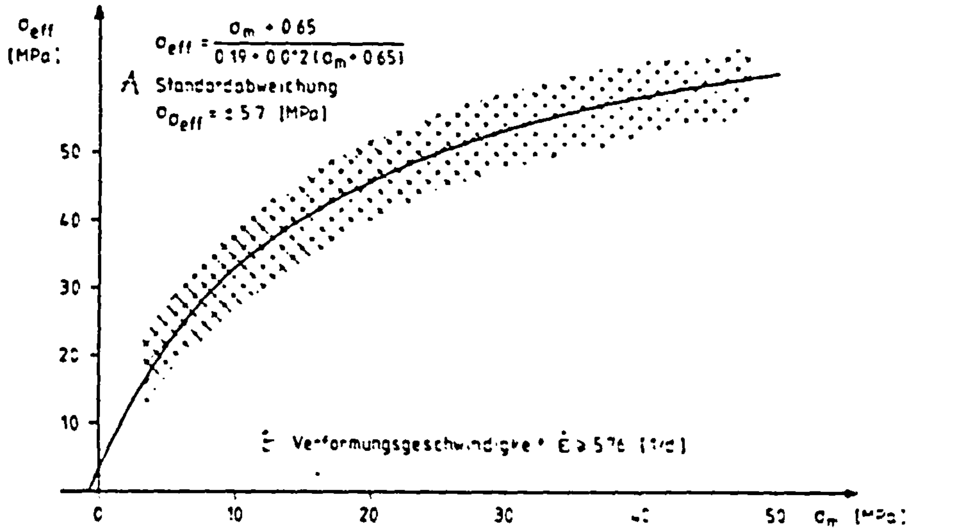


Fig. 31. Effective stress σ_{eff} as a function of the mean stress σ_m and the rate of strain $\dot{\varepsilon}$. Gorleben, borehole 1002, depth 734.3 m – 745.3 m and 849.51 m – 991.92 m (Na3) [A = standard deviation, B = rate of deformation]

Material Behavior of Rock Salt Chips or Fines
(Fill Material)

The estimation of convergence rates for filled boreholes, tunnels and chambers is essentially a function of the mechanical material behavior of the fill or packing material. Rock salt chips and fines obtained during excavation of new tunnels is intended as the fill material. This excavated material is compactable and capable of creep, i.e. large stresses reduce its pore volume and its permeability (leaching permeability) over long periods.

On the other hand, the fill material retards convergence.

As an example, Fig. 32 shows the rate of strain ($\dot{\varepsilon}$) as a function of the observation time for a petrostatic pressure at a depth of 800 m in the salt rock, and Fig. 33 shows the short-time compression behavior (strain ε – stress σ_m). When these two characteristic curves are known, then a material law (Fig. 32, 33) can be described for the salt chips.

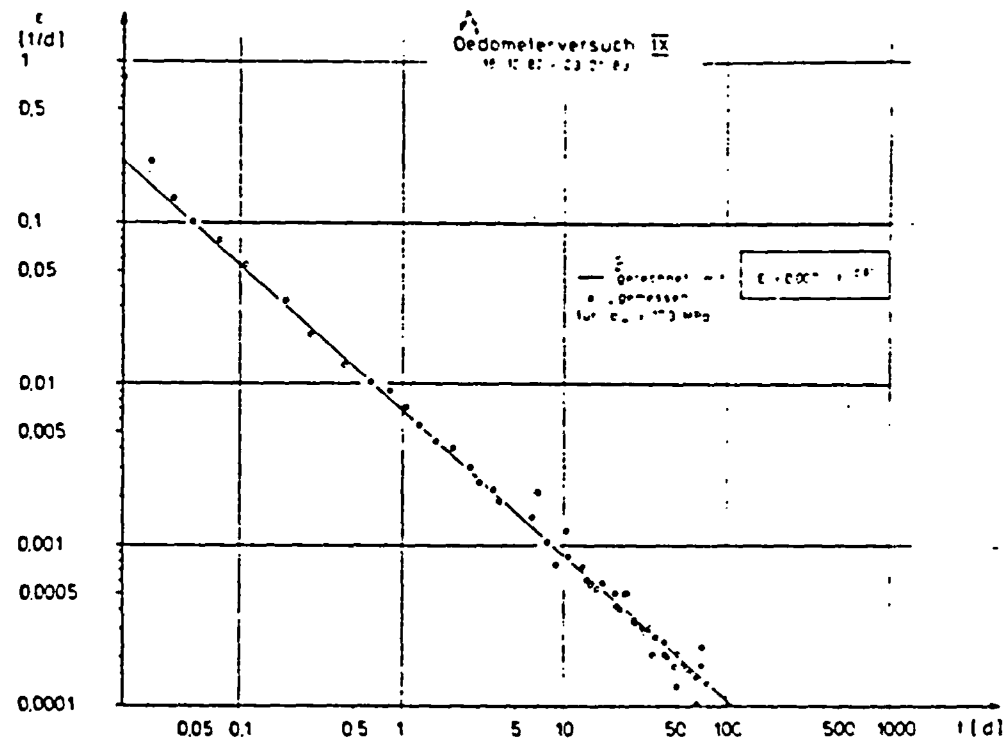


Fig. 32. ε(1/d) as a function of time t(d). Salt chips (Na 2) [A = odometer test IX, 10-18-82 to 01-03-83, B = calculated using ...., C = measured for ...]

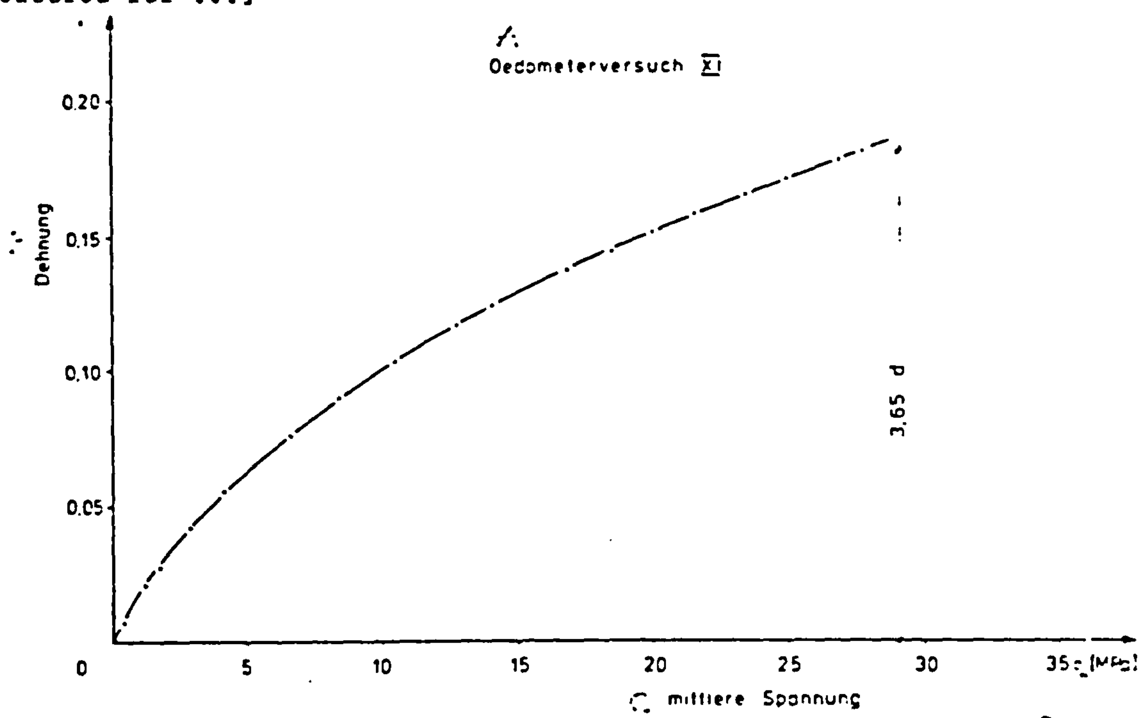


Fig. 33. Compression behavior of salt chips and fines [A = odometer test XI, B = strain, C = mean stress]

$$\varepsilon = \frac{\sigma_m}{E_o + b \cdot \sigma_m} + \int_1^n \dot{\varepsilon}\, dt$$

σ_m	=	$(\sigma_1 + \sigma_2 + \sigma_3)/3$	(MPa)	intermediate principal stress
E_o	=	60	(MPa)	initial tangent modulus
b	=	4		structural parameter
$\dot{\varepsilon}$	=	$0{,}007 \cdot t^{-0{,}92}$	(d^{-1})	creep rate
t	=	1	(d)	time

This material law is a statistic mean value of several tests [37].

6.1.2 Stability Calculations

In evaluating the stability of mined repository zones, one begins with safety principles which have been widely adopted in the general construction industry.

In that industry the stability (η) is defined among other things as follows:

$$\eta = \frac{\text{maximum possible stress}}{\text{mobilized stress}}$$

Calculations of the stability of mine workings are carried out primarily using large computer systems. Programs are used which are based on the method of finite elements. For the calculation of the thermomechanical stresses of underground cavity structures in salt rock, a special FE program called ANSALT was developed by BGR. Besides implementation of the previously explained material model for salt rock and different strategies for the solution of non-linear stress-strain problems, the program contains suitable computational techniques which permit a realistic determination of rock-mechanical processes (excavation, backfilling, rock-mechanical lining) and the similation of thermomechanical interactions. The computer program was checked by comparative calculations carried out in the United States. ANSALT proved that it can be used successfully for the solution of thermomechanical problems associated with final isolation.

For the purpose of validating the reliability of the calculations and the material laws described above, in-situ tests were recalculated, both with the program ADINA that was introduced many years ago and with the specially developed program ANSALT.

In the following, four examples of stability calculations will be presented.

Example 1 shows a tunnel and the rock surrounding it at a depth of 800 m. For reasons of symmetry only half a tunnel was calculated (Fig. 34). The local safety [factors] of the same order of magnitude have been connected to one another (isoasphals). The isoasphals shown are mean values from several time periods. The double area indicates a safety which is below 1. Here we must reckon with sheeting or uparching in the floor. The safety increases very rapidly, however, in the direction of the rock, so that at a distance of about 2 m from the rock wall no cracks or material fractures are expected.

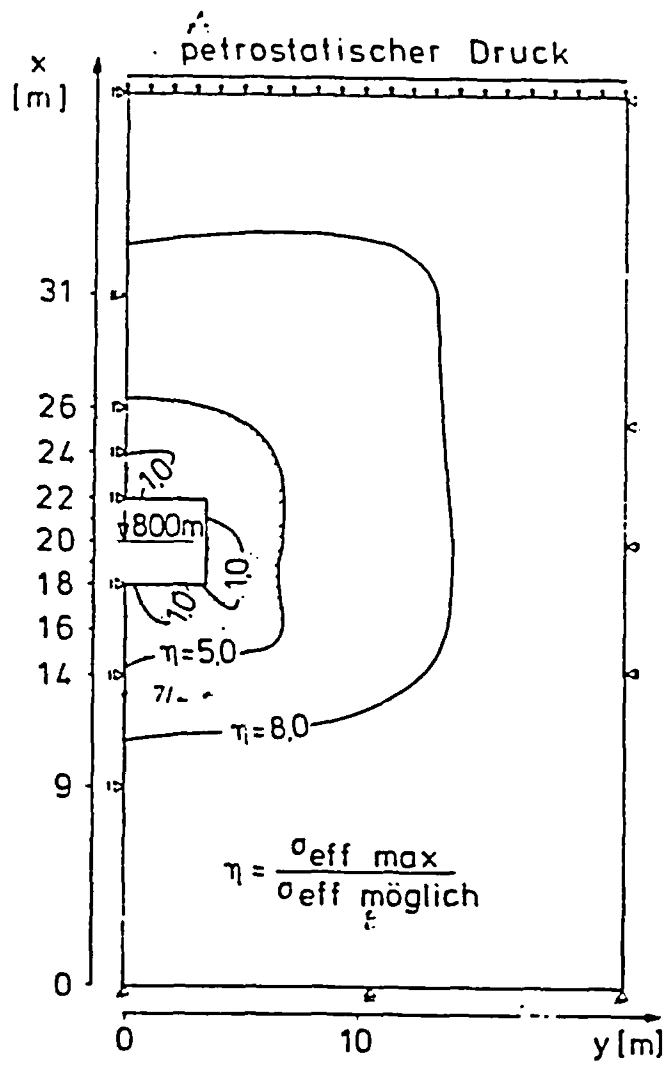


Fig 34. Isoasphals (lines of equal safety) for a 4 m X 7 m tunnel in rock salt [A = petrostatic pressure, B = possible]

Example 2 shows the calculation result for a heating test carried out in situ at a depth of 750 m in the Asse Salt Mine. The heater inserted in a borehole simulated the heat emission from a radioactive waste container.

The output of the heater was initially 1 kW/m and decreased over time. After 150 days no more heating was done. A possible zone of loosening around the tunnel resulting from the temperature load after a 50 day test period is included by the hatched area in Fig. 35. Here we can also see that the loosening zone is locally limited.

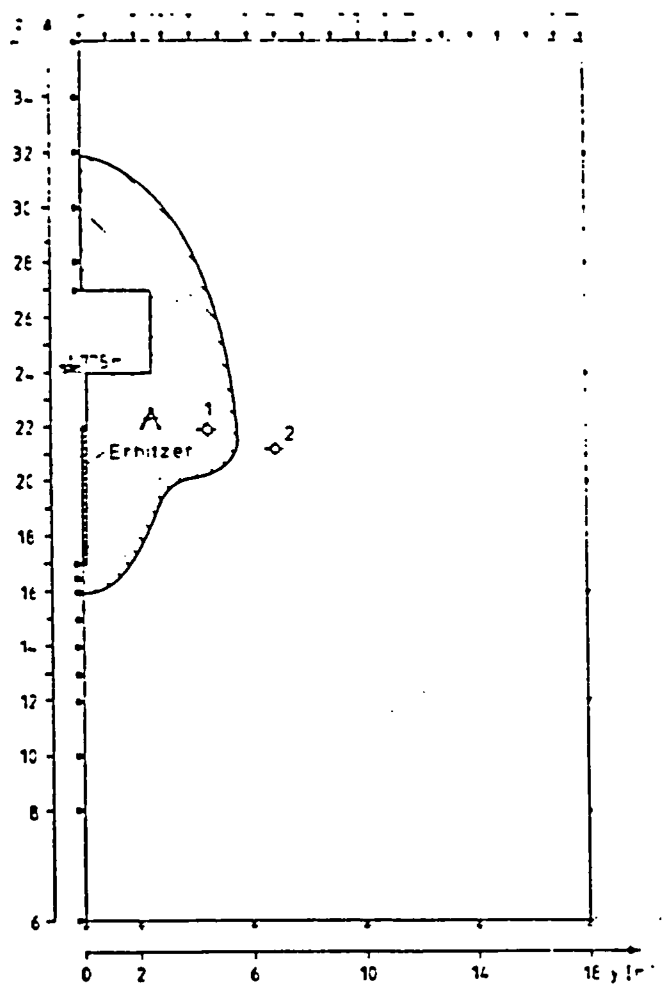


Fig. 35. Zone of loosening after 50 days [A = heater]

When point 2 is analyzed over time it is found that the local safety is very adequate, even during the entire duration of the test [31, 39]. At point 1 in Fig. 35 the safety decreases over time and increases again at the end of the test to $\eta = 5$. It is clear that a possible loosening under thermal loading is very limited and that this local disturbance is balanced out again by the creep properties of the rock salt.

Example 3 simulates the case in which an unfilled tunnel fills up (floods) after 3 years with a salt solution (density 1,200 kg/m^3) and the internal pressure corresponds to an 800 m brine column. The period until disappearance of the cavity (on the left side of Fig. 36) is about 870 years. If the internal pressure is approximately 0, then this period is shortened to about 130 years.

flooding after 3 years   without internal pressure

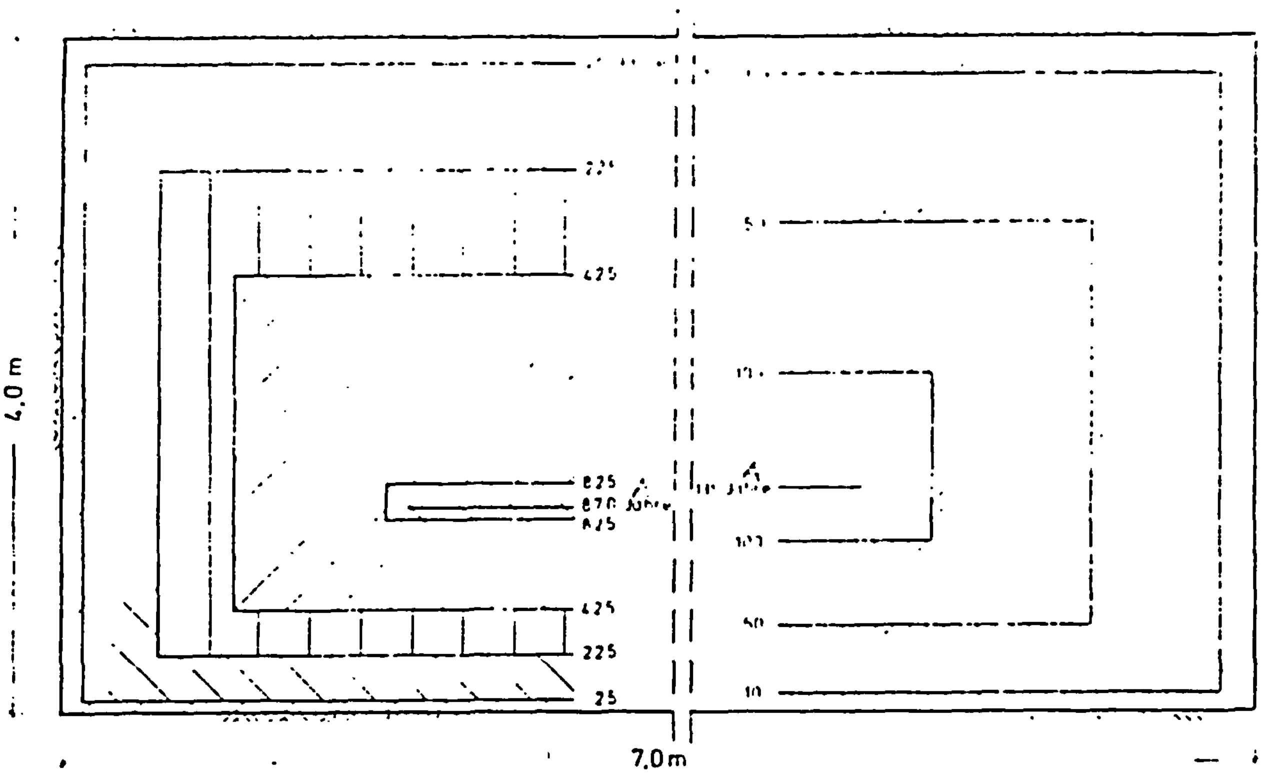


Fig. 36. Times until disappearance of the cavity of a tunnel in the salt mine at a depth of 800 m [A = years]

For the case in which the tunnel floods with brine, no new cracking or additional loosening zones were calculated after a period of more than 60 years.

Example 4 shows the displacements of the upper terrain edge above a salt dome in which a mined repository is located (Fig. 37). Fig. 38 shows the temperature curve in the center of the repository. This example has only limited value because of its model character, but the results are suitable for illustrating the geomechanical phenomena in the salt dome and permit an initial estimate by order of magnitude of the temperatures and shifts which may occur [40].

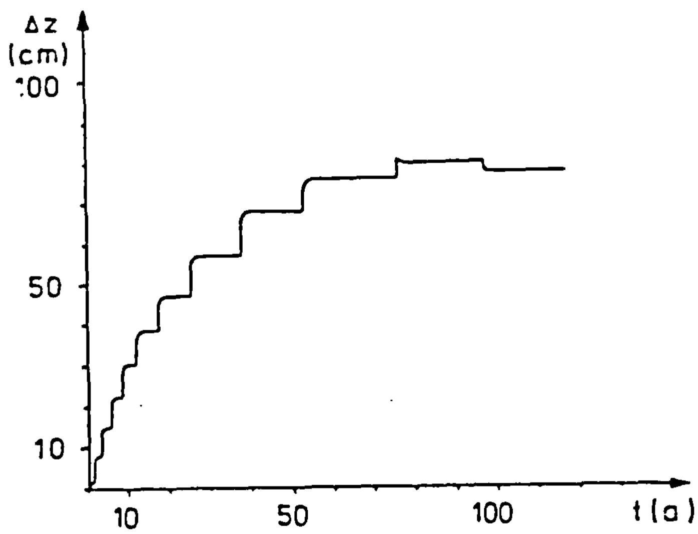


Fig. 37. Vertical displacement (uplift) of the upper terrain edge above a salt dome as a function of time. (The step-shaped curve is the result of the computational method.)

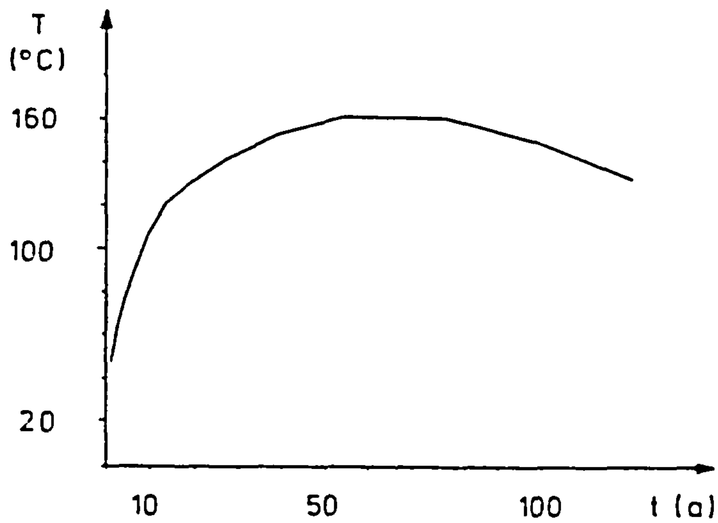


Fig. 38. Temperature curve in the center of the borehole field (BT-HAW) as a function of time

The calculation results shown are based on the material characteristics given previously. In connection with in-situ measurements, the calculations permit better and better estimates of stability in the operation and post-operation phases.

Because detailed exploration of the rock and thus certain knowledge [41] about the stability-relevant rock parameters cannot be possible until the mine workings are excavated, the stability calculations to be carried out for design purposes (planning phase) are only preliminary in nature.

During underground exploration the state of knowledge can be gradually improved by means of measurement checks of the calculation results. The final proof of stability as a part of the final proof of suitability for the mined repository will only be obtained during the exploration phase by measurement-based monitoring and long-time check measurements. For evaluation of these measurements a parallel evaluation of the special geological records and a comparison with stress-strain calculations are indispensable, since only in this way can the measured values relating to complex rock structures be correctly interpreted. The continuous process of completing and checking geotechnical data, which is adapted to the individual planning, construction and operation phases, is therefore an important part of the geotechnical proof of safety.

6.2 The Long-Term Integrity of the Salt Dome

Statements about the effects that are geologically possible on the long-term behavior of salt domes are based on the plausible assumption of processes which took place in the geologic past and of the transfer of these processes to the future. Along with the basic inventory and evaluation of the present condition of geologic events, an additional endeavor in recent years the attempt to describe the geologic processes mathematically and physically.

The following statements are essentially a summary of [42] and treat in general the possible geologic factors that can influence salt domes in northern Germany.

6.2.1 Earthquakes

The Northern German Lowland is considered to have an extremely low rate of earthquake occurrence. Since about 1000 AD only 4 damaging earthquakes with intensities * of $I_0 \geq$ VI have been recorded.

Possible earthquake causes are basically subsidence earthquakes (triggered by the cave-in of natural underground cavities, for example in salt dome caprock) and tectonic earthquakes. As the Soltau earthquake (1977) showed, such events cannot be ruled out in the future, and the intensities could reach $I_0 \leq$ VIII on the basis of past experience. For a mine in a salt dome itself, consequences are to be expected if the earthquake focus or center is in the immediate vicinity of the salt dome. Reports on the condition of mines after severe earthquakes show that the damage decreases rapidly with depth.

6.2.2 Ice Ages

From a geological standpoint we can expect in the future (in several thousand to a few ten thousand years) a new ice age. For the northern German area periglacial conditions would first be established, such as prevail today in Sibiria or northern Canada. Aside from drastic climatic changes with effects on the ground-water resources (precipitation in the form of snow, possibly lower amounts of precipitation), a permafrost would gradually form which could extend under some conditions several hundred meters into the subsoil. In this way the ground-water movements would be severely affected or would even come to a standstill, and the soil-mechanical behavior of the loose sediments would be altered.

In the event of continental glaciation with ice thicknesses of up to several hundred meters, possible mechanical effects would be expected. Shear paths in the subsoil, the result of ice loads or ice thrust, have been detected up to depths of 200 m. An influence on the already low uplift rate of the salt dome (cf. sections 3.1 and 3.2) from unequal ice loads (ice marginal grounds, obstructions in the subsoil or because of morphology) cannot be ruled out.

Other phenomena during continental glaciation are subglacial channels, which were especially pronounced in the Elsterian Ice Age and extend up to 400 m - 500 m (generally 100 - 200 m) below the present ground level into the subsoil, so that several salt domes were intersected.

Instead of a new ice age, a temperature increase in the future might also be assumed. Because of the so-called greenhouse effect, which is brought about primarily by the anthropogenically caused CO_2 increase in the atmosphere, the temperature gradually rises. This can cause the present ice caps to melt and bring about a rise in sea level of 50 - 75 m. The present eustatic rise in sea level is 0.5 mm/yr to 1.5 mm/yr (this can also include changes in the ocean basin volumes, ocean temperature, etc.). In the event of flooding of the North German Lowland we can expect slight erosion followed by sedimentation. The fresh water in the subsoil would be replaced by seawater. Ground-water movements thereafter would only be expected due to thermal potentials and the resulting gravitational potentials.

6.2.3 Epeirogeny

By epeirogeny we mean the slow uplift and subsidence of blocks in the earth's crust, which as a boundary case for fracture processes also allow the breakup of crustal sections into individual blocks. North Germany has primarily subsided since the Permian (290 million years). For the Tertiary (65 million years to 2 million years) we obtain a subsidence rate of 10^{-2} mm/yr to 10^{-3} mm/yr for the Gorleben area. The rates of movement are so small that important consequences for the Gorleben Salt Dome would not be expected for several million years.

6.2.4 Halokinesis and Subrosion

Regarding the process of halokinesis (uplift of salt domes through unstable stratified deposits) and the determination of uplift rates for salt domes, the reader is referred to [42]. As far as the future behavior of a salt dome is concerned, one must consider those factors which influence the mechanism of salt uplift.

These include:

- non-uniform changes in the imposed loads such as sedimentation or erosion, ice loading (see 6.2.2);
- changes in the stress conditions in the earth's crust, which are accomplished over millions of years, however;
- changes in the thermal conditions, which likewise require millions of years (e.g. the terretrial heat flow) and/or are very improbable for the North German area (e.g. intrusion of a magma hearth).

Subrosion (dissolution and removal of highly soluble rocks in the subsoil) is very much a function of the regional and local conditions. Average values of 0 mm/yr to about 1 mm/yr are given in the literature. On a short-term basis (less than 10 years) dissolution rates of cm to dm per year can be reached in a small area, which can be caused by exposed layers or rapid changes in the hydrogeologic or hydrologic conditions. Over the long term the subrosion rates tend toward a low equilibrium level, however, that is essentially a function of the salt dome uplift or the ground-water flow.

6.3 The Access of Solutions to the Emplaced Material

In the following we will present scenarios which assume and deal with the entry of water or brines into the mined repository. These scenarios are to form a foundation for accident analyses and determine their boundary conditions. In this way radioactive exposure to the biosphere via the water route, which is not very probable but which cannot be ruled out completely, can be analyzed conservatively.

The term 'water' is understood to mean influx stemming from the adjacent or the overlying rock. 'Salt solutions' are the inflow that is saturated or undersaturated with chlorides and sulfates, which in the salt mining industry is referred to as brine.

The scenarios and quantitative information are based on knowledge relating to the geology of mineral deposits as acquired in the potash and salt mining industries over a period of about 120 years and have been developed with reference to a mined repository for all types of radioactive wastes.

The periods analyzed include
1) the operating phase,
2) the post-operation phase.
These represent 1) the time period during which radioactive wastes are emplaced and 2) the period after decommissioning of the mined repository.

6.3.1 Operating Phase

Shafts: PTB has commissioned a document [43] which shows qualitatively than an influx of water or salt solutions through the lined section of a modern shaft (steel-concrete compound lining with asphalt backfilling) which leads to flooding of the repository is not possible during the operating period in all probability. Even if an influx is conservatively assumed, engineering measures can be taken with which complete flooding of the mine can be prevented.

Examples include:

1) controlled collection of the influx, limited to the fewest possible points, and controlled removal and disposal;
2) recementation in the foundation zone; reinforcement or repouring of the lining foundation;
3) new lining structures with reduction of the inside diameter (advance column);
4) extension of the lining structure.

In conjunction with the issues under discussion in this section, the only relevant data from the above mentioned document concerns the shafts after sinking operations are completed.

The study leaves the question open as to whether a water or brine influx into the repository can take place via the unlined portion of the shaft. The possibility that the mine will flood from inflow from the unlined part of the shaft is likewise ruled out, since the shaft area is explored in detail. The exploration of the shaft region begins with the drilling of the preliminary shaft borehole. The core material obtained clearly shows the stratigraphic sequence, characteristics and structure in the area of the planned shaft. In addition, knowledge regarding the environment of the shaft, for example the adjacent anhydrite and other rocks, is obtained using geophysical methods (e.g. HF reflection measurements).

When the shafts are sunk, detailed geological photographs of the walls will be prepared and interpreted. The resulting information about the rock strata together with knowledge relating to the geology of the mineral deposit will be evaluated with regard to possible reservoir rocks or flow paths. In addition, the behavior of rock strata of special interest, such as anhydrite, can be specifically investigated using geophysical methods.

Experience has shown that changes can occur in the rock system of the near field of the shaft after the shafts are sunk, changes which can be attributed to

1) changes in the state of stress around the cavity that is created (pressure relief, establishment of a new state of stress) or
2) cooling effects (ventilation system).

These changes in the state of stress occur in the first one to two years after the final depth is reached and after ventilation is begun if caused by 1) and in the first two to four years if caused by 2). At these points the operating phase (emplacement of radioactive wastes) has not yet begun, since the exploration phase lasts about 3-4 years and the subsequent construction phase at least 2 years. Therefore possible sources of danger are known before the beginning of the operating phase. Engineering countermeasures can be taken against them.

The effects on the shaft (possible stress changes), which can occur as a result of the introduction of heat into the salt rock from certain wastes, must be taken into account when designing the shafts. They can be affected by the geometric configuration and the distance between the emplacement fields and the shaft, as well as by the specification of the types and amounts of wastes to be deposited.

Tunnels and Emplacement Rooms

Significant influx of water or solutions in accessible mine rooms can be ruled out during the operating phase for all practical purposes because of the type of ongoing three- to four-year exploration of the emplacement zone. Before each tunnel is excavated, its planned course is explored by preliminary drilling. Underground exploration begins with horizontal boreholes from the shaft on the level of the exploration tunnels. The exploration tunnels are excavated in zones explored by preliminary boreholes (see also Chap. 4). Horizontal and sloped exploration boreholes are drilled from these exploration tunnels. Using the knowledge obtained from the exploration program (tunnels and boreholes), areas well suited for the final isolation of radioactive wastes are found within the salt dome. The corresponding waste types and amounts can be assigned to the different zones.

All significant information about brine and water deposits, including their genetic interpretation, will be developed during exploration. Additional knowledge will be accumulated during excavation of the development tunnels in the construction phase and excavation of the preparatory tunnels in the construction or operating phase. Inflow into accessible mine rooms during the operating phase (emplacement phase) is therefore not very probable. If it should nevertheless occur, it can in all probability be controlled: depending on the genetic interpretation of the solutions and the results of additional studies, the area of the inflow will be cemented, a horizontal lining structure will be inserted, a dam structure erected, or the emplacement field backfilled.

Water or brine influx into mine sections which are already abandonned or backfilled (waste emplacement is to take place in retreat fashion, cf. Chap. 5) is highly improbable. If it should occur, however, these field sections would no longer be accessible for direct observation, and countermeasures would hardly be possible. The dam structures which seal the abandonned and backfilled mine workings prevent an uncontrolled runoff of solutions into the mine workings that are still open.

Inflow with Limited Solution Volume

Experience shows that residual solutions in sealed reservoirs can be enclosed in salt diapirs in orders of magnitude from liters to an estimated 1000 m^3. Variations from the given volumes are possible. Jointed anhydrite is a primary candidate for reservoir rock, and secondarily chloride rocks. On the basis of geological observations of mineral deposits, the occurrence of flow paths in the evaporite body is demonstrated in the geologic past. It is assumed that as the result of heat-induced stress changes sealed paths between the emplacement fields (chambers and boreholes) and the possible solution reservoirs can be newly opened. If potential reservoir horizons are penetrated by tunnels, routes could form preferentially via the abandonned tunnels to the wastes.

In salt mining the influx of residual solutions into open mine rooms of ml/min up to the order of magnitude of l/min is known. This is not to be expected in the case of chambers in the mined repository (because of prior investigations), which are dry when they are constructed. However, it is assumed that this type of influx may occur after abandonment of an emplacement field.

Inflow with 'Unlimited' Solution Volume

Observations of joint fillings (chloride minerals such as halite, sylvin and carnallite) and joints in anhydrite and salt horizons prove that solution routes existed in these rocks. In the case of the restoration (regeneration) of old routes between a solution reservoir and the salt dome boundary, connections could also be established between the emplaced material and the surrounding rock of the salt dome. The transitional zone from anhydrite and salt clay horizons to the wall rock or overburden then represents potential inlet and outlet areas for solutions into and out of the repository zone, if the appropriate stresses are created by heat-producing wastes. In this case the solutions in the environs of the salt dome can have an 'unlimited' volume compared with the residual pore space of the repository, a volume which would suffice to fill the entire remaining cavity of the repository.

Main anhydrite could also contain a path for solutions in the Gorleben salt dome, a possibility which cannot be ruled out based on the present state of knowledge. According to present knowledge it occurs in the salt dome in three legs, two external sections and one central section. The two external deposits probably do not need to be penetrated by tunnels. The central deposit is probably disrupted internally and emergence of central main anhydrite in the salt surface area has not yet been detected anywhere, although several boreholes have intersected this stratigraphic level.

Through exploration, areas of central main anhydrite will be discovered and avoided if at all possible during excavation of the mine workings. If this should not be possible, the stress changes in the salt rock resulting from penetration can be limited. The possibility can be ruled out that far-reaching routes would be formed in this way. Stress variations occur both from the creation of mine rooms and from the emplacement of heat-producing wastes. The latter can place a much greater burden on the salt rock than mining activities. For the event that only non-heat-evolving wastes will be emplaced, minimum clearances between tunnels and relevant anhydrite sections can be developed in the course of further analytical stability investigations. If these clearances are observed, the formation of routes between the main anhydrite and the mine rooms does not need to be assumed.

6.3.2 Post-Operation Phase

A partially jointed anhydrite horizon must be interpreted as being worse for the dispersion of solutions than the barrier effect of the sealing structures such as chamber seals, borehole seals, shaft seals, dams and the tunnel and chamber backfill, which becomes more and more compact due to convergence.

In the case of final isolation of heat-producing wastes, the possibility is not ruled out, for conservative reasons, that inflow of water and solutions to the backfilled mine sections may occur. In this case joints in the main anhydrite represent the most important routing possibility for solutions. The inflow of solutions can only be of relevance from the point of view of safety for the period in which a permeability sufficient for flow movements exists in the backfilled mine sections.

In the case of the emplacement of only non-heat-producing wastes, the inflow of brine or water does not need to be assumed, given the implementation of appropriate measures during backfilling and sealing of the mine workings.

6.4 The Release and Spread of Radioactive Substances

In 1977 research was initiated by BMFT [Federal Ministry for Research and Technology] on the safety aspects of the federal government's waste management concept which brought together the ongoing research in universities, large research installations and industry with the goal of developing a complete body of safety-analytical tools. These efforts were combined in the Waste Management Safety Study Project (PSE).

To the extent that they concern the safety analyses of a geological repository for radioactive wastes, they deal exclusively with topics which pertain to the possible release of radioactive substances from the final repository via the water path through the geosphere (see Sec. 6.3).

The focus of the research was initially on the development of a set of safety-analytical tools for a total system composed of many individual barriers, tools which permit the calculation of the consequences of a water influx when remaining mine cavities still exist, without attempting to make any statement about the probability that this event will occur. Because of the complexity of the individual processes involved in a possible release of radionuclides and the different state of knowledge at the present time as regards subsystems, an iterative process based on rough assumptions was selected in developing the system. With this the preconditions for a later comprehensive proof of safety are to be created, on the one hand. However, the possibility is also created of carrying out at an early date sensitivity analyses that permit indications of the parameters which would have a more or less strong influence on the final result, namely radiation doses from a possible release of radionuclides, so that priorities can be set for ongoing R+D work and recommendations can be made for the planning for the eventual repository for the purpose of safety optimization of the system.

The scenario described as 'water inflow through main anhydrite' was assumed. For the purpose of initiating the methodical determination of the release processes in a final repository, the assumption was made that brine intrusion occurs immediately after the repository is sealed.

The following procedure was followed in determining the radiological consequences of water access to the waste in a backfilled and sealed mined repository, using as an example the plans for the Gorleben site:

1. Evaluation of the results of individual studies and specific expertise regarding possible processes during mobilization and also during the transport and retention of nuclides in the backfilled mine.

2. Summary of the important results of individual studies of barrier models, such as mobilization models of glass and cement, or models of boreholes, chambers and tunnels.

3. The coupling of barrier models to form a barrier system in accordance with the planning specifications and calculation of the quantities of radionuclides that might possible be released from the salt dome using the computer program EMOS, developed specifically for this research.

4. Evaluation of site-specific data and description of the physical, chemical and hydrogeologic properties of the overburden by the institutions participating in the project.

5. Mathematical description and modelling of the transport of nuclides through the overburden using the computer program SWIFT and taking into account site-specific data.

6. Estimation of the radiation exposure given contamination of the surface ground water.

On the basis of the results obtained to date in site exploration--especially the drilling results involving exploration of the Gorleben overburden--and on the basis of results of laboratory tests and a series of model assumptions, which must still be validated by results of ongoing research, PSE carried out on a trial basis calculations of the radionuclide release from a repository which is flooded after backfilling. These were based on an inventory of radionuclides from wastes stemming from the operation of nuclear power plants and from the reprocessing of spent fuel elements for the generation of an electric power of 2,500 GW/yr and also from wastes from research centers and regional collection points.

Boreholes, chambers, charging tunnels and flank tunnels were modelled for the area of the mine workings. Nuclide transport is preceded by the mobilization of nuclides from the waste containers by leaching after a period of delay for corrosion of the containers.

In the case of a number of elements, mobilization was realistically limited when solubility limits were reached to the extent that only as many nuclides were supplied from the wastes as can be transported out of the emplacement location (borehole, chamber) by diffusion and brine exchange.

Three effects--convergence (expression of contaminated brine), convection (brine exchange between different subzones of the mine) and diffusion were considered as causes of the further transport of mobilized nuclides through the pore space of the backfilled mine. The description of the convergence process took into account in a simplified manner the supporting effect of the brine-filled backfill and the increased temperatures. In the case of brine exchange between borehole and charging tunnel, effects of radiolytic gas formation were included approximately in the model.

The time curve of water inflow via routes between the salt surface and the central field of the mine workings and the percolation of solutions through dams and seals into the residual cavities were not modelled. For this purpose we must await on the one hand the results of underground exploration, which should provide information about whether main anhydrite or residual brines exist and if so, what their location and characteristics are. On the other hand, we must wait for results from ongoing R+D work on the effects of thermal stress on any existing anhydrite layers and also on the properties of the fill materials, dams and seals that are actually to be expected. Chemical processes during nuclide migration within the salt dome, such as sorption or precipitation in colder areas, and transport processes in the transitional zone from the repository area to the overburden have been largely omitted from consideration.

The individual effects not yet considered and the numerous rough assumptions involved in the scenario description, the submodels and the base data, as well as the salt dome conditions that are not yet known but that have a decisive influence on the design of the repository, mean that the results of the release calculations are still tentative in nature. They must be adapted to the respective state of knowledge using reliable data as site characterization progresses.

The results of initial model calculations of release from the salt dome show the following:

- The convergence processes determine to a decisive extent the time sequence of the accidents analyzed. Given an initial porosity of 40% immediately after the cavities of the mine workings are backfilled, the convergence processes insure that the residual porosity in these cavities will fall below the assumed standard value of 0.1% in a limited time period. Neither solution inflow or solution outflow is conceivable with this low level of residual porosity, so that the repository must be viewed as being integrated into the salt dome for all practical purposes after this time limit.

- The convergence processes are the decisive driving force for the release of contaiminated solutions from the mine workings.

- The solution transport in the boreholes is hardly affected by the heat produced there. The thermal uplift forces are too limited for this purpose.

- In conjunction with current modelling of the transport processes, the gases formed during radiolysis are a driving force for solution transport in the boreholes and must still be analyzed.

The calculations of release from the repository area are followed by calculation of the spread of radionuclides in the stratigraphic sequences of the overburden. The transport of radionuclides is brought about both by transport with the ground water and by dispersion, diffusion, sorption and desorption processes.

Modelling of the ground-water routing is based on the results of the hydrogeologic research program and can be considered validated for large areas south of the Elbe River. A two-dimensional vertical section was selected from the spatial structure of the overburden as the basis for calculations of the spread of radionuclides, a section which is oriented towards a main ground-water flow direction in the deeper area of the Quaternary channel. There are still simplifications in the model because of non-consideration of density effects due to different degrees of ground-water mineralization. The dispersion data was estimated to a great extent on the basis of theoretical studies. The sorption data used are in part supported by laboratory experiments. Differences between sorption in fresh water and sorption in salt water were considered approximately.

The radiation exposure resulting from nuclide migration is calculated as the 50-year secondary equivalent dose from a one-year drinking water consumption at the place of maximum nuclide concentration as based on the ICRP-30 recommendations.

Initial results based on preliminary calculations already indicate sensitive areas which must be verified by specific studies. These include, among others:

— statements concerning the stability and leaktightness of dams and bulkheads,
— experimental and theoretical studies of the penetration of brine into the repository rooms and of the exchange processes between repository rooms,
— further validation of time-dependent convergence processes,
— experimental proofs of solubility limits in salt solutions,
— studies of radiolysis processes in salt solutions and of the contribution to solution transport of any radiolytic gas formed,
— validation of processes of radionuclide sorption and precipitation in the different geochemical milieus during migration from the waste through the repository or salt dome and strata of the overburden,

— studies for the validation of dispersion lengths.

A final treatment of these areas is not possible until all the data from the underground exploration operations are available and until all design parameters, e.g. maximum temperatures, are established on this basis.

These continuing studies are necessary since it is impossible, using the previously applied conservative procedure for estimating the radiologic consequences of the analyzed accident scenarios, to provide proof that the limits are not exceeded for all conditions and processes conceivable within the framework of this scenario.

In spite of these limitations, which apply to the model development carried out to date for the purpose of describing the spread of radionuclides via the water path, it is already possible to make important statements about trends:

1. The preliminary results indicate that primarily Np-237 but also different uranium isotopes and Ra-226 as well as Tc-99, J-129 and C-14 are radiologically significant.

2. In sensitivity analyses it can be shown that by changing the requirements for the waste canisters containing these radionuclides and by modifying the repository engineering it is possible to influence to a considerable degree the radiological consequences of the spread of radionuclides via the water path. A high degree of flexibility with regard to the conditioning and repository conditions therefore allows for significant improvements from the standpoint of safety engineering.

3. The interim calculations to date have shown that a complete model for the total final isolation system is feasible and already exists in a rough form. With it the assumed accident involving water intrusion can be calculated, if main anhydrite or brines are found in the course of underground exploration and if it can be shown site-specifically that brines can reach the wastes by way of specific paths. For this purpose rock mechanical studies and data are indispensable.

7. Financial Cost

The amounts are calculated on the following basis:

For research already carried out the expenditures actually accrued were used, as were determined for the Repository Prepayment Ordinance (VIV). The basis for the cost of planned activities is a total cost estimate made by DBE. If it relates to categories a) to ba), this estimate is already based on concrete plans. The expenditures in categories bb) to d) are rough estimates based on conceptual ideas and still involve considerable uncertainty. The project phases shown are likewise not yet finally determined. In addition, the roughly estimated cost of PTB and BGR work was added, a cost that is substantially a function of time.

All cost figures, even those for later project phases, are based on 1982 price levels.

	thousand DM
a) Surface Site Investigation	
- deep drilling program (4 deep drillings including safety measures, geophysical measurements and sample tests, incl. filling and recultivating the drilling sites)	52,880
- hydrogeologic investigation program (110 exploration boreholes, 300 water-level boreholes, other investigations of the overburden, and seismic measurements. Ground-water measuring program and sample tests until the year 2000)	118,068
- preliminary shaft boreholes including drilling sites and safety measures	13,960
Total of a)	184,908

b) Underground Site Investigation

		thousand DM
ba) Sinking phase		
- infrastructure measures and survey work media supply and disposal		70,260
- sinking of shafts and recovery landings		257,250
- surface facilities (office and lounge building, workshops, gatehouse)		56,910
- operating costs 1983-1987 incl. safety measures		46,350
	Total	430,770
bb) Construction Phase Exploration mine		
- infrastructure		2,790
- surface facilities (shaft hall, hoist tower, hoist)		62,315
- underground operating rooms and near-shaft exploration		100,025
- operating costs for facilities 1988-1989		33,815
	Total	198,945
bc) Salt dome investigation		
- preliminary tunnel drilling		26,844
- excavation of exploration tunnels		195,125
- field exploration by drilling		42,499
- operating costs for mining facilities 1990-1993		34,647
- plant-related R+D work and studies		14,995
	Total	314,110
Total for b)		943,825

	thousand DM
c) Construction of Repository	
ca) Work on the plan verification decision including maintenance of mine in 1994-1995	124,195
cb) Modification for use as repository	
- expansion of infrastructure (media supply and disposal for new buildings, streets, Lüchow-Gorleben rail line, facility RR station	99,820
- construction of surface facilities (shaft tower with hoisting equipment for shaft 2, acceptance store and transfer facility, expansion of salt dump)	296,380
- underground operations (excavation of development tunnels and cross-cuts, emplacement chambers and tunnels, facility-related R+D work and tests)	609,592
- nuclear engineering and radiation protection (planning and construction of nuclear equipment for radiation protection, emplacement techniques and auxiliary nuclear facilities)	243,050
- operating cost of the mined facilities 1996-2000	61,765
Total	1,310,607
cc) Startup of the Mined Repository	76,465
Total for c)	1,511,267
Total for planning and construction of repository	2,640,000

d) Repository Operating Cost

	thousand DM/yr
- surface operations (infrastructure, plant office, grounds maintenance, operation, unloading facility and buffer store)	48,572
- underground operations (excavation of mine rooms, salt haulage, plant maintenance, tunnel maintenance)	42,772
- waste emplacement and radiation protection	28,656
Total	120,000

8. Summary Evaluation

The underground exploration of the Gorleben Salt Dome and its overburden is largely completed. It has resulted in a good overview of the stratigraphic sequence of the salt dome, initial concepts regarding the structural plan of its interior, and the determination of shaft sites. In addition, detailed information about the overburden and the ground water existing in it has been obtained.

The following important results have been obtained specifically:

- The internal structure of the salt dome appears to be simpler than that of the majority of salt domes opened by mines. The data regarding its internal structure and its material components indicate that sufficiently large rock salt zones exist in which the required emplacement fields can be demonstrated. Initial estimates of the possible emplacement areas lead us to expect sufficient emplacement capacity based on the planning specifications.

- Between the planned mined repository and the top of the salt dome, salt rock will remain in a thickness of about 400 to 500 m. That is far more than is customary in rock salt and potash salt mines, in which a water barrier 150 m thick is required. Because of its thickness, therefore, the salt rock can assume the function of chief barrier in the multibarrier repository system.

- Because the four deep boreholes are outside the future mine workings and the two shaft sites have only been explored by means of two boreholes, the salt rock above the mine workings has only been drilled through by the two preliminary shaft boreholes. Fewer intrusions of this type into the salt formation are not possible.

- The rock mechanical tests which have been carried out in the laboratory using samples from the exploration boreholes, also confirm with respect to the rock salt of the Gorleben Salt Dome the well-known advantageous mechanical properties of rock salt of the Stassfurt and Leine Series.

- The planned shafts are located in the salt dome exclusively in especially stable rock salt series. This is a very favorable situation for salt shafts.

- Of the potash salt seams found in the salt dome, only the carnallitic Stassfurt seam is significant from the standpoint of deposit protection, for only this seam occurs over a wide range in a thickness which would be necessary for the recovery of potash salts. Analyses show that the average K_2O concentration in the cores investigated to date is barely 6% and therefore below the level of mining profitability.

- Exploitable natural gas and oil deposits in the vicinity of the salt dome have not been found in the course of exploration work to date and are also not expected to be found in the future.

- Brine inflow was found in the salt dome exploratory boreholes Gorleben 1002 through 1005. The measured pressure conditions and the chemical composition of the solutions permit the conclusion that no routes exist between the adjacent rock and local brine reservoirs in the salt dome. Experience shows that one would also expect to find brines in the salt rock when exploring other salt domes by means of deep drilling and underground mining operations.

- The condensates found in the two preliminary shaft boreholes do not stem from the Pre-Zechstein period. They may have been formed by thermal transformation of the organic substances present in the salt dome itself or at its base. Their existence must be considered during shaft sinking operations and during further underground exploration, as well as during the excavation and operation of the repository.

- With regard to general geological influencing factors which are significant for the long-term safety of a repository (earthquakes, ice ages, epeirogeny and halokinesis), the Gorleben site does not differ fundamentally from other possible sites in the North German area.

- Leaching rates of up to 0.3 mm per year have only been detected locally (borehole GoHy 940) and within a limited time range in the period between 900,000 years and 700,000 years before the present. The long-term leaching of a salt dome is determined by its uplift movement. The latter is 0.01 mm per year for the Gorleben Salt Dome for the periods of millions of years, i.e. 10 m uplift in one million years. For the future no great natural uplift rates are expected. Uplift and long-term leaching therefore do not threaten the long-term stability of the planned repository in the Gorleben Salt Dome.

- An initial evaluation of the overburden with respect to its barrier function for potential contaminated ground water shows that the argillaceous sediments occurring above the central areas of the Gorleben salt dome do not have the thickness and continuous range that would enable them to retain contaminations from the biosphere on a permanent basis. When ground-water movement is calculated with a freshwater model only and without taking into account retentions and delays caused by sorption and other effects, then the results for computations to date of pollutant transport are transport times to the receiving points on both sides of the Elbe River of 600 years to 3,700 years, depending on the point of entry into the overburden.

  If the physical and chemical processes such as sorption, dispersion, etc., are considered, then the transport times for assumed radionuclide transport are in general longer. Safety analyses show that the barrier effect of the overburden is sufficient to meet the protective goals, even if brine intrusion is assumed, particularly if the analyses approximate the physical reality more or less and if plans are optimized, if necessary [44].

- Ground-water utilization in the vicinity of the Gorleben Salt Dome exceeds 0.5 million m^3 per year (upper aquifers). To the north and the south of the salt dome there is fresh water at great depths which has been largely unutilized to date. Additional removal of ground water from the freshwater-bearing stories for supply purposes would lead to an increase in ground-water runoff, but its effects would remain locally limited and its influence on the deeper ground-water runoff would be small.

In summary it is found that the findings described above pertaining to the Gorleben Salt Dome have confirmed previous statements about its potential suitability for the final isolation of the planned radioactive wastes.

Nonetheless, the findings concerning the site are not sufficient for further repository planning and for answering all safety-related questions, especially because of the fact that underground exploration still has to be done. To illustrate the necessity of underground exploration we will list in the following the issues which cannot be assessed until the previous research has been evaluated in connection with the results of underground exploration of the salt dome:

- The effects of the physical and chemical properties of the salt rocks found in the Gorleben Salt Dome and of its internal structure on the final design of the mine (maximum temperatures in the repository area of heat-producing wastes, maximum temperature increases in carnallitite, maximum temperature loading of the salt dome as a whole, waste types and quantities) cannot be considered until after underground exploration is finished and the results of parallel research are obtained.

- The effect on the ground water of temperature increases from the final isolation of heat-producing wastes cannot yet be finally evaluated.

- According to present knowledge, the possibility cannot be ruled out that with the emplacement of highly heat-producing wastes the main anhydrite in the salt dome barrier will be a weak spot with regard to possible brine inflow. In particular, a major input of heat into the salt dome could create the conditions under which presently sealed flow paths could be effectively reopened. Of relevance for safety engineering is only the brine influx in the post-operation phase for a limited period of time, in which sufficient permeability for flow movement exists in the backfilled portions of the repository. The conservative procedure used to date for estimating the radiologic consequences of such an event do not yet allow any reliable statements about the attainment of protective goals.

According to the available results of the site investigation, main anhydrite occurs in the salt dome in two external deposits and one central deposit. The two external deposits presumably do not need to be penetrated by tunnels. The central bed is probably internally disrupted. Emergence of central main anhydrite in the salt surface area is improbable, since the boreholes have not encountered it in its stratigraphic level. If these hypotheses should be confirmed by underground exploration, then a flow path via the main anhydrite would not need to be analyzed further.

In conclusion it is found that the verified potential suitability of the salt dome for the emplacement of the planned radioactive wastes justifies the sinking of shafts and the exploration of the salt dome interior. Only by means of these measures is it possible to obtain the necessary site-specific planning data for the repository. The latter form the absolute prerequisite for presentation of proof of suitability in the plan verification procedure.

List of References

[Translator's Note: references are given first as in the original, followed by a translation in brackets of the title only, with some exceptions. Page numbers of journal articles are preceded by the German abbreviation 'S.' which stands for 'pg.']

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