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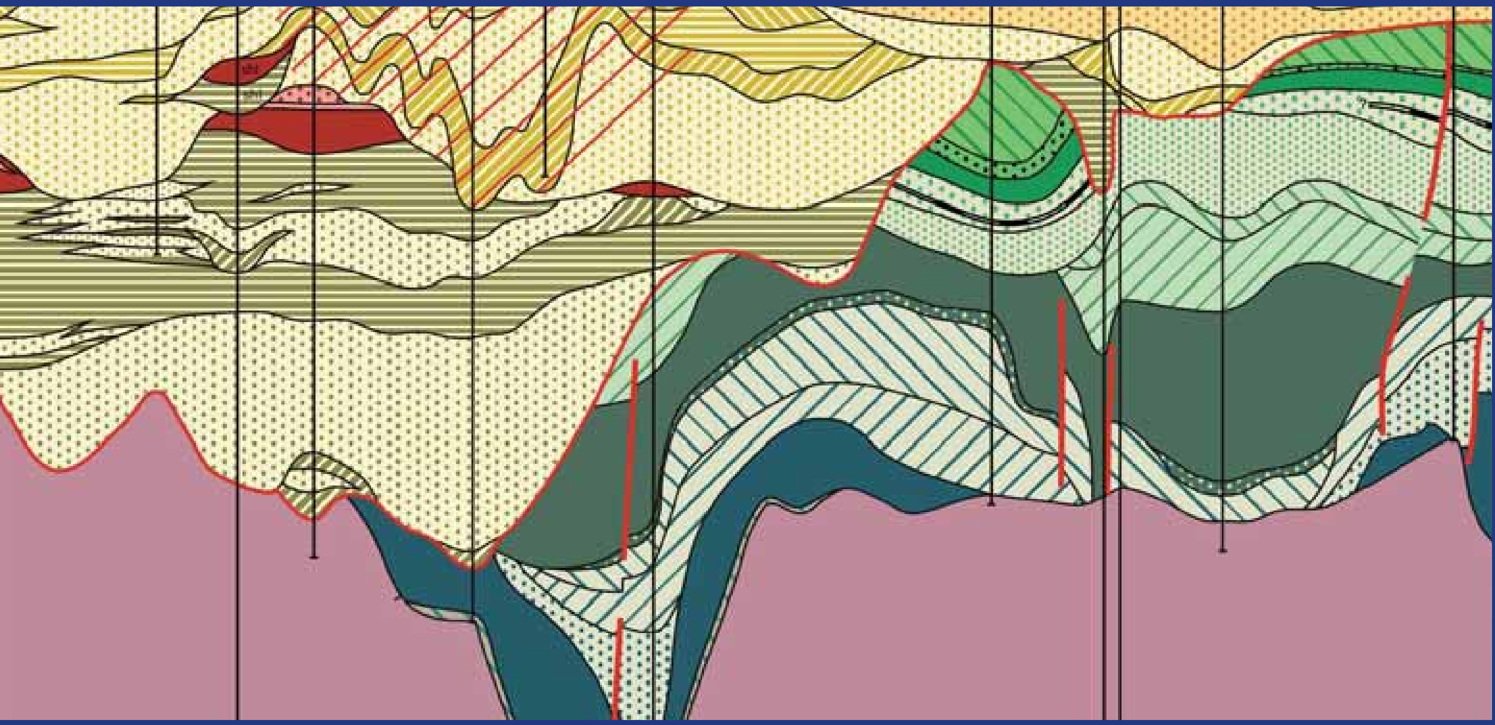
Part 2:

Geology of the overburden and adjoining rock of the Gorleben salt dome



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Geology of the overburden and adjoining rock of the Gorleben salt dome

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Foreword

Research has been carried out since 1979 on the Gorleben salt dome, located in the rural district of Lüchow-Dannenberg in Lower Saxony, to investigate its suitability as a geologic repository for radioactive waste. The investigation programme consists of surface and underground geological and mine engineering exploration, as well as analysing and evaluating all of the issues necessary to competently assess its suitability and long-term safety. The Gorleben site was investigated in detail for a period of more than twenty years to understand the internal structure of the salt dome, the overburden and the adjoining rock. The preliminary results of these investigations were published in interim reports in 1983, 1990 and 1995. The findings published in these reports substantiated the potential suitability of the salt dome as a geologic repository for radioactive waste.

The investigation work at the Gorleben site was suspended as a consequence of the agreement reached on 14 June 2000 between the German government and the power supply industry. This moratorium applied for a period of at least three years, but a maximum of ten years. Notwithstanding the moratorium, the German government issued a statement on Gorleben which confirmed that the previous findings from its investigation did not contradict the site's potential suitability.

It is now possible after the termination of the surface investigation programme, and for the purpose of documenting the results of the extensive underground exploration, to present the findings of the geoscientific investigation of the Gorleben site in an overall report. The first part presents the hydrogeology of the overburden. The second part presents the results of the geological and structural geological exploration of the overburden and the adjoining rock, and the third part covers the results of the exploration of the salt itself. These findings are supplemented in the fourth part by a description of the geotechnical investigations.

This compilation of the data, and the presentation of the technical evaluation of the geoscientific investigation results, as well as the documentation, should also help to bring more objectivity into the controversially discussed public and political debate concerning the Gorleben site.

(Volkmar Bräuer)

- Repository Project Manager -

Abstract

The Gorleben salt dome was investigated for its suitability as a repository for radioactive waste. From 1979 to 1984 and from 1996 to 1998, the cover deposits of the Gorleben salt dome were investigated as part of a comprehensive geological and hydrogeological site exploration programme. Simultaneously, a large number of reflection seismic and shallow seismic reflection surveys were conducted for a structural investigation of the salt dome and the rim synclines. The results of the geological examination of the cover deposits and the structural geological investigation are summarised here.

The structure of the pre-Zechstein underground and all the lithostratigraphic units that have been cored are described in detail, their occurrences and their beddings are explained and illustrated.

The cover deposits mainly consist of Tertiary and Quaternary sediments, whereas Cretaceous sediments are preserved as remnants. The Tertiary sequence includes sediments from Paleocene to Lower Miocene, which were originally present throughout almost the entire study area. As a result of erosion, mainly in the Quaternary channels, they are now absent in some places. The Tertiary sequence is clearly influenced by the halokinetic evolution of the Gorleben-Rambow salt structure. Above the salt structure, the sequence is condensed to about 50 m to 200 m, but in the northwestern rim syncline it is up to 1 100 m thick. A hiatus of approx. 15 million years separates the Tertiary sequence from the overlying Quaternary sediments.

The Quaternary sequence consists of sediments from the upper Menapian through to the Holocene and covers the whole of the study area. The base of the Quaternary is formed by elements of different ages and genesis. The most notable are the more or less parallel Quaternary channels. Above the central part of the salt dome the Tertiary sediments were eroded completely and therefore sediments of the Elsterian Glaciation have direct contact with the cap rock and in some places even with the salt. The bedding of the Quaternary sediments has been primarily determined by glacial processes such as erosion, exaration and glacial dynamics, and to a lesser extent by the effect of subrosion.

An analysis of the salt dome rim synclines showed that the uplift of the salt dome was 0.08 mm/year during the Upper Cretaceous and 0.02 mm/year during the Miocene through to the Quaternary. The epirogenic-tectonic and halokinetic movements were quantitatively evaluated and indicate a stable tectonic situation in the study area nowadays. The subrosion that took place at different times and with different rates was analysed, showing an expected low subrosion rate for the future.

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1 Introduction

The Federal Institute for Geosciences and Natural Resources (BGR), as the German government's central authority on geoscientific issues, works on the geoscientific aspects of the investigation of the Gorleben site as part of the geologic repository measures of the Federal Ministry for the Environment, Nature Protection and Nuclear Safety (BMU) and the Federal Office for Radiation Protection (BfS). All of the investigation findings resulting from the surface and underground geological exploration activities are interpreted and presented by the BGR. The results of the exploration and the safety analysis form the basis for the location assessment and the subsequent approval procedures conducted pursuant to the Atomic Energy Act.

From 1979 to 1984, the hydrogeological-geological drilling and exploration programme to explore the overburden and adjoining rock was the main focus of the site investigation. In order to identify the structural configuration, the drilling programme was supplemented and accompanied by geophysical methods (seismic, gravimetry and geoelectrical surveys).

To the north, the study area borders on the Elbe River, which used to form the border between the former two Germanys. After the German reunification, it was possible to extend the investigations to the area north of the Elbe. The study area "Dömitz-Lenzen" which is situated in the federal states of Brandenburg and Mecklenburg-Western Pomerania was explored between 1996 and 1998. It is situated between the eponymic towns of Dömitz in the west and Lenzen in the east and mainly comprises the Elbe-Löcknitz depression.

The nuclear consensus in the context of the withdrawal from the nuclear energy programme, an agreement made between the Federal Government and the power supply industry in 2000, laid the legal foundation for a moratorium on the exploration of the Gorleben salt dome. The surface exploration comprising the geological and structural site investigation had at this time already been completed.

This volume presents the results of the geological and structural-geological exploration of the overburden and adjoining rock. The results of the hydrogeological exploration of the overburden at Gorleben are presented in KLINGE et al. (2007), the results of the underground exploration are presented in BORNEMANN et al. (2007).

2 Geological and structural exploration at Gorleben

2.1 Exploration objectives

In 1979, the government of the Federal State of Lower Saxony proposed the Gorleben salt dome (Fig. 1) as a possible site for a mine for the final disposal of radioactive wastes. The Federal Government of Germany adopted this proposal and initiated investigations to assess the suitability of the site for the disposal of such wastes. The objective of the investigations was to demonstrate the safe construction and operation of the repository in the salt dome as well as the long-term safety. To this end, the geologic and hydrogeologic site conditions were explored from the surface and underground.

During the exploration of the overburden emphases was laid on the investigation of the hydrogeology/hydrology and geology/structural geology. The objectives of the geological and structural-geological exploration were the stratigraphic, lithologic/lithogenetic description of the geologic structure of the overburden as well as the description of the geologic development of the overburden and the salt structure in recent geologic times. The data were obtained in order to create a basis for scenario assessments concerning the long-term safety of the repository, e.g. subrosion, diapirism, and glacial channel formation.

2.2 Exploration activities

The surface exploration should assess the geologic and hydrogeologic conditions at the site. Furthermore, it should deliver reliable background information and data for the long-term safety assessment.

The exploration activities described below are individual components which can be combined into a comprehensive pool of basic knowledge for the analyses of the long-term safety. They are the basis for establishing hydrogeologic and geologic scenarios of the Gorleben site.

The detailed knowledge of the extent and thickness of the beds and their hydraulic parameters (grain size, permeability, porosity), gained from sample analyses and borehole logs, is, in addition to data from hydraulic tests, further input data for hydrogeological calculation models to determine the large-scale groundwater movement. Such calculation models are part of the long-term safety analysis of a repository as they describe possible migration paths for radionuclides. The information on recent developments of the salt structure (Tertiary to Quaternary) provides scenarios for the prediction of future salt uplift and subrosion.

Previous knowledge before the start of the Gorleben exploration programme

When drilling and mapping operations for the planned repository site were started, the deeper-lying structure and the Quaternary development of the study area were less well known than those of neighbouring areas in Lower Saxony and Brandenburg.

The sheets GK 25 Nr. 2834 (Gorlosen), 2835 (Rambow), 2934 (Lenzen), and 2935 (Schnackenburg) dating back to the earliest stages of geological mapping were the only annotated geological maps of scale 1 : 25 000 that were available. In the mid-1970s, the part of the study area situated in Lower Saxony was mapped at a scale of 1 : 200 000 for the geological map sheet CC 3126 Hamburg-East as a general overview.

In the study area, deep-boreholes had only been drilled for local water-supply (wells) or when prospecting for salt and oil. Regional geological information about deeper-lying structures of the Quaternary and Tertiary were provided by rare and widely scattered boreholes of approx. 150 m to 200 m depth that had been drilled in the 1970s for water development, e.g. boreholes for water resources planning (Lower Saxony) or for hydrogeological exploration works in the area of Dömitz (Mecklenburg-Western Pomerania and Brandenburg).

The Gorleben salt dome itself had been identified by four deep boreholes prior to the exploration programme. These were the potash boreholes Nordenhall I and II, which were drilled before World War I, borehole Meetschow I from 1929, and the oil exploration borehole Gorleben Z1 (1957). The latter identified a rim syncline with a thick Tertiary layer on the northwestern flank of the salt dome.

From 1947 onwards, the area was surveyed using modern seismic reflection methods while prospecting for hydrocarbons. Based on these investigations, Jaritz (1973) was able to provide a salt dome map that included the structures in Gorleben area.

In the 1950s and 1960s, several deep boreholes were drilled and seismic reflection surveys were performed northeast of the Elbe in the former German Democratic Republic while prospecting for oil. These activities produced information on the outline of the Rambow salt dome, its adjoining rim synclines, and the enveloping anticlinal structures Dömitz-Gorlosen in the northwest and Aulosen-Karstädt in the southeast.

On the whole, the documentation (seismic sections and drilling results) that was available prior to the exploration programme permitted a preliminary assessment of the site but was not sufficient for a project-related evaluation.

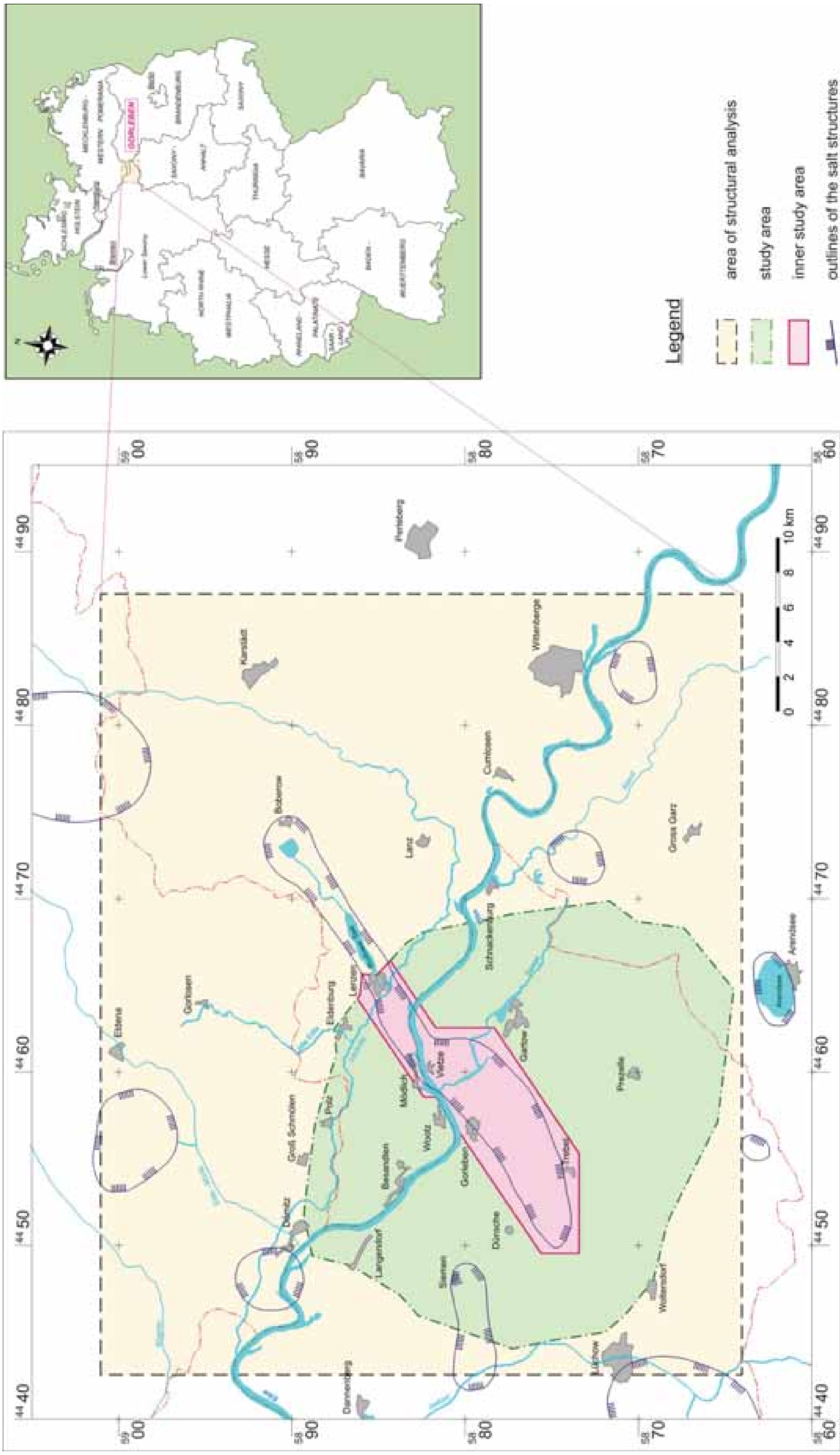


Figure 1: Location of the study area

2.2.1 Drilling programme

Based on the information status described above, an extensive drilling programme provided the basis for the site exploration programme. The drilling programme was primarily conFigured to meet the exploration requirements for a safety assessment of the site with regard to the hydrogeological modelling. Thus, 281 project boreholes were drilled for the surface geological exploration of the Gorleben salt dome between 1979 and 1998. In the course of the exploration, the initially wide-meshed exploration grid was refined step-by-step by additional boreholes in order to gain sufficient knowledge for the geological and hydrogeological exploration, e.g. on the course of the quaternary channels and the structure of the northwestern rim syncline. The field activities were mainly composed of two drilling campaigns. In the study area Gorleben-Süd, 219 boreholes (especially 158 exploration and 44 salt table boreholes) were drilled between 1979 and 1985. In the study area Dömitz-Lenzen, 62 boreholes (27 exploration boreholes, 22 shallow boreholes to investigate the Quaternary geology, and 13 boreholes for pumping tests) were drilled between 1996 and 1998.

The majority of these boreholes (185) were drilled as hydrogeological exploration boreholes. They were planned to reach the base of the Tertiary or Quaternary aquifer system. Their final depths were between 120 m and 444 m. Based on the results of the exploration boreholes, the number of ground-water measuring points (five max.) and the core sections for these adjoining boreholes were determined for each measuring group. Another 44 boreholes (down to 520 m depth) were drilled to explore the salt table, the features of the cap rock and the topmost sections of the salt formation as well as to explore the salt dome (four boreholes with final depths of approx. 2 000 m). The Quaternary shallow boreholes were meant for the exploration of the composition and depth of the sediments of the Weichselian Lower Terrace, the upper deposits of the Holocene, and the sediments adjoining the base of the Lower Terrace. These boreholes were sunk by dry drilling. The final depths varied between 17 m and 50 m.

The positions of the boreholes can be found in Figure 2. In addition to this, 175 external boreholes were assessed for geological and structural-geological interpretation.

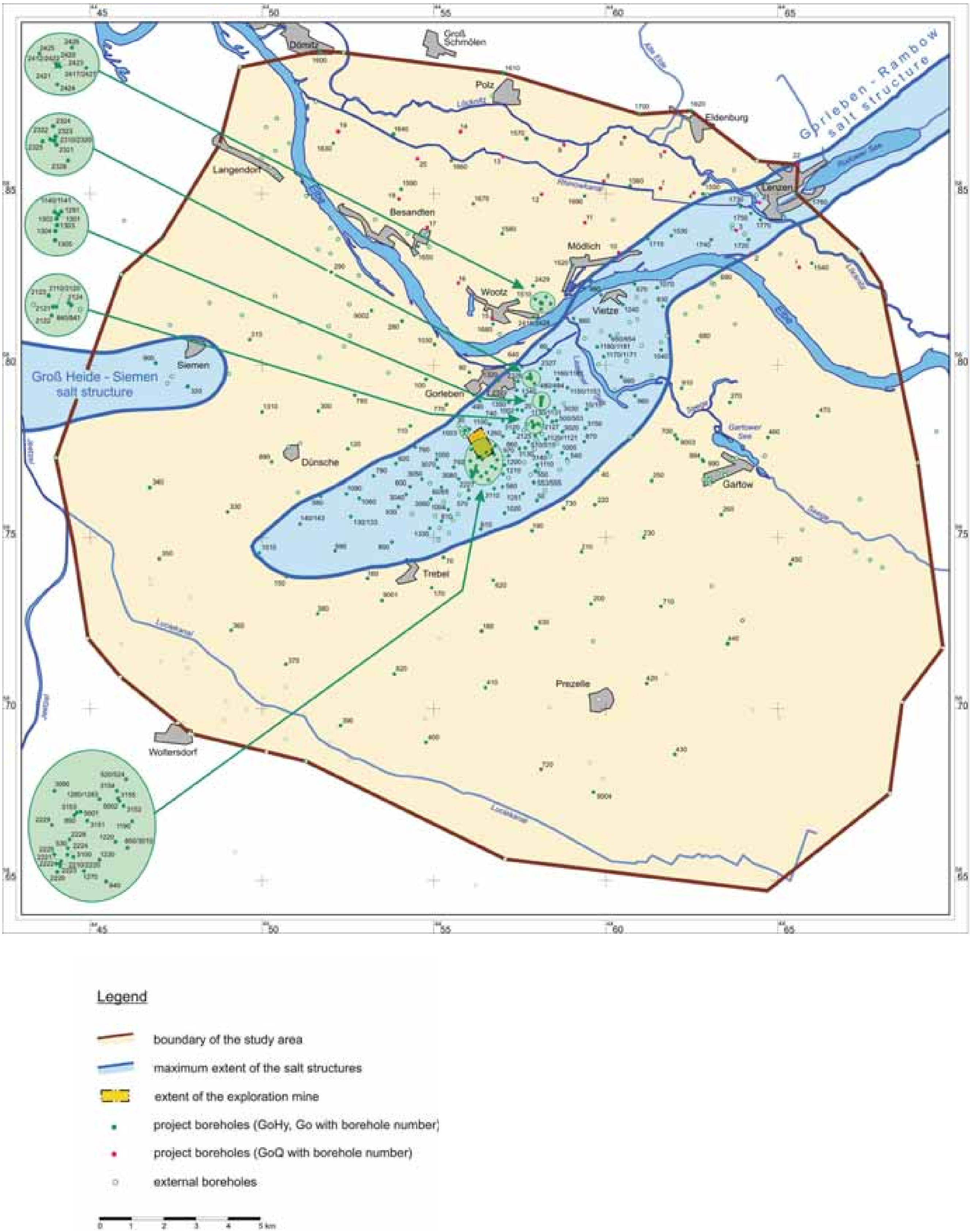


Figure 2: Positions of the project boreholes and external boreholes

In order to interpret the drilled stratigraphy and its correlation, a complex survey programme of geophysical borehole logs was used. All boreholes except the shallow Quaternary boreholes were the object of geophysical logging. The majority of the methods were chosen because they allowed the interpretation of the petrographic properties of the penetrated rock units and hydrogeological assessment. These included the measurement of natural gamma radiation (GR-log), self-potential log (SP log), focused electric log (FEL log) in all boreholes, and density log in almost all boreholes. The borehole caliber (caliber log) was recorded for all boreholes. In several selected boreholes, neutron logging was performed in order to quantitatively determine their porosity.

2.2.2 Geophysical exploration programmes

To identify the geometry of the overburden and adjoining rock, several geophysical surveys were performed between 1980 and 1997.

In 1980, the flanks of the salt dome were surveyed with downhole reflection seismics using the deep boreholes Go 1002 and Go 1003 to register the reflections of the seismic waves that were generated at the surface (Prakla-Seismos 1981).

In 1984, seismic reflection surveys were carried out in the area of the Gorleben salt dome. They were supplemented by seismic refraction surveys and undershooting of the salt dome. These measures were used to explore the geometry, surface relief, outline, and base of the salt dome. Altogether, seismic reflection data were recorded and analysed on 16 profiles with a total length of approx. 150 km. From 1994 to 1997, two survey campaigns were carried out in the areas Gorleben-Süd and Dömitz-Lenzen producing 313 km of high-resolution seismic reflection profiles (shallow seismics). These investigations were carried out to identify the structure of the Tertiary and Quaternary sediments as well as the salt surface structure of the Gorleben salt dome and adjoining parts of the Rambow salt dome in more detail. At the same time, vertical seismic profiles were surveyed in 42 boreholes, the results of which were used for the interpretation of the shallow seismics.

The results of the geophysical exploration programmes permitted the analysis of the rim synclines, the identification of possible migration paths in the overburden, and a more precise definition of the salt dome boundaries.

2.2.3 Mapping of the Quaternary geology

In the whole study area, loose Quaternary rocks has cropped out at the surface. As no or only outdated geological maps of scale 1 : 25 000 of the study area existed, the site investigation included mapping of the Quaternary geology in order to explore, describe and map the lithology, thickness, structure, and extent of the Quaternary beds near the surface and at shallow depths.

These mapping efforts helped to expand the knowledge on the sediments of the Lower Terrace and of the more recent stages of the Holocene, i.e. the last 100 000 years. Thus, the most recent processes that shaped and altered the area above the salt dome and the overburden were assessed, facilitating extrapolation on the future development of the salt dome.

Mapping of the Quaternary geology Gorleben-Süd

The main focus of the geological survey was the overview mapping at a scale of 1 : 25 000 (Fig. 3). In addition to the overview mapping of the whole area, a special map of the Höhbeck push moraine was created at a scale of 1 : 5 000. This detailed map of the complex glacio-tectonic bedding disturbances should serve to help understand and recognise disturbed bedding in the exploration boreholes.

The Weißes Moor and the Elbe terrace in Gorleben were mapped at the same scale, as, according to Grimmel (1980), these areas exhibit a type of subrosion controlled by fracture tectonics or a deep faulting that is visible to the surface (see chapter 8.4).

The mapping is mainly based on approx. 5300 sounding rod drillings to a minimum depth of 2 metres. In some areas, e.g. the Elbe terrace, drilling went further down in order to penetrate the Holocene and reach the surface of the Lower Terrace.

In order to understand the structure of the Höhbeck push moraine, the natural exposures were registered and the complex pattern of glaciotectonic bedding disturbances was interpreted using petrofabric and lithostratigraphic analysis (gravel counts).

At selected points, the geological mapping was supplemented by a morphogenetic interpretation of the topography in order to investigate possible correlations between the salt dome and the surface relief.

Mapping of the Quaternary geology Dömitz-Lenzen

The mapping of the Quaternary geology in the Dömitz-Lenzen area was to expand the knowledge on the Holocene, the structure of the Lower Terrace and its underlying bed. Furthermore, assumed peaks of older beds, e.g. glacial till of the Saalian Glaciation, were to be identified. The boundaries of the mapped area are shown in Figure 3. The mapping was performed from 1997 to 1999.

The mapping efforts resulted in a Quaternary-geological surface map and a structural map of the Weichselian Lower Terrace at a scale of 1 : 25 000. The base of the Lower Terrace is of special importance as it was not overrun and altered by glacial ice unlike the bulk of the Quaternary sediments. Thus, it is together with the Holocene the most recent geologic marker horizon that can be used for the assessment of continued halokinesis. A focal point of the work was the interpretation of the Quaternary shallow boreholes, especially the samples gained for pollen and gravel analysis. The positions of the shallow boreholes were coordinated with the exploration boreholes so that areas above the northwestern rim syncline of the Gorleben–Rambow salt formation were targeted that had not or only scarcely been explored before. An additional source for the mapmaking process were the stratigraphic data of approx. 350 external boreholes that had been drilled in the Dömitz-Lenzen study area for diverse objectives, mainly for shallow wells and building site investigations for dike building.

The Quaternary geological maps of Gorleben and Dömitz-Lenzen, together with the results of the exploration boreholes and the Quaternary shallow boreholes, are the basis for the survey and interpretation of the post-Holsteinian Interglacial Quaternary stratigraphic sequence, its extent near the surface, and its bedding structure.

2.2.4 Pedological mapping

During the hydrogeological investigation of the study area, a pedological survey was performed in order to gather areal data on groundwater recharge rates. For this purpose, sampling rod drillings and mapping excavations were carried out, which were supplemented by soil-physical surveys and soil-physical and soil-mechanical lab tests. Based on these efforts and on available maps and data, soil maps and land usage maps were created. The boundaries of the mapped area are shown in Figure 3.

Pedological mapping in the area Lüchow-Gartow-Schnackenburg

The mapped area encompasses approx. 300 km^2. The pedological mapping at a scale of 1 : 25 000 was carried out in 1980. In order to determine and areally distinguish the soil type, land usage and key values of the soil water balance, approximately 2 000 manual drillings to a depth of 2 m and approx. 150 excavations were carried out.

Expanding the pedological mapping Gorleben-Süd, an area of approx. 40 km^2 between Siemen and Langendorf was included in the pedological mapping of the Dömitz-Lenzen area. These efforts involved approx. 200 sounding rod drillings of 2 m depth maximum and six excavations of characteristic soil types.

Pedological mapping Dömitz-Lenzen

The mapping involved approx. 300 sounding rod drillings of a maximum depth of 2 m and 14 excavations of characteristic soil types where samples were taken for sedimentological analyses, for example.

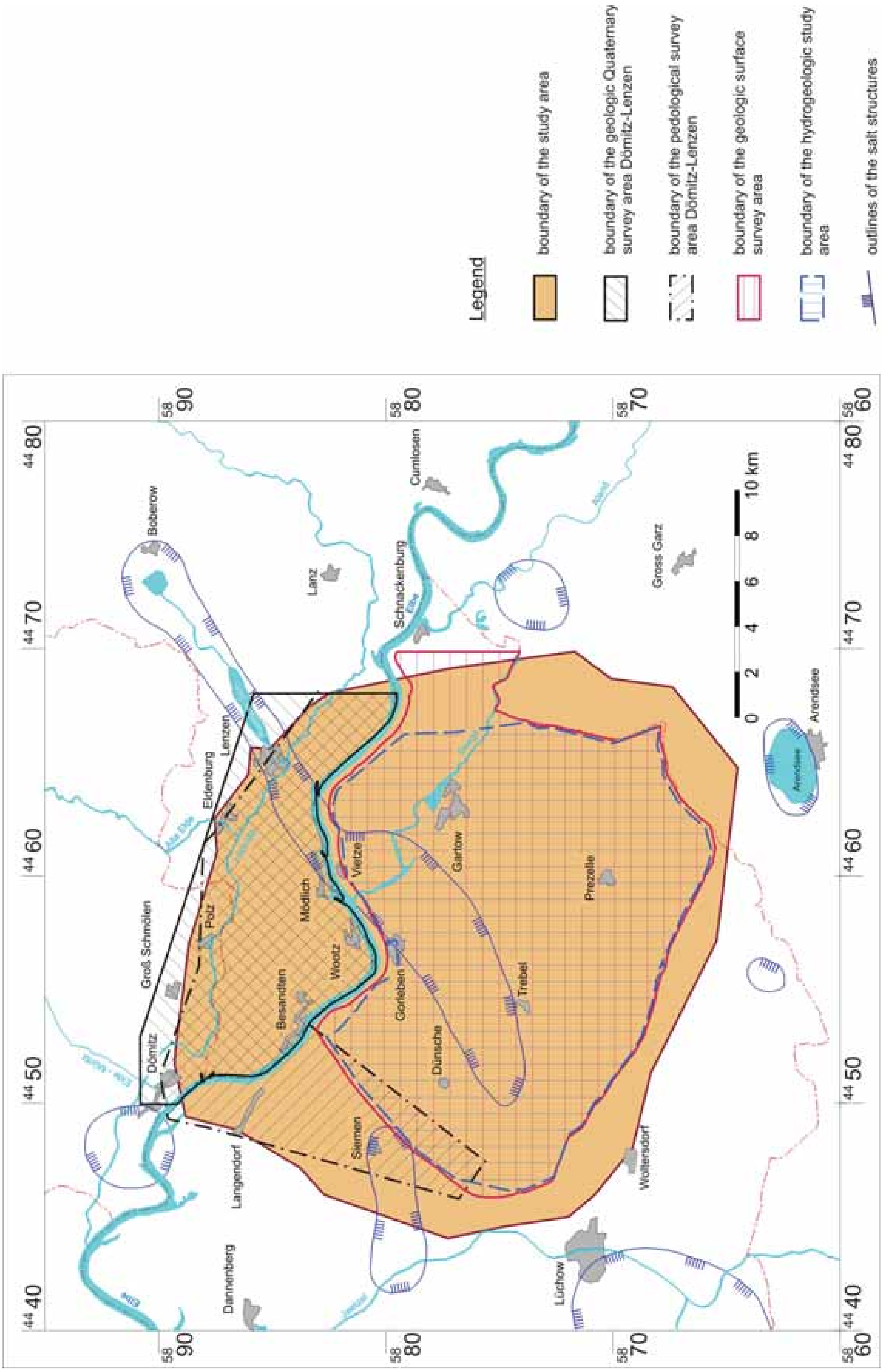


Figure 3: Boundaries of the geological Quaternary survey area and the pedological survey area

Table 1: Overview of the samples analysed in the Gorleben project

Method	Study Area	Sample Count	Timeframe of analysis
grain-size analyses	Gorleben-South	244	1980 – 1981
	Gorleben-South	162	1987
	Gorleben-South	45	1982 – 1988
	Dömitz-Lenzen	167	1996 – 1998
carbonate content analyses	Gorleben-South	45	1982 – 1988
	Dömitz-Lenzen	58	1996 – 1998
organic carbon content analyses	Gorleben-South	45	1982 – 1988
	Dömitz-Lenzen	44	1996 – 1998
heavy mineral analyses	Gorleben-South	44	1980 – 1981
	Gorleben-South	41	1982 – 1988
	Gorleben-South	72	1991
clay mineral analyses	Gorleben-South	135	1979 – 1981
	Gorleben-South	45	1982 – 1988
Till gravel and debris (gravel) analyses	Gorleben-South	approx. 1250	1979 – 1985
	Shaft Gorleben 1	46	1989, 1992
	Shaft Gorleben 2	41	1991
	Gorleben-South	18	1992
	Gorleben-South	64	1994
	Dömitz-Lenzen	58	1997
	Dömitz-Lenzen	97	1999
indicator pebbles and stone counts	Shafts Gorleben 1 + 2	51	1989, 1992
biostratigraphy	Gorleben-South	3790	1979 – 2001
	Dömitz-Lenzen	1092	1996 – 2001
paleomagnetic techniques	Gorleben-South	9	1982
	Gorleben-South	86	1988

2.2.5 Analyses of rock samples

A large number of rock samples from the project boreholes and the shafts Gorleben 1 and 2 were analysed using sedimentological (grain size analyses, carbonate content, organic carbon content, heavy-mineral analyses, and clay mineral analyses), lithostratigraphic (gravel analyses, indicator pebbles and stone counts), and biostratigraphic methods, and paleomagnetic dating techniques.

The sedimentological investigations were to clearly determine and prove by analysis the lithological/petrographical structure of the sediments and to clear issues of facies genesis. Special care was taken to gain a representative sampling of all stratigraphic strata The grain size analyses were used to record the grain size spectrum and to determine k_f values (hydraulic conductivity), an important parameter for hydrogeological modelling.

The biostratigraphic and paleomagnetic investigations were used to determine as precisely as possible the relative ages of the penetrated strata. The use of paleomagnetic techniques proved to be helpful for preglacial sediments. Thus, strata that had been classified as preglacial (approx. 2 million to 500 000 years before now) could be dated more precisely. By detecting zones of inverse polarity (older than 780 000 years) and the Jaramillo event (approx. 1 million years ago), reliable values for the extent of preglacial subrosion could be defined. The sampling points were determined using geological and hydrogeological criteria.

Table 1 lists the analysed samples. The importance of the biostratigraphic analyses for relative age classification of the stratigraphical sequences is obvious from the sheer number of samples, exceeding others by far.

The results of the sample analyses contributed significantly to the interpretation of the structure of the overburden and to the analysis of the structural geology.

3 Description of the study area

3.1 Location and boundaries

The Gorleben study area (Fig. 1) is situated in Northern Germany on the borders of the federal states of Lower Saxony, Mecklenburg-Western Pomerania, Brandenburg, and Saxony-Anhalt. The area has a maximum width of 25 km, a maximum north-south extension also of 25 km, and covers a surface area of 475 km^2. It is bounded by the rivers Löcknitz (north), Jeetzel (west), and the Lucie Channel (south). The eastern boundary was defined by local watersheds. The precise boundaries of the study area are defined by the linear connection of drilling sites.

The inner study area is the central area, i.e. the area above the Gorleben–Rambow salt structure marked by closely spaced drillings. The salt structure consists of the Gorleben salt dome southwest of the Elbe and extends to the Rambow salt dome. Figure 1 clarifies the terms “study area” and “inner study area”.

For the analysis of the structural geology, the area to be explored was expanded in order to encompass the secondary rim synclines of the Gorleben–Rambow salt structure. Thus the **“area of structural analysis” (“Gebiet der Strukturanalyse”)** covers a surface area of 1665 km² that stretches 45 km from east to west and 37 km from north to south. In addition to the salt structure, the term “Gorleben–Rambow structure” also designates the structures of the overburden.

The study area is mainly wooded (40 %), consisting mostly of pine trees that are largely found in the southeast of the area (“Gartower Tannen”). 32 % of the area is used for agriculture and 25 % is grass- and wetlands, mostly situated in the Elbe valley. The remaining parts are 2 % open water and 1 % built up areas (settlements, roads, industrial sites).

The Elbe divides the study area into a southern and a northern part and forms the boundary between the two partial study areas Gorleben-Süd and Dömitz-Lenzen.

3.2 Overview of the geologic morphology

The study area is situated in the Elbe glacial floodplain, which is particularly wide in this area. Three characteristic morphological terrain elements can be distinguished: Floodplains from the late glacial to Holocene times, Weichselian sandy valley plains and low hills (geest). The distribution and shape of the landscape types are shown in Figure 4.

The **floodplains of late glacial to Holocene times** form a wide strip parallel to the current bed of the Elbe and its tributaries Löcknitz and Seege. The surface of the Elbe terrace outside the dikes is formed by sandy Holocene sediments that are named Elbe embankment (“Elbuferwall”). On the insides of the dikes, the original flood sediments are floodplain loam, found in large contiguous areas, and fluvial sand of the Holocene, found in small areas. In some areas of the tributary floodplains, bogs and peat were formed. Often small, water-filled residual depressions reflect former watercourses (oxbow lakes). The floodplains show an extremely flat relief. The terrain elevations are between 17 m above sea level in the east and 13 m above sea level in the northwest. The lowest point at 12 m above sea level is at Dömitz at the confluence of the Old Löcknitz and the Elbe.

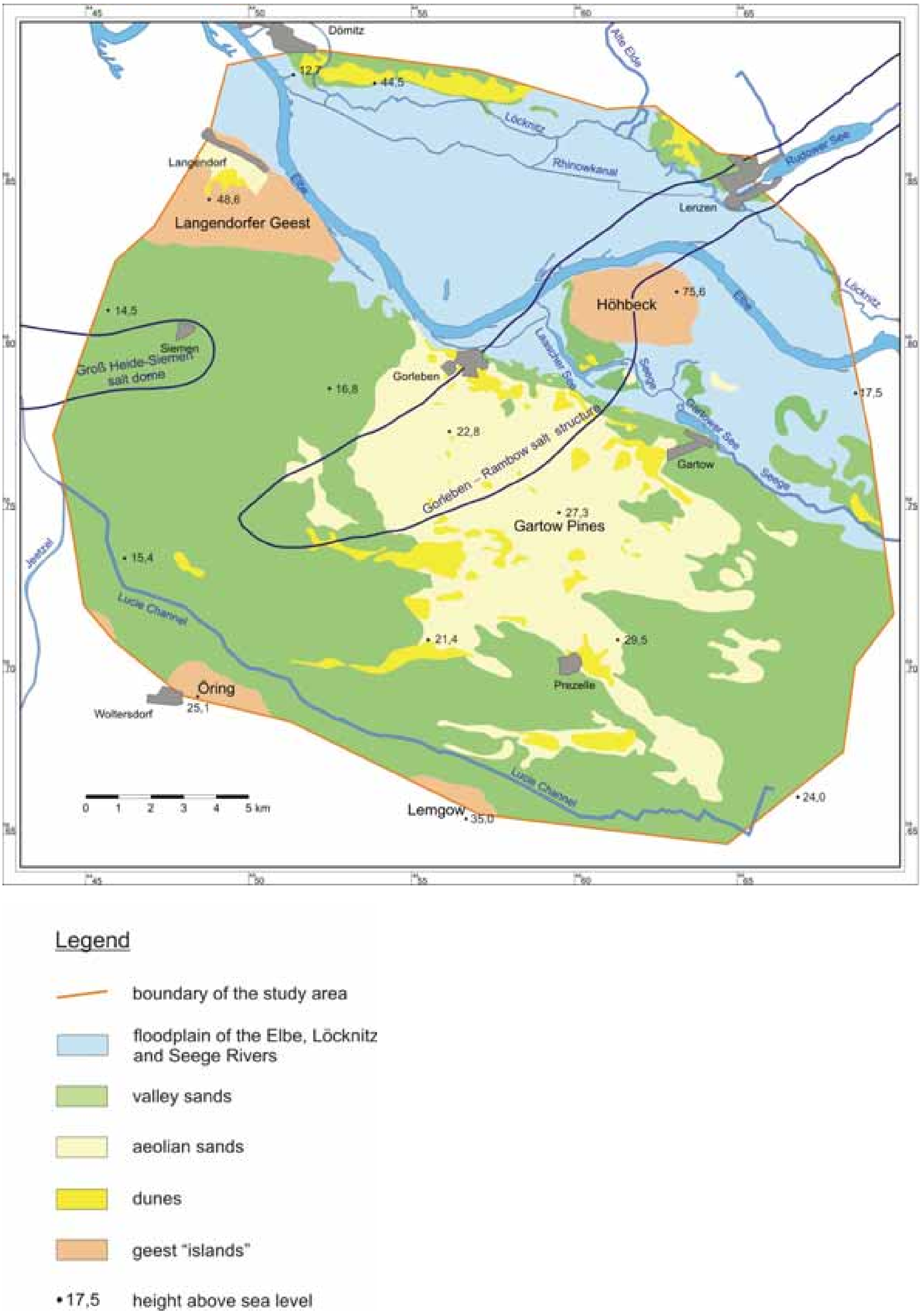


Figure 4: Morphological geological overview

The largest part of the study area consists of **Weichselian sandy valley plains**. They consist of Weichselian ice-marginal valley sediments that are called Lower Terrace sediments and form a wide plain. Towards the edges in the northeast (outside the study area) and south the plain rises slowly. The plain is interrupted by the Elbe terrace and the hills of the geest “islands”. In the late glacial stage, large areas of the valley plains were covered by layers of aeolian sands of a thickness of up to 2 m. During the Holocene, local dunes and dune fields of several metres thickness were deposited on these aeolian sand areas. There, the present-day relief is particularly disturbed and shows small scaled structure. The terrain elevations of the sandy valley plains are roughly between 17 m and 22 m above sea level and slightly higher in the areas covered by aeolian sands and dune fields, at roughly between 20 m and 30 m above sea level. On the northwestern edge of the study area, a dune belt that reaches a height of 44.5 m above sea level stretches from Klein Schmölen and Polz.

Some isolated **flat uplands** rise from the mostly flat sandy valley plains and valley river terraces. At the Elbe, these hills are the eastern parts of the Langendorfer Geest and the prominent “geest island” of the Höhbeck. In the south, the fringes of the Öring and Lemgow reach into the study area (Fig. 4). In the flat upland areas the oldest sediments can be found at the surface. These are complex sedimentary units of the Saalian Glaciation, mostly till and loam as well as outwash sand of the Drenthe substage, that are partially compressed and partially superposed by structures of the Warthe substage (Höhbeck). The terrain elevations of the flat uplands are mostly between 25 m and 50 m above sea level. The highest elevation (75.6 above sea level) is at the Höhbeck.

The mostly simple morphological structure of the more recent sediments hides a complex, halotectonically influenced structure below. An important feature is the **Gorleben–Rambow salt structure** and its adjoining rim synclines on both sides. The Gorleben–Rambow salt structure strikes from southwest to northeast. It has a length of approx. 30 km and runs from Liepe via Gorleben to Vietze, passes beneath the Elbe southwest of Lenzen and reaches as far as Rambow (Fig. 1). Southwest of the Elbe, in the area of Gorleben-Laascher Lake, it has a width of approx. 3.5 to 4 km. Directly south of the Elbe, it narrows to approx. 1.5 to 2 km and widens back to 3.5 km at Rambow. The salt structure consists of the Gorleben salt dome situated southwest of the Elbe and the Rambow salt dome. The narrow part is sometimes referred to as a transition area between the two salt domes. The average depth of the salt table is between 200 m and 300 m below sea level.

The **rim synclines** were formed by migration of Zechstein salt from the surrounding area into the salt structure. In the early formation stage (salt pillow), the primary rim synclines were formed due to an increase in bedding thickness above the outward migration zones of the salt. The strata overlying the salt structure thinned out during this time. The salt structure became a diapir at the turn of the Jurassic to the Cretaceous when it penetrated the overburden. The salt domes Gorleben and Rambow were formed. Large amounts of salt were leached at the surface and additional salt flowed from the rims of the structure into the salt domes so that the ground above the rims subsided. The secondary rim synclines were formed where primarily sediments of the Late Cretaceous and the Tertiary were deposited. The halokinetically induced thickness of these layers in the centre of the rim synclines can be several times the normal thickness. The Upper Cretaceous, which has a normal thickness of approx. 50 m in this area, has a maximum thickness of approx. 900 m at the northwestern rim syncline of Rambow. In the area of the salt dome flanks, the Mesozoic and Tertiary beds were twisted upwards, partially dragged and lifted above the salt structure. Later on they were even eroded or, in some areas, were never deposited at all. The geological structure of the overburden and adjoining rock above the salt structure is shown in a simplified geological cross section (Fig. 5).

In the rim synclines, the **Mesozoic sediments** are almost complete. Above the salt structure, they are absent, except for a few erosional remnants of Cretaceous sediments.

The same applies to the **Tertiary sediments**. The overburden contains mainly stratigraphic strata of the Paleogene, most of them having a reduced thickness. In the rim synclines, however, the Tertiary deposits are thicker and the sequence of strata is more complete, reaching into the Neogene (Lower Miocene).

The **Quaternary sequence of strata** is present in the whole study area. It starts after a large gap in the bedding sequence that reaches from the Middle Miocene far into the Early Quaternary. The sequence begins with preglacial sediments and reaches into the Holocene. The major part consists of Nordic sediments from five glacial transgressions (two of the Elsterian Glaciation and three of the Saalian Glaciation) and of the Weichselian Glaciation.

The relatively frequent occurrences of easily datable deposits of the Holsteinian Interglacial are of importance as a marker horizon. Over large areas, the thickness of the Quaternary is roughly between 50 m and 100 m, but reaches 250 m to 300 m in deep channels.

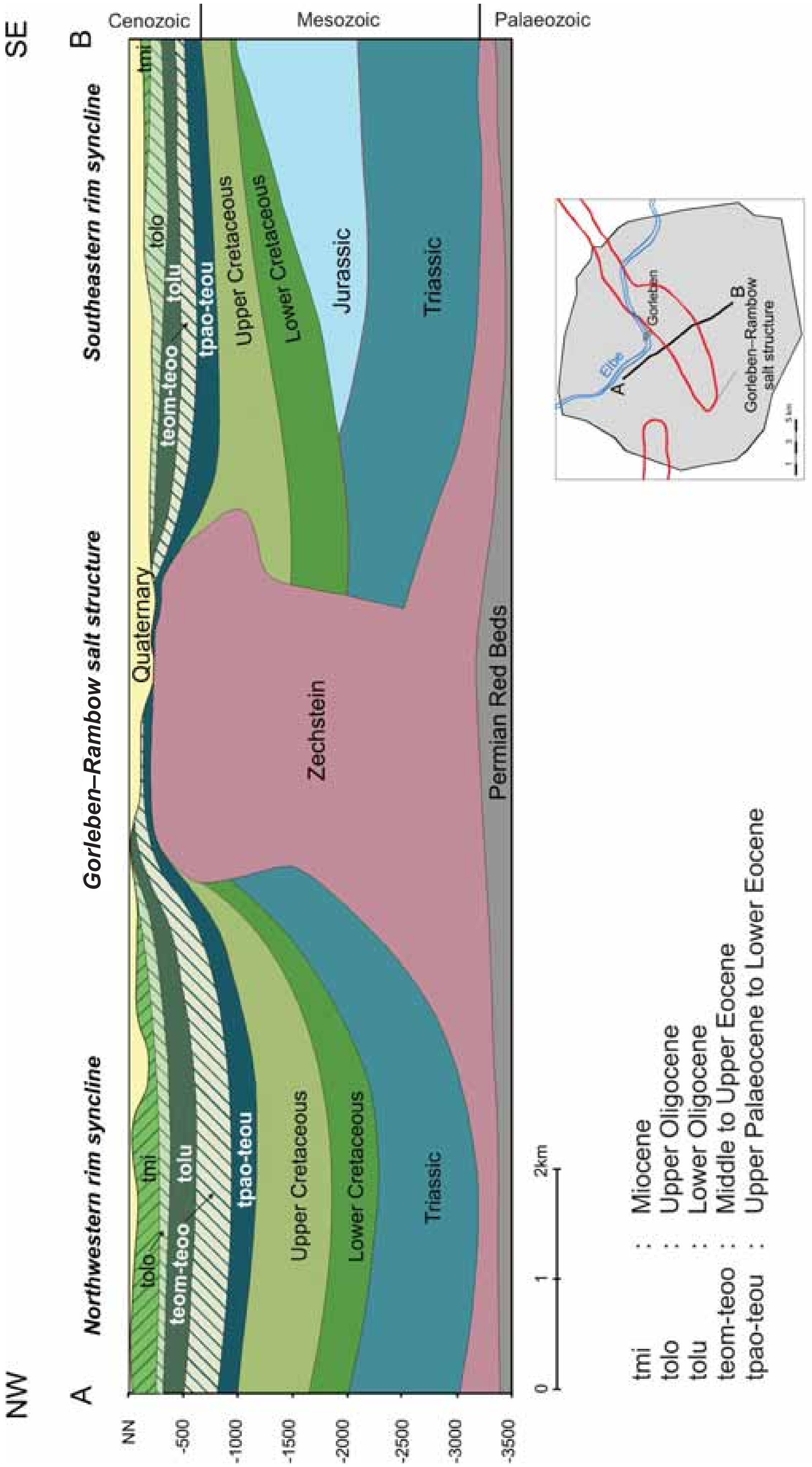


Figure 5: Simplified geologic cross section of the study area

4 Stratigraphy, lithology and lithogenesis

In the Gorleben study area, the project boreholes penetrated sediments of the Quarternary, Tertiary, to a lesser extent of the Cretaceous and the Bunter Sandstone as well as of the Permian period.

4.1 Zechstein to Cretaceous

The results of the surface and underground exploration of the Zechstein as well as an in-depth presentation of the inner structure of the salt formation can be found in Bornemann et al. (2007).

On the southeastern flank of the Gorleben salt dome, boreholes Go 1004 and Go 1005 penetrated the Upper **Bunter** and borehole Go 1004 the Middle Bunter, which have lower thicknesses here.

Above the Gorleben–Rambow salt structure, only one borehole (GoHy 553/555) encountered the **Lower Cretaceous**. Based on microfauna and foraminifers, the 12-m-thick sediments were dated as Albian. The sediment consists of calcareous marine silt to clay that sometimes contains gypsolyte. The colour varies from green to grey. The bottom is at 251.4 m below sea level.

Above the Gorleben–Rambow salt formation, sediments of the **Upper Cretaceous** were encountered only locally and of small thickness. These relicts are from different ages of the marine Upper Cretaceous and represent erosional remnants. In eleven boreholes, non-specific sediments of the Upper Cretaceous were found. The largest thickness of 25.0 m was encountered in borehole GoHy 1171. In seven other boreholes, a more precise classification was performed, mainly based on microfauna and foraminifers. One borehole (GoHy 560) penetrated a layer of the Cenomanian stage. It consists of brecciated limestone of white, partially grey colour that has a thickness of 1.3 m, the bottom of which is at 227.5 m below sea level. In three boreholes, strata of the Cenomanian to Coniacian stage or Cenomanian to Upper Campanian stage were encountered. The thickness is between 2.4 m and 10.3 m, the bottom is between 256.1 m and 203 m below sea level. They consist of limestone, marlstone, non-calcareous clay and highly calcareous fine sand, sometimes oöids and glauconite occur. The colour varies from grey to green to whitish. Borehole Go 1002 encountered Turonian to Santonian sediments consisting of fine-grained limestone of light-grey to light-grey-white colour. The thickness is 9 m, the bottom is at 215.9 m below sea level. Another borehole (GoHy 3110) penetrated 14.2 m of limestone with marlstone and claystone of white-grey colour that was dated as Coniacian to Santonian. The bottom of these sediments is at 237.9 m below sea level. In borehole

Go 5001, white-grey marlstone of 0.7 m thickness was encountered, which is partially brecciated and becomes fine sandy and very silty towards the top. This marlstone, whose bottom was 213.5 m below sea level, was dated as Santonian.

In the southeastern rim syncline of the Gorleben salt dome, white-grey chalk with layers of marlaceous limestone was encountered by cored borehole GoHy 994. According to calcareous nannoplankton analysis, it belongs to the Upper Campanian. At a final depth of 732.8 m below sea level, a thickness of 5 m was measured.

4.2 Tertiary

The Tertiary sediments are mostly clastic (sand, silt, clay) and were deposited on a marine shelf. The average thickness (undisturbed by halokinetic movement) is approx. 600 m.

During the Tertiary, sedimentation was strongly influenced – in addition to the halokinetic movement – by the changing extent of the North Sea in that period. Paleogeographically, the area around Gorleben belonged to the southern shelf of the North Sea basin for the whole time from the Paleocene to the transition from the Oligocene to the Miocene. This is evidenced by the mainly marine sequence of sediments. In the Early Miocene, the area around Gorleben was still part of an alluvial plain that reached far to the east. Sediments from the latest Tertiary (Middle / Late Miocene, Pliocene) were not found in the Gorleben area.

The Tertiary sequence of strata was clearly influenced by the halokinetic development of the Gorleben–Rambow salt structure. Whilst the Tertiary sediments display a highly increased thickness in the secondary rim synclines on both sides, the sediments above the salt structure show a reduced thickness. No major bathymetric or facies differences between the salt dome roof and the rim synclines were found. Sequence gaps are present at the regional and supraregional scales.

The **subdivision of the stratigraphic sequence** is mainly based on biostratigraphy, lithostratigraphy and log correlation (gamma ray and density). The stratigraphy corresponds to the international subdivision of the Tertiary. Only biostratigraphic methods enabled the detailed dating of the Tertiary beds, 50 % of which are non-calcareous and which are dominated, particularly in the Lower Tertiary, by monotonous clay/silt sequences. The biostratigraphic classifications were carried out based on different groups of microfossils (foraminifers, dinocysts, calcareous nannoplankton) depending on the facies, petrography and calcium carbonate content. The provinciality of the faunae and florae made the biostratigraphic classification difficult. The bio- and lithostratigraphic subdivision of the Tertiary in the Gorleben area is shown in Figure 6.

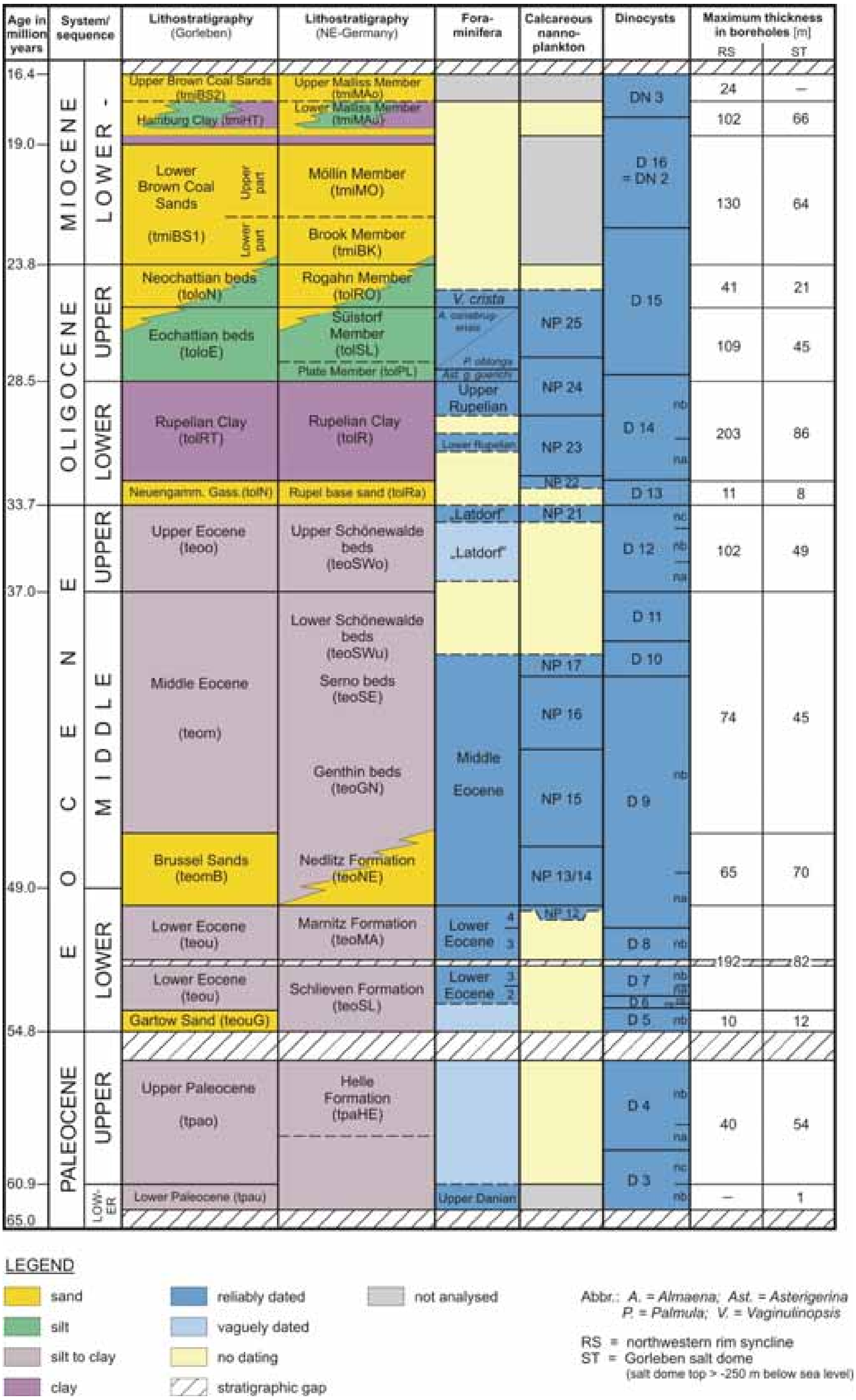


Figure 6: Lithostratigraphic and biostratigraphic subdivision of the Tertiary (according to Klinge et al. 2002; Northeast Germany enhanced in accordance with Deutsche Stratigraphische Kommission 2002)

The naming of the strata of the whole study area corresponds to the customary subdivision of the North Sea Basin and Northern Germany (Preuss et al. 1991). A correlation to the subdivision used in Mecklenburg and Brandenburg (Northeast Germany) is given in the descriptions of the individual beds.

4.2.1 Paleocene

Lower Paleocene

In the whole study area, only one borehole above the Gorleben salt dome (GoHy 133) encountered the Lower Paleocene. Based on microfauna and foraminifers (lower Upper Danian) as well as dinocysts (subzone D3 nb) it was biostratigraphically dated as latest Lower Paleocene. Based on the dinocyst dating, this deposit can be correlated with the upper part of the “Dano-Mont Formation” of the borehole Söhlingen H1 (Köthe 1990: Fig. 4). As no other deposit of Lower Paleocene was found in the numerous Paleocene profiles that were analysed, this must be the erosional remnants of a local occurrence that is outside of the known extent of Lower Paleocene north of the study area.

The Lower Paleocene is present as a cored section of borehole GoHy 133. The sediment consists of highly calcareous clay with single shell fragments and irregularly scattered glauconite clusters. The colour varies from grey to dark grey. The bed is 1 m thick, underlain by cap rock and overlain by Upper Paleocene.

Upper Paleocene

Based on dinocysts, the sequence of Upper Paleocene strata was divided into the subzones D3 nc, D4 na, and D4 nb. The microfauna/foraminifers and the calcareous nannoplankton were of no help in dating. In some boreholes, the sequence starts with weakly silty to silty, partially weakly clayey, often glauconitic to highly glauconitic, non-calcareous to weakly calcareous fine sands, with a thickness of 1.3 m to approx. 4 m and a maximum of 9.3 m (borehole GoHy 1251). The colour varies from grey to dark grey and greenish grey to green. However, the beds of the Upper Paleocene consist mostly of silty to highly silty clays, that often turn to clayey, more fine sandy silts in the lower part. The sediments are glauconitic to weakly glauconitic and of grey to green-grey colour. Less often, concretions of pyrite occur. Non-calcareous and weakly calcareous sections alternate.

In the gamma ray log, the Upper Paleocene often starts with a low amplitude that reflects the sandy bottom zone. Above it, the log displays a relatively homogeneous section with values above 100 API, which represents the silty clayey sediments.

Grain-size analyses are only available from the cored borehole GoHy 994. The analysed samples show a homogeneous clay silt package with very low to low fine sand contents.

The strata of the Upper Paleocene were originally present in the whole study area. The present gaps above the Gorleben–Rambow salt structure are mostly due to Quaternary erosion in the Gorleben channel. Minor gaps northeast of the Elbe and in the southwestern part are due to erosion during the Early Eocene or, more rarely, the Late Paleogene.

The base of the Upper Paleocene is largely identical to the base of the Tertiary. Above the Gorleben salt dome, it lies between 167.5 m and 324.2 m below sea level. In the rim synclines on both sides, the base has sunk deeply and lies deeper than 1 100 m (northwestern rim syncline) and deeper than 800 m (southeastern rim syncline) below sea level. The thickness of the sediments of the Upper Paleocene is mostly between 5 m and 20 m, in some boreholes even up to 55 m and, in borehole GoHy 1251, 85.8 m maximum (= apparent thickness). Due to the position of this borehole in the area of the sloping edge of the Gorleben salt dome with dip values of approx. 25°, the true thickness in this borehole is approx. 78 m. Except for locally increased thicknesses – due to the morphology of the cap rock surface and the apparent increase of thickness in the area of the sloping edge of the salt structure – there are, in contrast to the beds of the younger Tertiary, no major differences in thickness between the Gorleben salt dome and the rim synclines on both sides.

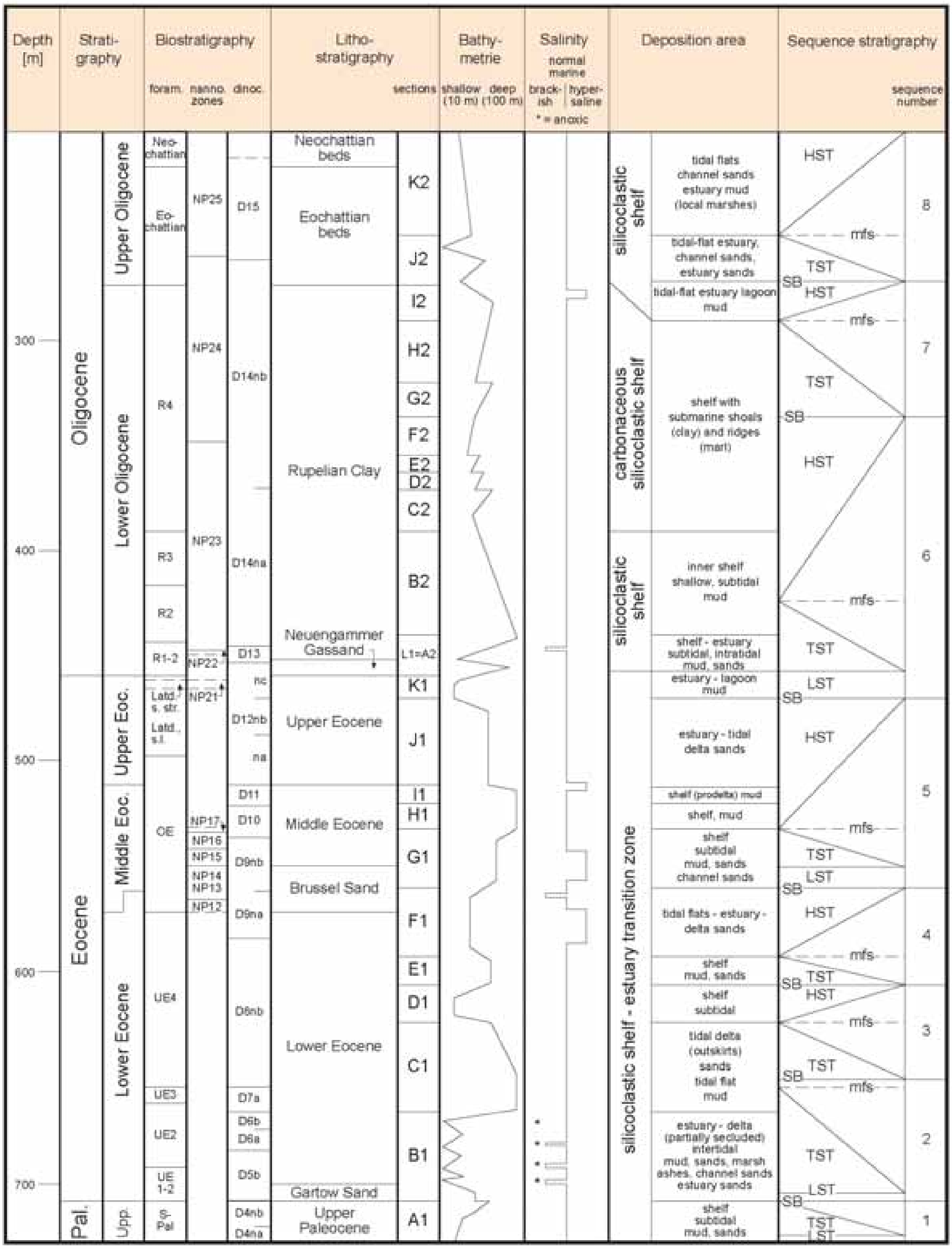
4.2.2 Eocene

Gartow Sand

The Gartow Sand proves the transgression of the Lower Eocene over the underlying beds. With respect to the microfauna/foraminifers, it is characterised by sand-shelled assemblages of the Lower Eocene UE1 (Fig. 7). Biostratigraphically it belongs to the dinocyst subzone D5 nb. Due to the missing subzone D5 na, as well as the abrupt change in the dinocyst flora, a hiatus between the Upper Paleocene and the Gartow Sand must be assumed (Fig. 6). This hiatus can be found throughout Northern Germany.

The sediments of the Gartow Sand were encountered in 31 boreholes. Its average thickness is only 5.9 m, the maximum is 12.4 m (borehole GoHy 810).

Figure 7: Stratigraphy, paleoenvironment, and sequence stratigraphy of the Paleogene sequence in borehole GoHy 994 (according to DILL et al. 1996, 1997; DILL 1998)



Petrographically, the Gartow Sand consists of an alternating sequence of decimetre- to metre-thick, highly fine sandy silts to fine sandy silts and clays. Less often (e.g. in boreholes GoHy 600 and GoHy 994), highly silty fine sands form the beds. The beds consistently contain glauconite, are mostly non-calcareous, less often weakly calcareous, and are of grey-green to green-grey colour.

The Gartow Sand causes a distinctive negative pulse in the gamma ray log. It was identified by this feature in a considerable number of boreholes.

Grain-size analyses were performed on samples of the cored borehole GoHy 994. The analyses prove the alternation between clayey-silty fine sands and highly fine sandy, highly clayey silts.

The Gartow Sand was penetrated above the Gorleben salt dome as well as in the rim synclines on both sides.

Beds of the Lower Eocene

The beds of the Lower Eocene are the stratigraphic member of the Tertiary sediments with the widest distribution. Above the Gorleben salt dome, they are only missing in parts of the Gorleben channel due to Quaternary erosion, and above the Gorleben–Rambow salt structure in a small area southwest of Lenzen.

Based on microfauna/foraminifers, beds of the Lower Eocene were dated as UE1 to UE4 (Lower Eocene). These classifications proved to be difficult when, for instance, microfaunae were scarce and without index fossils. Due to the prevalent facies in the study area, the classification based on dinocysts is more precise. In the beds of the Lower Eocene, the subzones D5 nb, D6 na, D6 nb, D7 na, D7 nb, D8 nb, and D9 na (Lower Eocene) were found. As in the cored borehole GoHy 994 (Köthe 1990) and the closely sampled exploration borehole GoHy 1730, the subzone D8 na (middle Lower Eocene) could not be found in the rest of the Gorleben study area. From a lithological point of view, no hiatus is discernible at the corresponding position (Dill et al. 1996). In Northern Germany, the subzone D8 na could only be found in the borehole Wursterheide near Cuxhaven (Köthe 2005).

The beds of the Lower Eocene mainly consist of highly clayey, very weakly to weakly fine sandy silts, less often highly silty clays. Occasionally, streaks and thin layers of stronger fine sandy sections or silty-clayey fine sands occur. The layers of fine sand seldom attain a thickness of several metres. Except for scattered accretions, the sands consistently contain little glauconite. The content of mica is small as well. Pyrite occurs in clusters and concretions. The beds are non-calcareous, seldom very weakly calcareous. At some positions, bioturbated sedimentary structures could be found. The colours vary from olive-grey to dark grey and grey-green to brownish.

In the basal part, single, decimetre-thick consolidations to siltstone or mudstone are interstratified.

In cored borehole GoHy 994, 13 layers of volcanic tuff with thicknesses varying from several millimetres to several centimetres were penetrated close to the bottom of the bed. These layers are of the same age as the more than 70 ash layers that were found in the research borehole Wursterheide south of Cuxhaven (Knox 1989). In both boreholes the age was dated as dinocyst zone D5 nb. The extent of the tuffite layers of the lowest part of the Lower Eocene from the North Sea and Denmark (Knox 1989) to the Hanover area (Frisch & Kockel 2004) and western Mecklenburg (Wienholz 1958) has been reported.

The gamma ray log of the layers of the Lower Eocene is on a high level between approx. 100 and 150 API, marked with minor pulses where higher fine sand or clay contents are present. The lower and upper boundaries are characterised by a strong negative pulse towards the Gartow Sand and Brussel Sands (Brüssel Sand) respectively.

Numerous grain-size analyses are available for cored borehole GoHy 994.

The sequence of strata of the Lower Eocene was encountered in 108 boreholes; in 14 cases it was not fully penetrated. With the commencement of the beds of the Lower Eocene, distinctive differences in thickness between the Gorleben–Rambow salt structure and the neighbouring rim synclines can be observed, as first indicated in the base of the Paleocene. Above the structure, the stratigraphic sequence of the Lower Eocene is 34 m thick on average, with considerable differences between the salt dome roof (borehole GoHy 900 = 5.5 m) and the salt dome edge (borehole Go 1003 = 107 m). Larger thicknesses between 60 m and 80 m occur mainly on the edges. Major thickness reductions were found in the crest area of the salt structure, where thicknesses of only 5 m to 7 m were recorded. In these areas, the sequence shows no gaps, but is only highly condensed. The base surface is at a level between 106 m and 340 m below sea level.

In the rim synclines, the thickness of the Lower Eocene sediments grows enormously. In the northwestern rim syncline, a thickness of more than 300 m (>200 m in the southeastern rim syncline) is assumed, based on seismic data. The largest thicknesses penetrated are in the boreholes E RmwL 14/69 (northwestern rim syncline) and E RmwL 4/59 (southeastern rim syncline) situated inside the salt structure with 196 m and 171 m respectively. The base surface of the Lower Eocene drops to more than 1 150 m below sea level in the northwestern rim syncline, and to more than 800 m below sea level in the southeastern rim syncline .

Brussel Sands

In the lower Middle Eocene, the clayey/silty and mostly non-calcareous beds of the Lower Eocene are followed by sandy calcareous sediments, which start a new transgressive sediment cycle. These beds are called “Brussel Sands” (Brüssel Sand) or “calcareous sandstone horizon of the Upper Eocene” (obereozäner Kalksandstein-Horizont). They form a distinctive marker bed on the southern edge of the northwest European Tertiary basin (BEST et al. 1989). According to GRAMANN & KOCKEL (1988), this near-shore marine sand accretion can be traced from Belgium to Mecklenburg-Western Pomerania/northwestern Brandenburg.

The Brussel Sands are biostratigraphically dated as dinocyst subzones D9 na and D9 nb, and calcareous-nannoplankton zones NP 12 to NP 14 (Fig. 6). However, zone NP 12 (middle Lower Eocene) was only found in borehole GoHy 994, presumably due to a reworking of the index marker. Based on microfauna and foraminifers, only a few samples presented an old “OE” (corresponds to the Middle Eocene). Most samples did not contain any microfauna or foraminifers.

In the stratigraphic records, the Brussel Sands are petrographically described as weakly medium-sandy fine sand with alternating (low to high) clay and silt contents. Occasionally, coarse sand and fine gravel occur. The glauconite content is distinctive to high, which explains the grey-green hue. The calcium carbonate content decreases from top (high) to bottom (low). At the base, the sand is often non-calcareous. A characteristic feature is the isolated occurrence of conglomeratic concretions to calcareous sandstone, which are between and one and four decimetres thick and sometimes contain fossils.

The Brussel Sands are characterised in the gamma ray log by low intensities and stand out clearly as a minimum from the clays and silts above and below. The banks of calcareous sandstone show as marked positive peaks within the low intensities.

The composition of grain sizes of the Brussel Sands has been determined by a large number of analyses. All grain-size analyses show fine sand as the dominating main component.

The base of the Brussel Sands is a distinctive reflector in shallow seismics and is present throughout almost the whole study area. Figure 8 shows the distribution gaps, which are mainly caused by Quaternary, less often by intra-Tertiary erosion. The main distribution gaps are above the Gorleben–Rambow salt structure and follow the course of the Gorleben channel. Another gap is above the salt dome Groß Heide–Siemen.

The Brussel Sands were encountered in 50 boreholes. The largest thicknesses are in the northwestern rim syncline, with more than 60 m; in the southeastern rim syncline, only approx. 30 m are reached (Fig. 8). Above the Gorleben–Rambow salt structure, the thickness is generally lower, with an average of 16 m, but it varies considerably. The maximum is 70.5 m (borehole GoHy 790). The base surface reflects the general structure. The base depths are in the northwestern rim syncline, at almost 900 m below sea level, and in the southeastern rim syncline, at approx. 650 m below sea level. Above the Gorleben–Rambow salt structure, the base depths are between 76.3 m (borehole GoHy 810) and 385.8 m below sea level (borehole GoHy 1070).

Middle Eocene strata

The Brussel Sands are followed by a monotonous sequence of silts and clays, which Daniels & Gramann (1988) termed Upper Eocene Clay Sequence and Lotsch (1981) called Serno and Schönewald beds or Clay Marl Group. This complex of strata up to an including the Upper Eocene is hard to subdivide lithologically and is thus treated as a unit in drilling profiles and structural geological investigations.

Middle Eocene strata are biostratigraphically defined as ranging from the upper part of dinocyst subzone D9 nb to zones D10 and D11. Zones NP 15, NP 16, and NP 17 were found in calcareous nannoplankton analyses (Fig. 6). Based on microfauna/foraminifers, this section is often heterogeneously and indistinctly dated as “Non-calcareous agglutinating foraminiferid assemblages of Paleogene age”.

The complex of strata consists of green-grey, clayey to highly clayey silts, in some parts also highly silty clays. The content of fine sand is slight to low with a tendency to increase towards the bottom. Mica and glauconite occur rarely to very rarely; in some parts, the beds show bioturbations that are recognisable by pyritised burrows. The upper parts of the sequence are mostly non-calcareous. Towards the bottom, correlated with the increasing content in fine sand and glauconite, the sediments become weakly calcareous, in some parts calcareous.

The gamma ray curve shows an almost undivided section of high intensities. In the upper part of the sequence, which is stratigraphically in the interval of dinocyst zone D11, a distinctive positive anomaly often shows, due to a higher clay content.

Grain-size analyses are available from twelve samples of the cored borehole GoHy 994.

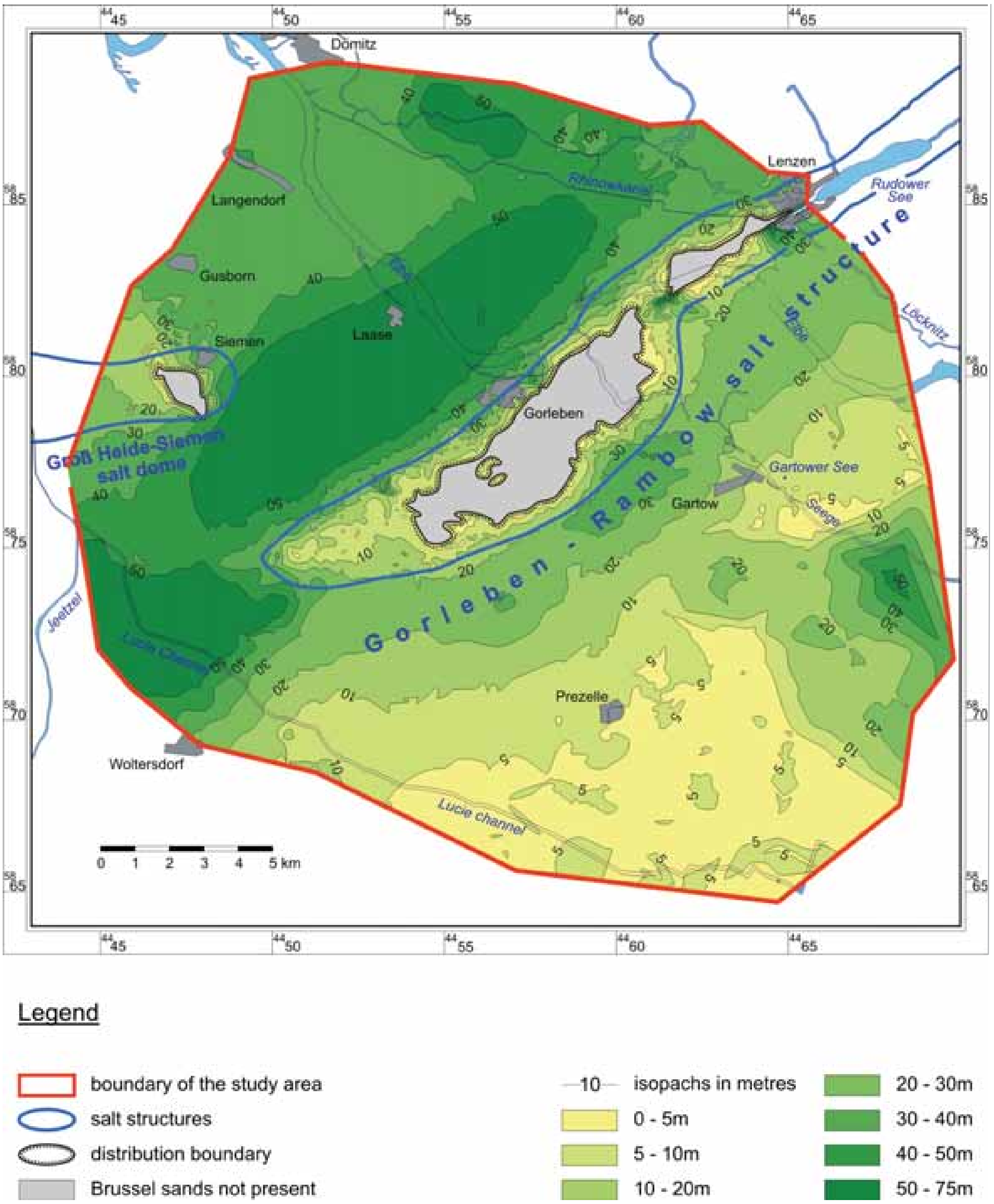


Figure 8: Extent and thickness of the Brussel Sands

The Middle Eocene strata were encountered in 55 boreholes. In older stratigraphic-records, especially those of oil wells, the Middle and Upper Eocenes are not differentiated. The average thickness of the Middle Eocene strata is 21 m above the Gorleben–Rambow salt structure, the maximum thickness is 45 m (borehole GoHy 140). The base surface is at a level between 73 m and 326 m below sea level. The thickness increases to approx. 80 m in the northwestern rim syncline and to 50 m in the southeastern rim syncline. The maximum base depths drop to approx. 800 m (northwestern rim syncline) and approx. 580 m below sea level (southeastern rim syncline).

Upper Eocene strata

The silty clayey marine facies continues in the Upper Eocene. Based on dinocysts, the Upper Eocene strata can be biostratigraphically subdivided into subzones D12 na, D12 nb and D12 nc (Fig. 6). In the upper part of the sequence, a calcareous section was encountered, where microfauna, foraminifers and calcareous nannoplankton were found. The microfauna/foraminifers correspond to the “Latdorf stage” of the Tertiary stratigraphy of Germany. Based on the calcareous nannoplankton flora, it was dated as zone NP 21.

The Upper Eocene strata consist of a monotonous series of weakly clayey to occasionally highly clayey, very weakly to weakly fine sandy grey-green to olive-green silts. In some places, approximately in the middle section, stronger fine sandy zones and seldom layers and streaks of silty-clayey fine sands occur. The content in glauconite and mica varies between low and very low, rarely showing slightly higher contents. In the upper areas, microfossils and pyritised burrows are present.

The gamma ray log is mainly undifferentiated and in the API range of clayey-silty sediments. A slight API decrease occurs in the more fine sandy sections of the profile in the middle part of the Upper Eocene strata.

Grain-size analyses of the Upper Eocene sediments are available from the cored borehole GoHy 994.

The Upper Eocene strata were found in 63 boreholes, sometimes undifferentiated as Middle to Upper Eocene (see above). The average thickness of the Middle Eocene strata is 27 m above the Gorleben–Rambow salt structure, the maximum thickness is 49 m (borehole GoHy 140). The base surface is between 75 m and 344 m below sea level.

The complex of Middle to Upper Eocene was primarily present throughout the whole study area. Gaps occur only in the area of the Gorleben–Rambow salt structure. One cause is Quaternary erosion in the course of the Gorleben channel, the other is erosion of the Upper

Eocene strata due to the transgression of the Early Oligocene. Sediments of the Middle and Upper Eocene were encountered in a total of 65 boreholes. The largest thicknesses are in the northwestern rim syncline, with more than 275 m, and approx. 200 m in the southeastern rim syncline. Above the Gorleben–Rambow salt structure, the thicknesses average only 49 m, the maximum is 138 m. The considerable changes in thickness are partially due to truncation of the beds due to Quaternary erosion, but also to condensation of the sediments as well as subrosion processes and relief formation in the cap rock. For the level of the base surface, see the description of the Brussel Sands.

4.2.3 Oligocene

The Oligocene is subdivided into Lower Oligocene (Rupelian stage) and Upper Oligocene (Chattian stage).

Lower Oligocene

Most boreholes that penetrated the Lower Oligocene showed a fine sand-silt horizon of a few metres thickness at the base, the **Neuengammer Gassand** or **Rupel-Basissand**. This horizon marks the start of a new transgressive phase after the marine regression at the end of the Upper Eocene. The biostratigraphic dating of the sand is based on dinocysts, which show no evidence of a hiatus, as the base of the Neuengammer Gassand was determined as zone D12 (Upper Eocene) and the middle and upper parts as zone D13 (lowermost Lower Oligocene). Due to the absence of calcareous contents, the microfauna contained no index fossils; the analysed samples also contained no calcareous nannoplankton.

The Neuengammer Gassand consists of an alternating sequence of weakly clayey to in parts clayey fine sands and silts. The proportion of medium and coarse sand is very small. The dominance of the petrographic main component (silt or fine sand) varies from borehole to borehole. The glauconite content varies from low to high, in some areas, glauconite-enriched streaks occur. The colour varies depending on glauconite content, from grey-green to olive-green to green-grey. In contrast to the Brussel Sands of the Middle Eocene, which are calcareous to highly calcareous in the upper parts, the Neuengammer Gassand is consistently non-calcareous.

In the borehole log, the sand horizon is characterised by a distinctive minimum in the gamma ray curve and a drop in the resistivity curve.

The grain-size analyses (Table 2) clearly illustrate the alternation of silt and fine sand as the main component of the sedimentary sequence.

The beds of the Neuengammer Gassand were encountered in 46 boreholes, 33 of which are situated above the Gorleben–Rambow salt structure. The average thickness above the salt structure is approx. 5.7 m (8.3 m maximum in borehole GoHy 30) and the base depths vary between 55.3 m and 330.7 m below sea level. In the rim synclines on both sides, only few boreholes reached this horizon. In the northwestern rim syncline (four boreholes), the thickness increases (average 14.9 m, maximum 25 m) and the base surface drops to lower than 580 m below sea level. In the southeastern rim syncline (three boreholes), the thickness is between 6.5 m and 9.6 m, the base depths are lower than 440 m below sea level. In the centres of the rim synclines, the Neuengammer Gassand was not encountered in boreholes. At these positions, its base lies even deeper.

Above the Gorleben–Rambow salt structure as well as in the adjoining rim synclines, the Neuengammer Gassand is widely present at the base of the Lower Oligocene.

Table 2: Grain-size composition (wt%) of the Neuengammer Gassand

GoHy-borehole	Depth [m]	Clay	Silt	Fine sand	Medium sand	Coarse sand
994	450.0 – 450.3	23.2	39.8	30.3	0.7	1.0
994	452.8 – 453.1	23.6	18.2	57.0	0.8	0.4
994	454.8 – 455.1	17.2	16.5	65.7	0.3	0.3
994	455.1 – 455.3	13.3	42.7	43.1	0.6	0.3
994	457.7 – 458.0	16.6	21.2	57.7	3.5	1.0
994	458.7 – 459.0	16.8	77.2	6.0	0	0
1282	197.0 – 197.1	8.0	58.6	32.3	0.4	0.7

Towards the top, the sandy facies of the Neuengammer Gassand is quickly replaced by the monotonous lithographic facies of the offshore basin area. In this basin, the **Rupelton** (Rupelian Clay**)**, which documents the highest sea level of the whole Tertiary in this region, was deposited as a relatively monotonous sequence.

The biostratigraphic age classification of the Rupelton was mainly achieved on the basis of microfauna/foraminifers. For classification purposes, the zones Rupelian 1 to Rupelian 3 (lower Rupelian) and Rupelian 4 (upper Rupelian) according to Spiegler (1965), or lower Rupelian and upper Rupelian were used (Köthe et al. 2002). In the zones Rupelian 1 and Rupelian 3, microfauna are very scarce. Mostly agglutinated foraminifers and fish fossils dominate these zones. Zones Rupelian 2 and Rupelian 4, however, are rich in microfauna species and specimens. In the Rupelton, dinocyst subzones D14 na and D14 nb as well as calcareous nannoplankton zones NP 22 to NP 24 were found.

The sedimentation starts with clayey to highly clayey silts, less often highly silty clays with slight to low fine sand content. At the base, the beds are non-calcareous; towards the top a weak calcareous content appears that alternates with non-calcareous intervals. This section approximately represents zone Rupelian 1. The clay content slightly increases in zone Rupelian 2. The alternation between non-calcareous and very weakly to weakly calcareous intervals continues. The clay content is highest in zone Rupelian 3, where mostly unctuous, scarcely silty, non-calcareous clays were deposited.

In the more or less complete profiles, the Rupelian 1 to Rupelian 3 sections make up approximately one third of the profile of the Rupelton. The remaining two thirds (e.g. in borehole GoHy 994), in some places only half, of the Rupelton consist of zone Rupelian 4 or upper Rupelian. This zone displays a rather monotonous sedimentary sequence, starting with unctuous silty clays to clayey silts that turn to clayey, weakly fine sandy silts towards the top. This part of the section is mainly calcareous to highly calcareous, though seldom also weakly calcareous. Profiles containing several Rupelian zones were found e.g. in boreholes GoHy 30, GoHy 880, and GoHy 994.

The whole sequence is characterised by a grey-green to green-grey, and less often bluish-grey colour, as well as by the occurrence of pyrite in streaks, clusters, and concretions, a pyritised burrows and fossils (foraminifers). Occasionally, small fish fossils are preserved. Seldom, mostly towards the top, sideritic-calcitic concretions (septarian nodules) of up to decimetre size occur.

After the strong decrease in intensity in the Neuengammer Gassand, the gamma ray curve of the Rupelton lies in the high API range. Within this high range, zone Rupelian 3 causes an even higher peak.

Grain-size analyses were performed on samples of boreholes GoHy 32, GoHy 792 and GoHy 994. The area of the highest clay content (80 %), which is zone Rupelian 3, was covered by two analyses of borehole GoHy 30.

Rupelton was encountered in 119 boreholes, 59 of which penetrated the beds completely. It used to be present throughout the whole study area. Gaps currently exist above the salt structures. Above the Gorleben–Rambow salt structure, they are mainly due to erosion in the Gorleben channel. The average thickness of the Rupelton above the Gorleben–Rambow salt structure is 38.3 m. There is great variation in thickness, e.g. 2 m in shaft pilot borehole GoHy 5002 and 85.5 m in borehole GoHy 1750 in the area of the crestal trench zone southwest of Lenzen. The Rupelton is particularly thick in the rim synclines on both sides. According to the results of shallow seismics, more than 240 m must be assumed (maximum penetration was 203 m in the northwestern rim syncline). The base surface of the Rupelton is parallel to the base surface of the Lower Oligocene. In places where Neuengammer Gassand was encountered in the drilling profiles, it is a few metres above the base of the Lower Oligocene.

Gaps in the areal extent of the **Lower Oligocene sequence of strata** occur above the salt structures and are identical to those of the Rupelton. The base of the Lower Oligocene sequence is again deepest in the rim synclines on both sides. The shallow seismic analysis showed the base depth in the northwestern syncline to be lower than 640 m below sea level and 520 m below sea level in the southeastern rim syncline. Above the Gorleben–Rambow salt structure, however, the base depths are between 55.3 m and 253.7 m below sea level.

Upper Oligocene

The Upper Oligocene is subdivided into the older Eochattian and the younger Neochattian. In the area of northwestern Brandenburg/ southwestern Mecklenburg, the lithostratigraphic subdivision comprises – from bottom to top – the Plate, Sülstorf and Rogahn members (cf. Fig. 6).

After the deep marine clays of the Lower Oligocene, increasingly shallow marine conditions prevail in the Upper Oligocene, where clayey silts were deposited at the base, above them fine sandy silts, and towards the top silty fine sands .

The **Eochattian beds** are evidenced by two, sometimes three zones of foraminifers. The zone of *Asterigerina guerichi guerichi* (Asterigerina horizon), an abundant occurrence of the species, lies at the bottom. The upper part of the Eochattian comprises the zones of *Palmula oblonga* and *Almaena osnabrugensis,* which can occur interchangeably in the facies (Fig. 6.) Both zones are rich in associations of calcareous-shelled foraminifers. Based on dinocyst analyses, the lowest part of the Eochattian beds was dated as subzone D14 nb. The upper part of the Eochattian beds as well as the the upper part of the Neochattian beds and the lower part of the Untere Braunkohlensande (Lower Brown Coal Sands) were dated as zone D15. It was impossible to define the base and top of the Eochattian beds more precisely by dinocyst analysis. Using calcareous nannoplankton, the lower part of the Eochattian beds were determined as zone NP 24, and the upper part as well as the Neochattian beds were determined as zone NP 25.

The Eochattian beds start with highly, partially very highly silty fine sands that are glauconitic to highly glauconitic. These bottom beds are approx. 5 m to approx. 15 m thick, non-calcareous, and of olive-grey to grey-green colour. These beds are lithologically characterised as highly fine sandy silt, in some boreholes over the whole penetrated depth, in others only in the upper part. In the boreholes of the Dömitz-Lenzen study area, in the transition towards the underlying Rupelton, pocket-like and cluster-like potholes and burrows that are filled with glauconitic sand are found in the Rupelton. A so-called hardground facies with omnidirectional bioturbation, like Bülow (2000a) reported for the same stratigraphic position in the layers of Plate above the Rupelton, was not found in the Gorleben study area. The more coarsely clastic base of the Eochattian beds can be lithostratigraphically correlated with the distinctive boundary glauconite above the septarian clay (Kuster 2005) and with the lower Sülstorf member. This section is characterised as weakly transgressive, which suggests there is a small sedimentation gap between the Rupelton and the Upper Oligocene. This horizon is biostratigraphically characterised by an abundance of *Asterigerina guerichi guerichi* (Köthe et al. 2002) and can thus be dated as lower Eochattian.

Above the fine sandy base layers of the Eochattian, mainly brown-grey to dark olive-green, often greenish, alternatingly clayey and fine sandy silts occur. In the complete profiles of the rim synclines, the fine sand content increases continuously towards the top. In many boreholes, the upper part occurs as silty fine sand with thicknesses between approx. 4 m and 15 m. Compared to the silts, the fine sandy parts in the northern part of the Dömitz-Lenzen study area occupy about half of the sequence, with thicknesses between 30 m and 50 m (boreholes GoHy 1610, 1620, and 1700). The whole area, however, is clearly dominated by silty layers, which make up 70 % of the bedding sequence. The sediments, no matter whether they are silty or fine sandy, are calcareous to highly calcareous, contain glauconite, often residues of mollusc shells and low to very low contents of mica. Occasionally, bioturbations and carbonate concretions occur. These siltstones or fine sandstones attain decimetre size and do not form a horizon.

The gamma ray log of the Eochattian beds shows a characteristic curve. The clear minimum at the base horizon is followed by the highest intensities in a lower section; in the middle section, the curve declines. The upper section is characterized by a renewed rise in gamma intensity, with the topmost part clearly divided by interbedded sands. On the whole, the curve is similar to an upwardly stretched, not completely closed letter “S”.

Sedimentological analyses (grain-size analyses, in some cases analyses of calcium carbonate content) are available for four boreholes: GoHy 994, GoHy 1525, GoHy 1543, and GoHy 1603. The three samples from borehole GoHy 1525 show a spectrum of fine sands: fine sand 55 % to 60 %, medium sand 25 %, coarse sand 5 % to 8 %, and silt 10 % to 12 %. The three samples from borehole GoHy 1543, on the other hand, show silt and clay as the main components: silt 30 % to 40 %, clay 15 % to 25 %, fine sand 10 % to 30 %, and medium sand 8 % to 20 %. The calcium carbonate content in borehole GoHy 1525 varies between 2.8 and 4.1 %.

Eochattian beds were encountered in 127 boreholes, 76 of which penetrated the beds completely. They were originally deposited in the whole study area, but are missing today above most of the Gorleben–Rambow salt structure, above the salt dome Groß Heide–Siemen, as well as in the deep parts of the Gorleben channel south of the Gorleben salt dome. In the area of the Gorleben–Rambow salt structure, the average thickness is 32.3 m, the maximum is 45 m (borehole E RmwL 12Ah3/69) and the minimum is 8 m (borehole GE 1_2934). The sediments were mainly preserved at the edge of the structure, in the ring wall (Fig. 9, cross section A–A', Fig. 10, cross section B–B'). The sequence is partially condensed, partially truncated at the top by subsequent erosion. The highly sandy and glauconitic base horizon is missing in the majority of the boreholes.

In the rim synclines, the Eochattian beds are thicker and are biostratigraphically and lithostratigraphically fully preserved. According to drilling results, the maximum thickness is 109 m in the northwestern rim syncline (borehole E RmwL 14/69) and 85.3 m in the southeastern rim syncline (borehole E RmwL 4/59).

In the **Neochattian beds**, the sandy facies of the upper part of the Eochattian beds continue, seemingly without interruption. Only a further decrease in silt content occurs. The Neochattian beds are of the same age as the Rogahn member in northeastern Germany (Fig. 6).

The Neochattian, which is characterised by a microfauna of few species and seldom rich in specimens, and by carbonaceous residues in the sediment, was evidenced by microfauna and foraminifers as a near-shore facies in the study area Gorleben-Süd.. Due to the development of the facies (increasingly high terrigenous content), no more Chattian index fossils are present. The age classification as Neochattian is also partially based on the proportion of carbonaceous residue in the sediment.

In the Dömitz-Lenzen study area, the Neochattian beds were dated as a *Vaginulinopsis crista* zone (Köthe et al. 2002), which is equivalent to the *Saracenaria magna* zone. In the Neochattian, *Vaginulinopsis crista* occurs for the first time (cf. Spiegler 1974). The index species *Saracenaria magna* was not found in the sampled boreholes of the Dömitz-Lenzen study area.

Based on dinocysts, the Neochattian beds – like the Eochattian beds and the lower part of the Untere Braunkohlensande – were dated as zone D15 (Fig. 6). The boundary between Neochattian beds and Untere Braunkohlensande could not be evidenced by dinocysts. In contrast to the Untere Braunkohlensande, almost all samples of the Neochattian beds contained dinocysts, even if the numbers were only low in some samples.

Using calcareous nannoplankton, the Neochattian beds were dated as NP 25. The content of calcareous nannoplankton continuously decreases in the Neochattian beds from bottom to top. Relocated species from the Cretaceous occur relatively often. The topmost part of the Neochattian beds no longer contains any calcareous nannoplankton.

The petrographic composition of the Neochattian beds is dominated by green-grey to olive-grey, brown-grey to dark brown, alternatingly micaceous and glauconitic, silty to highly silty, weakly medium-sandy fine sands. In the middle and upper parts, layers of fine sandy silts are interstratified. The calcium carbonate content alternates between low and locally high, and sometimes mollusc shells are embedded in the sediment. In some boreholes, a small number of decimetre-sized sideritic to quartzitic concretions to fine sandstone were encountered.

Due to the increasing grain size, the Neochattian beds are differentiated from the Eochattian below and the base of the Braunkohlensande above by a distinctive intensity minimum in the gamma ray log. In addition, the curve is more structured than that of the Eochattian beds, due to grain-size variation.

Due to their importance as a part of the lower aquifer, grain-size analyses of the Neochattian beds were performed on samples taken from ten boreholes. All samples are dominated by fine sand as the main component. Series of grain-size analyses were performed on samples taken from boreholes GoHy 1525, GoHy 1543, and GoHy 1603 (IMS 1998). According to the analyses of these boreholes (26 samples), the fine sand contents are between 50 % and 75 %, those of medium sand between 13 % and 30 % and those of silt between 5 % and 10 %. Occasional intercalations of silt of 1.2 m to 1.8 m thickness show a silt content of 41.8 % to 61.3 %. In borehole GoHy 1525, the calcium carbonate content varies between 0.1 and 2.3 % (average 0.8 %) and is thus considerably lower than in the Eochattian.

The Neochattian beds were encountered in 119 boreholes, four of which did not fully penetrate the beds. Their occurrence is similar to that of the Eochattian beds. In contrast to the Eochattian beds below, the average thickness of the Neochattian beds displays no large variations. Above the Gorleben–Rambow salt structure, it is 22.8 m, in the northwestern rim syncline it is 23.7 m, and in the southeastern rim syncline it is 27.4 m.

The structurally insignificant differences in thickness between the salt structure and the rim synclines are due to the fact that the Neochattian beds do not occur on top of the salt structure but only on its edges. The drilling results showed that the greatest depths of the base of the Neochattian beds are 304.3 m below sea level in the northwestern rim syncline (borehole GoHy 1580) and 212.5 m below sea level in the southeastern rim syncline (borehole GoHy 270).

The areal extension of the Upper Oligocene sediments corresponds to that of the Eochattian beds. The average thickness of the Upper Oligocene is 43.2 m above the Gorleben–Rambow salt structure, 101.1 m in the northwestern rim syncline, and 78.3 m in the southeastern rim syncline. The largest depth of the base is 420 m below sea level in the northwestern rim syncline. The maximum depth in the southeastern rim syncline is in the eastern part, at 280 m below sea level. At 9 m below sea level (borehole GE 1_2934), the base of the Upper Oligocene is highest in the area of the ring wall southwest of Gorleben.

4.2.4 Miocene (Lower Miocene)

The Lower Miocene is lithostratigraphically subdivided into the Untere Braunkohlensande, the Hamburg-Ton (Hamburg Clay) and the Obere Braunkohlensande (Upper Brown Coal Sands). The sediments of the Middle Miocene (Reinbek beds) were only found as an allochthonous block in deposits of the Drenthe substage of the Saalian Glaciation in borehole GoHy 110.

Lotsch (1981) introduced the lithostratigraphic designations Brooker member, Mölliner member, and Malliss member for age-equivalent beds in the area of northwestern Brandenburg/southwestern Mecklenburg. The correlation of the stratigraphic/lithostratigraphic units can be found in Figure 6.

At the end of the Late Oligocene and the beginning of the Early Miocene, the paleogeographic conditions changed fundamentally. Due to marine regression of the sea, a considerable shallowing of the whole marine area occurred in eastern Northern Germany. The marine facies retreated to western Schleswig-Holstein and western Lower Saxony.

In the non-calcareous Miocene sediments, only dinocysts are of importance for biostratigraphic dating. Microfauna (particularly foraminifers) produced only inaccurate results. Calcareous nannoplankton was only analysed in the Hamburg-Ton which is barren of these microfossils. The age classifications based on pollen and spores were no more specific than “Neogene”, "Lower to Middle Miocene", or “Middle to Upper Miocene". The subdivision of the Lower Miocene is thus mainly based on lithological criteria.

Untere Braunkohlensande

The Untere Braunkohlensande can be lithostratigraphically subdivided into a lower part that is predominantly only fine sandy, and an upper part that chiefly consists of fine and medium sands, less often coarse sands (Fig. 6). In the upper part, intercalations of brown-coal seams are common. Kuster (2005) suggests that the lower fine-grained facies of the Braunkohlensande and the Brook member are of the same age, and that the upper, more coarse-grained bed is of the same age as the Möllin member. Except for the major part of the Gorleben–Rambow salt dome, the top of the salt dome Groß Heide–Siemen and the Gorleben channel, the Untere Braunkohlensande occur as a continuous sedimentary unit in the study area.

The microfauna, i.e. foraminifers, of the Untere Braunkohlensande produced no index fossils for the Miocene or the base Miocene. They either contained uncharacteristic microfauna from the Oligocene/Miocene boundary or no microfauna at all. A detailed dinocyst analysis of the Untere Braunkohlensande is available for borehole GoHy 1603 (Köthe 2003). In the lower part of the Untere Braunkohlensande, zone D15 could be determined, which extends from the lower Upper Oligocene to the lower Lower Miocene. The upper part of the Untere Braunkohlensande contained almost no dinocysts. The absence or scarcity of dinocysts indicates temporarily brackish to limnic sedimentation conditions. Due to the absence or low content of calcium carbonate, no analysis for calcareous nannoplankton was performed.

In most boreholes, the **lower part of the Untere Braunkohlensande** starts with a 4 to 10-m thick, dark grey-brown to dark brown, micaceous, fine sandy silt, which changes to highly silty fine sands, partially due to an increase in fine sand layers and streaks. Locally, a low calcium carbonate content is found and occasional shells of molluscs and gastropods occur, as in the lower Neochattian. There is a strong lithological similarity with the Unterer Glimmerton (Lower Mica Clay) northwest of the study area that was deposited during the Lower Miocene (“Vierlandium”).

Above this, brownish grey to dark grey, sometimes grey-brown, alternatingly micaceous, silty, weakly silty towards the top, medium-sandy fine sands occur. Sections of thin silt layers are interstratified with the non-calcareous sands, causing a distinctive layering to narrow lamination of the sands. In some boreholes, very low to low calcium carbonate content occurs, and occasionally to rarely glauconite is embedded. In the lower part of the sand sequence, light brown to brownish grey, partly calcareous and partly sideritic fine sandstones, which are several decimetres thick, occur often. In the upper section, zones of fine to coarse-sandy medium sands occur, thus rendering the distinction to the upper part of the Untere Braunkohlensande sometimes difficult.

The grain-size composition of the lower part of the Untere Braunkohlensande was analysed in 45 representative grain-size analyses in 21 boreholes. All samples are dominated by fine sand and, on average, low silt and higher medium sand contents. Grain-size analyses of the whole sand sequence, spaced approx. 2 to 4 m apart, are available from borehole GoHy 1603. These show a very even and homogeneous grain-size spectrum of 70 to 77 % fine sand, 20 to 27 % medium sand, and 3 to 8 % silt.

In the gamma ray log, the lower part of the Untere Braunkohlensande shows little structure. The curve starts sometimes with a positive intensity peak, similar to the Unterer Glimmerton, e.g. in boreholes GoHy 210 and GoHy 730. Subsequently, a clear trend of decreasing gamma intensity from bottom to top is evident, which is due to the continuously diminishing silt content. Banks of sandstone are clearly identifiable in the resistivity log.

The lower part of the Untere Braunkohlensande was encountered in 120 boreholes, 13 of which did not fully penetrate. According to drilling results, the average thickness is 45.6 m, with only small differences between the northwestern and southeastern rim syncline (46.4 m and 45.5 m respectively). The maximum thickness of 73.7 m was encountered in the northwestern rim syncline (borehole GoHy 1510). Above the Gorleben–Rambow salt structure, the sands were preserved only in the area of the crestal-trench disturbance zone southwest of Lenzen. The thicknesses in that area are between 20 m and 50 m. The values for the base are given below in the description of the whole Untere Braunkohlensande.

The **upper part of the Untere Braunkohlensande** is mainly composed of light grey to brown-grey fine to medium sand, in some parts coarse sand with low silt and mica contents. Neither calcium carbonate content nor fauna have been evidenced yet. On the whole, the continental sedimentation conditions grow stronger. In the lower half, coarse-sandy medium sands to medium-sandy coarse sands often occur. Occasional fine gravels are also interspersed. The sand consists almost exclusively of quartz, hence the older name “Quartz Sand Group” for this bed.

In the sand sequence, up to three brown-coal seams are interstratified, which are several metres thick in parts.. Due to erosion and alteration during the Miocene as well as splitting of the facies into several seams, the regional extent and contemporaneous formation of the two rarely occurring bottom seam horizons cannot be proven. According to Lotsch et al. (1982), the two seams belong to the fourth Lusatian seam horizon.

The upper seam horizon, however, is almost ubiquitous, except for areas of Quaternary erosion, and is in a consistent position of approx. 10 m below the Hamburg-Ton. The thickness is between 1.5 m and 3.0 m on average, 5.0 m to 7.5 m are maximum values (boreholes GoHy 340, GoHy 1600, GoHy 1690, and GoHy 2422). Occasionally, the seam is split into two seam banks by a thin sand interbed (approx. 1 m). Three analyses of organic carbon content that were sampled in borehole GoHy 1603 showed that the TOC values are between 46.3 % and 50.7 %.

An analogous stratigraphic position and continuous extension of the brown-coal seam below the Hamburg-Ton was found by Kuster (2005) for the Wendland area. Lotsch et al. (1982) classified this seam as contemporaneous with the third Lusatian seam horizon and also indicated its widespread presence and its “expansion” to salt pillow structures in northern Brandenburg. In this context it has to be noted that relicts of this seam were penetrated in boreholes GoHy 1740 and GoHy 1760 above the top of the Gorleben–Rambow salt structure, in the area of the crestal-trench disturbances southwest of Lenzen.

Grain-size analyses are available from 40 samples taken from 13 boreholes, showing an alternation of fine sand and medium sand spectra with low coarse sand proportions. One profile from borehole GoHy 1603 produced wide ranges in the grain-size spectrum: in some parts 70 % fine sand, up to 58 % medium sand, and up to 55 % coarse sand.

In the gamma ray logs, the upper part of the Untere Braunkohlensande is characterised by very low intensities. Determining the boundary to the lower part of the Untere Braunkohlensande proved to be difficult where the transition is in a fine sand area. In the Dömitz-Lenzen study area, the density log was considered as well in such cases, and the boundary was set where the density had generally sunk below 2 g/cm^3 (last coarser quartz sand accretion). The upper boundary, however, is clearly identifiable by a distinctive positive peak of the gamma ray log at the start of the Hamburg-Ton.

The upper part of the Untere Braunkohlensande was encountered in 123 boreholes, 24 of which did not fully penetrate. The larger thicknesses are in the centre of the northwestern rim syncline, with 81 m maximum (borehole HWW 127) and 48.4 m on average. In the southeastern rim syncline, the maximum thickness was 73.8 m (borehole BKN 103), the average was 40.9 m. Above the Gorleben–Rambow salt structure, the Braunkohlensande were reported only from the area of the crestal-trench disturbances southwest of Lenzen, with thicknesses between approx. 15 m and approx. 30 m.

The base surface of the horizon reflects the thicknesses. According to drilling results, the base is deepest in the centre of the northwestern rim syncline, at 219.1 m below sea level, in borehole GoHy 1580. In the southeastern rim syncline, the base lies generally higher. The deepest depth was encountered in borehole GoHy 1540, at 152.1 m below sea level.

The extent and thickness of the **Untere Braunkohlensande** are as described for the lower and upper parts of the Sands. The overall average thickness is 82.6 m, in the northwestern rim syncline the average is 89.5 m, and 80.9 m in the southeastern rim syncline. The largest thickness of 130.4 m was also encountered in the northwestern rim syncline, in borehole GoHy 1580 (southeastern rim syncline: 112.7 m in borehole GoHy 9004). The base surfaces of the two rim synclines differ by approx. 100 m. The maximum base depths are all north of the Elbe, reaching values of >300 m below sea level in the northwestern rim syncline and >200 m below sea level in the southeastern rim syncline. The base has its highest point of approx. 20 m below sea level in the area of the ring wall above the southwestern part of the Gorleben salt dome.

Hamburg-Ton

Above the Untere Braunkohlensande, a clay/silt sedimentation sets in abruptly, which is increasingly interstratified towards the top with sandy formations. The thickness and facies of the sediments are characterised by considerable variation in conditions. The bedding thicknesses depend on the location within the rim synclines and the depth of Quaternary erosion. The facies reflects a repeated alternation between limnic-brackish and fluvial-terrestrial environments, with increasingly continental influences towards the top. Kuster (2005), who described comparable formations in the area of northeastern Lower Saxony, thus refers to a “Hamburg-Ton-Komplex” (Hamburg clay complex).

In southwestern Mecklenburg/northwestern Brandenburg, this sequence is referred to as the Malliss member, based on the description of the brown-coal Tertiary of Malliß (Gehl 1966). This is subdivided into the Lower Malliss member, which corresponds to the Hamburg-Ton, and the Upper Malliss member, which is classified as contemporaneous to the Obere Braunkohlensande. The Lower Malliss member borders on the topmost bank of the second Lusatian seam horizon (Mallisser Oberflöz, Maliss top seam) (Lotsch et al. 1982).

The beds of the Hamburg-Ton occur especially in the northwestern rim syncline and southwest of the Gorleben salt dome. Southeast of the Gorleben–Rambow salt structure, there are large gaps in its distribution.

The Hamburg-Ton contains no calcareous microfauna, but layers of dinocysts were found. The lowermost section contains no dinocysts. Several metres above the base of the Hamburg-Ton, zone D16 (=DN2), lower to middle Lower Miocene, could be identified. On the whole, the dinocyst content is low. The middle part of the Hamburg-Ton, which is dated as DN3 (middle to upper Lower Miocene), contained few dinocysts species and specimens. The upper part of the Hamburg-Ton is barren of dinocysts.

The increasing scarcity of dinocysts from the bottom to the top of the Hamburg-Ton and the occurrence of freshwater and brackish-water algae like *Pediastrum* and *Botryococcus* are interpreted as a gradual transition from brackish to limnic sedimentary conditions.

All samples of the Hamburg-Ton contained no calcareous nannoplankton.

In its main area of occurrence between Dömitz and Lenzen, five widespread horizons could be identified within the Hamburg-Ton (Köthe et al. 2002):

- Mallisser Oberflöz (Maliss top seam)
- Upper sand sequence
- Silt/sand alternating sequence
- Lower sand layer
- Clay/silt bottom bank.

By interpreting the gamma logs, this subdivision could be partially translated to boreholes south of the Elbe during the hydrogeological modelling process.

The **clay/silt bottom bank** consists of dark to black-brown, in some parts dark grey to dark grey-brown, seldom light grey-brown, micaceous clayey silts alternating with silty clays. The layer surfaces are characterised by accretions of mica. The clayey zones usually form the bottom part. They are indistinctly interstratified by millimetre-thin to paper-thin layers of bright silt to coarse silt at large intervals. In the silty zone, the layering becomes denser, the layers become slightly thicker, and often fine sand layers that are rich in mica also occur, so a ribbon structure is formed. Occasionally the clays/silts contain pyrite and show bioturbations (cored sections of boreholes GoHy 1584 and GoHy 1603). The base of the bottom bank is mainly highly carbonaceous. In many boreholes a thin brown-coal seam occurs in this zone.

The grain-size analyses of borehole GoHy 1584 confirmed the general structure of the sequence: the lower sample showed 51 % clay and 49 % silt; in the upper part 17 % clay, 30 % silt, and 43 % fine sand were found. The content of organic carbon is 52.1 % in the seam of borehole GoHy 1584; in the carbonaceous clays and silts it is 4.2 to 7.2 % (borehole GoHy 1584) and 26.0 to 33.0 % (borehole GoHy 1603). The thicknesses of the clay/silt bottom bank range from 2.7 m to 18.6 m (Table 3). These beds are marked by a distinctive intensity peak in the gamma ray log.

Above the compact clay/silt bottom bank, a clastic accretion can be found in the whole study area, which causes a distinctive intensity drop in the gamma ray log. This **lower sand layer** mainly consists of light to dark grey, in some parts grey-brown, occasionally micaceous, weakly silty to silty, medium-sandy fine sands. In some places, fine sandy silt layers whose thickness ranges from a few decimetres to 3.9 m are embedded. Towards the top, the grain size often becomes coarser, up to the formation of coarse sands. The bed has a thickness of approx. 2 m to 14 m (Table 3). In the grain-size analyses of borehole GoHy 1584, the grain-size spectrum varies from 78 % fine sand to 69 % coarse sand. The sands are consistently non-calcareous. In some boreholes (GoHy 1650, GoHy 1660, GoHy 1670, and GoHy 1690), the occasional to rare occurrence of glauconite as well as the interpretations of the dinocysts indicate temporarily brackish sedimentary conditions or alterations of older beds.

The largest part of the Hamburg-Ton-Komplex is occupied by the **silt/sand alternating sequence**. Its thickness values vary in a wide range between 6.5 m and 64.0 m (Table 3) depending on the position in the northwestern rim syncline and the depth of erosion in the Quaternary, which explains differing facies. In the deeper area of the rim syncline, the average thickness is 45 m to 60 m. The sequence consists of grey-brown to dark brown, micaceous, variably fine sandy and clayey silts alternated with light grey to brown-grey, micaceous, slightly silty to highly silty, medium-sandy fine sands, occasionally also fine sandy medium sands. The silt zones dominate the sequence and are 7 m to 20 m thick on average, interbedded by sand horizons of approx. 3 m to 12 m thickness. In some parts, the described alternating sequence is also present in sizes of a few decimetres to centimetres within the larger beds. In these cases, the silts, amplified by smears, streaks, and thin layers of fine sand to coarse silt, display a striped silt disposition. Occasionally, carbonaceous to highly carbonaceous sections occur, even forming seams, e.g. in boreholes GoHy 1560, GoHy 1570, GoHy 1580, and GoHy 1690. The seams are up to 4.2 m thick. These are probably tentative formations of the second Lusatian seam horizon.

Table 3: Occurrences and thicknesses of the five horizons of the Hamburg-Ton (selection) sorted by geological structure

GoHy-Borehole	**Hamburg Clay whole sequence**		**Clay/Silt Bottom Bank**	**Lower Sand Layer**	**Silt/Sand Alternating Sequence**	**Upper Sand Sequence**	**Mallisser Top Seam**
	thick-ness [m]	base depth [below sea level]	thickness [m]				
northwestern rim syncline							
1580	82.3	157.9	17.8	14.0	50.5	–	–
1690	96.0	151.0	18.6	3.0	49.2	25.2	–
1560	82.9	128.0	17.0	8.0	57.9	–	–
1670	99.0	119.2	15.6	13.4	51.0	17.0	2.0
9002	98.0	119.8	12.0	4.0	35.0	46.0	1.0
1650	102.5	116.7	17.0	3.5	64.0	16.0	–
1570	59.5	90.1	10.5	6.0	43.0	–	–
1700	46.0	86.7	15.2	7.5	21.7	–	1.6
330	78.0	83.8	12.0	3.0	63.0	–	–
290	70.8	82.4	13.8	3.5	43.5	10	–
1660	72.0	79.3	9.4	5.6	35.5	20.0	1.5
1590	59.4	77.9	8.2	9.8	40.2	–	1.2
1630	57.5	64.2	5.8	6.2	45.5	–	–
salt structure							
1740	65.5	105.2	10.0	9.0	46.5	–	–
1760	30.5	50.0	9.1	1.6	19.8	–	–
1770	13.5	83.7	13.5	–	–	–	–
southeastern rim syncline							
350	29.7	70.5	2.7	5.5	21.5	–	–
9003	33.0	67.0	9.0	14.0	10.0	–	–
820	24.5	39.2	9.5	3.0	12.0	–	–

According to grain-size analyses of single samples from borehole GoHy 1584, the clay content varies within the silt zones between 10 % and 26 %, the silt content varies between 63 % and 83 %, and the sand content varies between 8 % and 23 %. The proportion of organic carbon in two samples of the brown-coal seam was 34.3 % and 36.9 %. The silt/sand alternating sequence is totally non-calcareous.

In the gamma ray log, the silt/sand alternating sequence shows a differentiated curve of repeated changes from high to low intensities. The pattern of the gamma ray curve resembles that of the Lauenburger-Ton-Komplex (Lauenburg Clay Complex). The values of the density log are significantly below 2.0 g/cm^3, in contrast to the higher values in the Lauenburger-Ton-Komplex.

The lithostratigraphic distinction of the **upper sand sequence** is somewhat problematic if the Maliss top seam is missing, as petrography and logs of the geophysical borehole survey show no significant difference to the Obere Braunkohlensande. The distinction is made based on the division of the Lower and Upper Malliss members in the area of the second Lusatian seam horizon (Maliss top seam) as well as on the contemporisation of the Lower Malliss member and the Hamburg-Ton (Lotsch 1981, Lotsch et al. 1982).

Below the seam mentioned above, five boreholes (Table 3) penetrated light grey to brown-grey, weakly to highly silty, in some parts weakly medium-sandy fine sands of 16 m to 46 m thickness, in which silt layers of several decimetres to two metre thickness are interstratified. The sand sequence is weakly micaceous and non-calcareous.

The sequence of the Hamburg-Ton is concluded at the top by the **Maliss top seam**. The brown-coal seam was also found only in a few boreholes and attains a thickness of 1.6 m to 2.0 m, in the two boreholes GoQ 17 and GoQ 18 up to 5 m. Its occurrence is limited to the part of the study area that is north of the Elbe, except for borehole GoHy 9002. Due to Quaternary erosion, the seam occurs only sporadically (Pl. 1: Fig. 9, cross section A–A', Fig. 10, cross section B–B'). According to the few exposures, it consists of silty lignite that is interbedded with fine sand layers or highly carbonaceous silts with layers of brown coal.

The subdivision of the Hamburg-Ton into five horizons is an attempt to divide the sequence of the sedimentary unit with considerably varying facies into single sections. This allows the parallelisation of the sequence of beds that were later reduced by Quaternary erosion, or vary considerably in thickness due to halokinetic processes.

In the centre of the northwestern rim syncline, the complete sequence of the Hamburg-Ton reaches thicknesses of 80 m to >100 m (Table 3).

The sedimentary sequence of the Hamburg-Ton was encountered in 107 boreholes, 20 of which did not fully penetrate the sequence. The average thickness is 37.7 m on the whole, 46.6 m in the northwestern rim syncline and 22.1 m in the southeastern rim syncline. In the area of the crestal-trench disturbances southwest of Lenzen, the beds were encountered in three boreholes showing thicknesses between 13.5 m and 65.5 m.

In the northwestern rim syncline, the beds show almost no gaps. They are absent in the Gorleben channel and in parts of the channel of Siemen–Wootz due to Quaternary erosion. The deepest areas of >190 m below sea level are in the northwestern rim syncline northeast of the Elbe. In the southeastern rim syncline, small residual deposits occur locally. A major continuous occurrence only starts north of the Elbe, where the base depths sink to approx. 100 m below sea level.

Obere Braunkohlensande

Northwest of the Gorleben–Rambow salt structure, in the area of the Tertiary highland of Gusborn–Groß Schmölen, sandy deposits occur that represent the youngest stratigraphic member of the Miocene and are lithostratigraphically assigned to the Obere Braunkohlensande. In some parts, these deposits lie directly on top of the Maliss top seam.

Based on two samples containing dinocysts, these beds cannot be distinguished biostratigraphically from the Hamburg-Ton. Like the upper part of the Hamburg-Ton, they are dated as DN3, middle to upper Lower Miocene. Due to the absence of calcium carbonate, no analysis for microfauna, foraminifers or calcareous nannoplankton was performed.

The sediments are mostly grey to brownish grey, weakly micaceous, weakly medium-sandy to medium-sandy, weakly silty to silty and silt layer-bearing, non-calcareous fine sands. Medium to coarse sands occur rarely (borehole GoHy 290).

The Obere Braunkohlensande were found in 18 boreholes. According to drilling results, their thickness is between 3 m and 24 m. Due to denudation after the Lower Miocene as well as to Quaternary erosion, they are preserved only in relicts and reduced in their overall thickness. The base surface is mostly between 10 m and 20 m below sea level. In the area of boreholes GoHy 1690 and GoHy 1700 in the area of the centre of the northwestern rim syncline southwest of Eldenburg, the base depths sink to 40 m to 55 m below sea level.

4.3 Quaternary

In the continental sequences of central Europe, the Quaternary comprises a time span of approx. 2.6 million years (Litt et al. 2002). In Northern Germany, its lower boundary is defined by the base of the Pretiglian, corresponding to the Dutch stratigraphy. The subdivision of the Quaternary is based on climatic changes that led to an alternation of glacial stages and interglacial. The Early Quaternary consists of complex units, that each comprise several glacial and interglacial periods (Fig. 12).

In the study area, the Quaternary sediments superpose the Tertiary beds with a temporal hiatus of approx. 15 million years. After the retreat of the sea from the Northern Germany in the Upper Miocene and Pliocene, a long time span of low sedimentation started. Instead, the Tertiary beds were subjected to profound weathering and erosion, and a scarcely structured relief was formed, which was only marginally altered during the first Pleistocene glacials and interglacials. The area was cut by a wide-fanned fluvial system that drained generally westwards. Relicts of these fluvial-limnic-terrigenous sediments displaying a mainly sandy facies were found in boreholes in a very limited area southwest of Gorleben. Embedded in these are peats and muds that were classified in the time span of the Bavelian to Cromerian Complex.

The main volume of Quaternary rocks was deposited by Nordic glaciation. During the Elsterian and Saalian Glaciations, the Scandinavian ice sheet advanced to the northern edge of the Central German Uplands. During the last glaciation (Weichselian), however, the Scandinavian glaciers did not cross the Elbe and stopped approximately 40 km northeast of the study area.

The Tertiary and Early Pleistocene subsurfaces were subjected to deep cutting erosion by meltwater and to high pressure strain due to continental glaciation, which is evidenced by the deep Quaternary channels and the push moraine structure in the Höhbeck, as well as by glacigenic deformations in the upper part of the Hamburg-Ton found in several boreholes.

The Quaternary sequence of strata has a maximum thickness of 317.5 m (borehole GoHy 1240) and generally consists of an alternating sequence of glaciofluvial deposits, glaciolacustrine deposits (clays, silts, fine sands), and till. Mainly in the area of the Quaternary channels, silts and muds of the Holsteinian Interglacial are embedded between the deposits of the Elsterian and Saalian Glaciations. The surface is dominated by fluvial to limnic sediments of the floodplains and the Weichselian valley sands of the Elbe ice-marginal valley, partially covered by eolian sands and dunes.

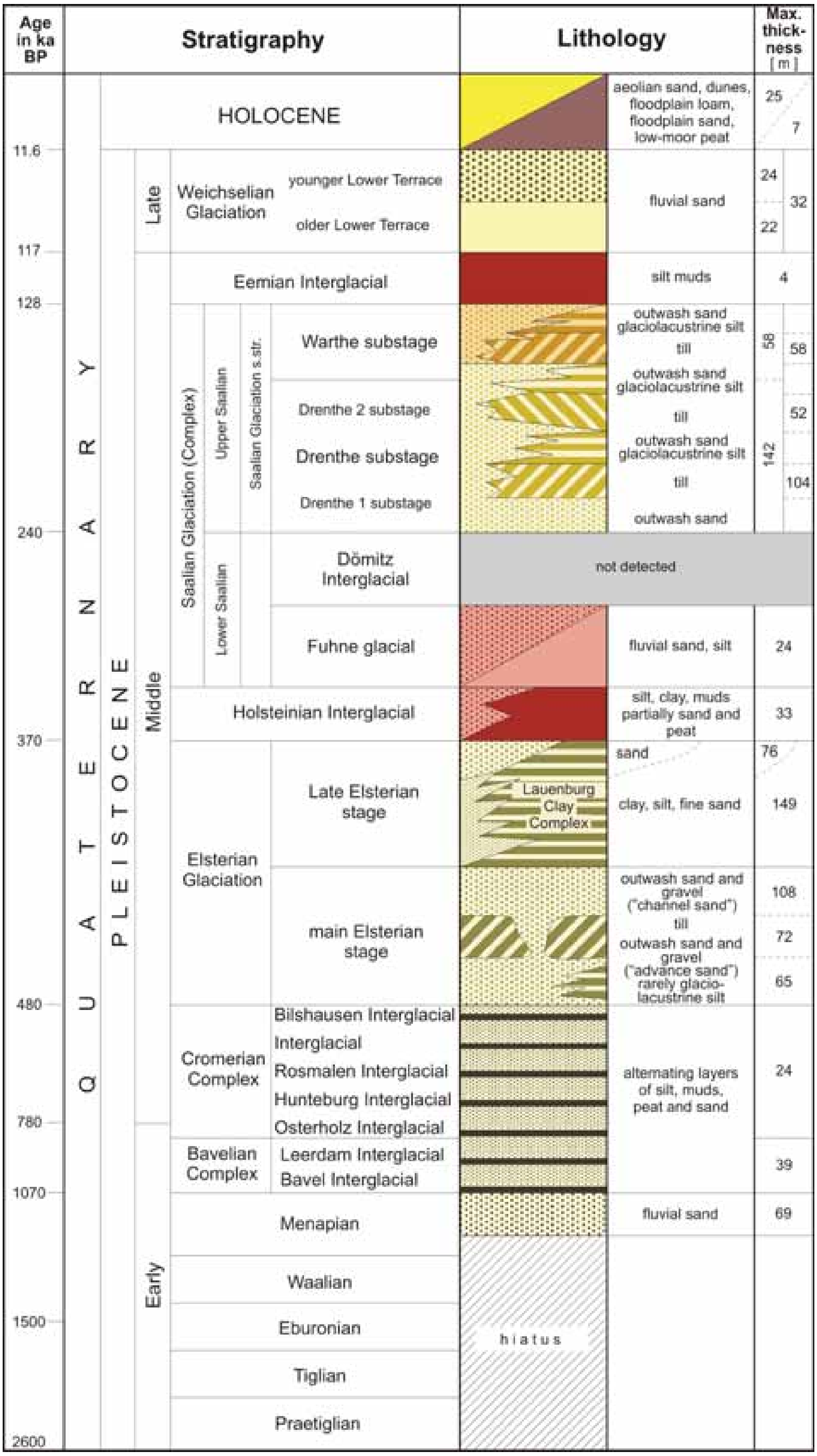


Figure 12: Stratigraphic and lithological subdivision of the Quaternary (ages according to Litt et al. 2002 and Lippstreu 2002)

Based on a wide range of investigation methods (pebble and boulder counts, sedimentological and palynologicalal analyses), the lithologically diverse sequence of strata could be subdivided and subsequently its bedding structure could be determined.

Figure 12 provides an overview of the stratigraphic subdivision and the lithological structure of the Quaternary in the study area.

The following description of the lithological units mainly deals with the glacial sediments as these dominate the sequence in terms of areal extent as well as thickness.

4.3.1 Preglacial age (pre-Elsterian glacial stage)

The preglacial age comprises the long time span from the beginning of the Quaternary to the beginning of the Elsterian Glaciation, approximately 480 000 years ago (Fig. 12). The climatic depressions of the pre-Elsterian Glacial stages did not reach the dimensions of the three later glacials, so no continental glaciation occurred in Northern Germany during this time. Sediments of this period have only rarely been reported below the glacial sediments. Thus, it is even more remarkable that pre-Elsterian Glacial stage sediments have been preserved in an isolated depression of approx. 3.5 km^2 in size above the western end of the Gorleben–Rambow salt structure.

The sequence can be subdivided into a lower sandy area and an upper section with an alternating sequence of clayey-silty and humous beds. The latter reflect intense climatic changes. Using palynologicalal analyses, the sequence was dated by Müller (1986, 1992) as belonging to the Bavelian to Cromerian Complex. The lower section was determined as belonging to the Menapian, due to the sequential context, where the overlying sediments showed no unconformity and were biostratigraphically dated as Bavelian sediments. Older sediments of the Lower Pleistocene were not found in the study area.

The stratigraphic subdivision of the Lower Pleistocene and earliest Middle Pleistocene in the North German glaciation area is mainly based on findings from the Netherlands (Zagwijn et al. 1971, Zagwijn 1985). Figure 13 shows the integration of the subdivision of the “pre-Elsterian Glacial stage Quaternary”, which was prepared by Müller (1992) for the study area, into the Quaternary stratigraphy.

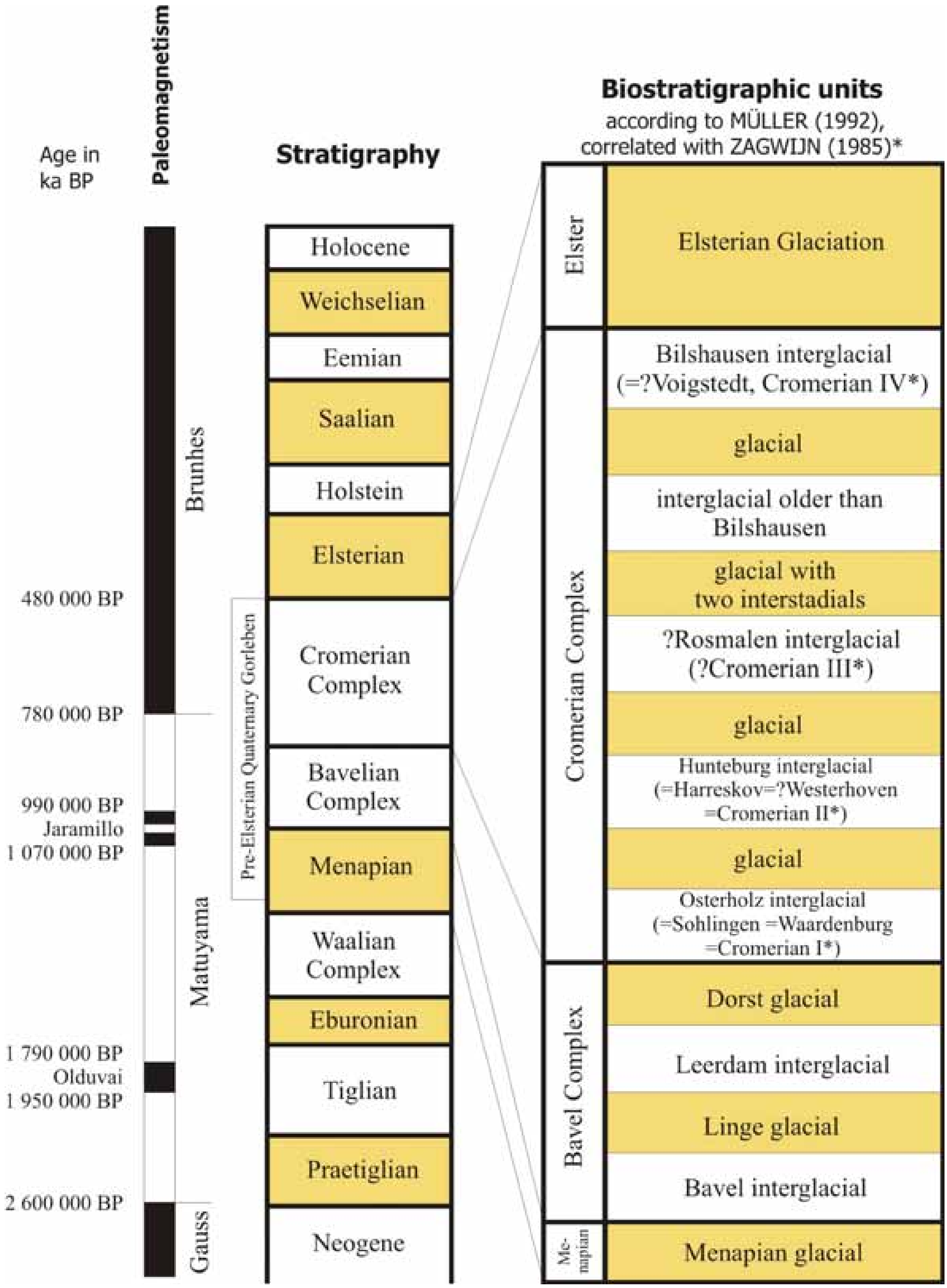


Figure 13: Biostratigraphic units of the Bavelian and Cromerian Complex (modified according to MÜLLER 1992)

Menapian

The sediments of the Menapian have a maximum thickness of 69 m, the average thickness is 33.9 m. The sediments mainly consist of homogeneous, occasionally fine to medium gravelly, quartzitic fine to medium sands. Zones of decimetre-thick layers of weakly fine-gravelly, sometimes weakly medium gravelly and rarely coarse gravelly coarse sands are embedded in the sequence. These sands mostly display a high degree of sorting and are well rounded. A characteristic feature differentiating this bed from almost all other sandy sediments of the Pleistocene is the absence of calcium carbonate. Occasionally, centimetre-thin humous layers occur, which are dated as cool periods in the pre-Elsterian Glacial stage Quaternary based on palynologicalal analyses.

Petrographic analyses of the gravel content were performed on the few more coarse-grained layers in the cored sections of boreholes GoHy 1270 and GoHy 1231. The gravel counts, mainly in the fractions of 2 mm to 4 mm and 4 mm to 6.3 mm, revealed a “preglacial Nordic quartzitic gravel association” of rocks of Fennoscandian origin. The composition and formation of the gravel resemble the kaolin sands, white quartzitic, mainly fine gravel-bearing sands of Pliocene to Lower Pleistocene origin, which can be found on the North Frisian island of Sylt and at other locations in Northern Germany. The sediment is dominated, with approx. 85 % to 90 %, by the quartz aggregate group and siliceous sandstones. Quartz single crystals and residual silica as well as feldspar each form a fraction of 5 % to 10 %. Among the first group, smoky quartz and amethystine quartz can often be found. The feldspars are mostly white, opaque or dark grey, and often weathered and crumbling. They cannot be mistaken for the fresh, red feldspars of more recent glacial material. Occasionally, silificated Palaeozoic fossils are found among the non-quartzitic gravels, which prove a Fennoscandian-Baltic origin. Accessory minerals in the sediment are touchstone and chert (probably from the Central German Uplands) (Table 4). The results of the heavy minerals analyses that were also performed are given in the section on the Cromerian Complex.

The sediments of the Menapian Glacial were deposited under fluvial conditions. Gravel analyses and heavy minerals analyses showed that these are mainly relocated sediments of the Neogene (Braunkohlensande), with a fraction of highly weathered Fennoscandian material of northern origin and a very low fraction of southern material.

Due to the similar gravel facies and assumed equal stratigraphic positions, Duphorn (1983, 1986) correlated the preglacial gravels of Gorleben with the gravels of Loosen in southwestern Mecklenburg. Bülow (1969) reported several occurrences of these gravels situated approx. 15 km to 25 km northeast of the study area. The gravels of Loosen, however, display significantly higher contents of feldspar and porphyry, which indicates a greater southern influence. In addition, they are from the Late Pliocene, according to Bülow (most recently 2000a).

Bavelian to Cromerian Complex

Except in the case of two boreholes, the beds of the Menapian are superposed by sediments of the Bavelian to Cromerian Complex. The llithological boundary is in some parts at the base of one- to several metre-thick fine sandy silts with a low content of plant residues. Just as often, the base is sandy and only characterised by the increased occurrence of approximately decimetre-thick, silty and humous, less often peaty layers. A stratigraphically reliable boundary can be set where the start of the Bavelian Interglacial sediments is proven by palynologicalal analysis.

Bavelian Complex

The sediments of the Bavelian Complex are subdivided into the beds of the Bavel and Leerdam Interglacials. In between and above are glacial deposits (Fig. 13). The average thickness of the bedding complex is 16.4 m, the drilling results varying between 3 m and 39 m (except for borehole GoHy 940 with 64 m).

The sediments of **both interglacials** were dated using palynological analysis on the cores of four boreholes (GoHy 600, 940, 1270, and 2227) (Müller 1986, 1992). Except for borehole GoHy 940/944, the thicknesses are mainly in the range of a few decimetres to 2.50 m maximum. The petrographic composition comprises a wide spectrum from silty clays via clayey silts to silty fine to medium sands with a recognisable proportion of organic matter up to layers of mud and peat.

The **glacial** sequence of strata is dominated by non-calcareous, quartzitic, highly fine sandy medium sands with low coarse sand content. Occasionally, coarse sandy or more coarse sandy and less fine gravelly to rarely medium gravelly zones are embedded (e.g. borehole GoHy 2227). The sands attain the greatest thicknesses of 29 m and 29.7 m in boreholes GoHy 530 and GoHy 2227 respectively. Layers of silt to silt mud some centimetres to decimetres thick, which partially contain organic matter, are often interstratified in the sands. Palynological analyses dated these single samples mostly as glacial, less often as pre-Elsterian Interglacial or interstadial deposits. These sequences were thus assigned to the Bavelian to Cromerian Complex.

Table 4: Petrographic composition of gravels of varying age (fraction 2-4 mm, values in percentage of pieces)

Borehole/depth [m]	**Preglacial debris composition**							**Glacial debris composition**				**Sample count**	**Age**
	quartz aggregates and siliceous sandstones	thereof smoky quartz aggregate	thereof amethystine quartz aggregate	**quartz single crystals and residual silica**	**feldspar,** mainly grey	**cherty limestone**	**touchstone**	**flint**	**crystalline**	**quartzite, sandstone**	**limestone**		
Shaft 1/ 153.3	11							14	37	31	6	1	Elsterian
GoHy 1231/ 130.7 – 130.8	26							3	54	6	11	1	Elsterian
Shaft 1/ 156.7 – 161.0	80	14	8	5	9		1					3	Bavelian- to Cromerian Complex to Menapian
GoHy 2227/ 123.2 – 129.6	81	13	6	8	9	0.5	0.5		1			6	Bavel Complex
GoHy 1231/ 158.6 – 159.3	84	9	6	6	9	1						1	Menapian
GoHy 1270/ 196.4 – 221.4	85	7	6	6.5	7.5	0.5	0.5					5	Menapian
GoHy 1171/ 344.7 – 358.0	86.5	11	7	5	7.5							4	in the caprock: Menapian to Bavelian Complex

The petrographic characteristics of the sands do not differ from those of the Menapian. Gravel analyses showed that the local accretions of gravel have a rather homogeneous composition (Table 4). They consist mostly of quartz and other silica varieties, which together make up approx. 90 %; among them are smoky quartz and amethystine quartz, typical for the kaolin sands, which account for a large fraction of approx. 15 % to 20 %. Compared to older Tertiary quartz sands, a characteristic feature is the content of mostly grey, opaque, often weathered feldspar (approx. 7 % to 10 %). Accessory components are siliceous limestones as well as rounded and polished flints of Nordic origin and touchstone of southern origin. For comparison, Table 4 also lists the gravel spectrum of the upper Elsterian age outwash, which is characterised by glacial Nordic components.

Cromerian Complex

Similar to the Bavelian Complex, the sequence consists of an alternating sequence of sand, silt, silt mud, and occasional peat, reflecting intense climatic changes. Using palynological analyses, Müller (1986, 1992) found a total of five interglacials within the Cromerian Complex. According to the analyses, the Cromerian Complex starts with Cromerian I, which is equivalent to the interglacial of Osterholz (Fig. 13). Biostratigraphic analyses showed several glacial-interglacial changes on top of each other in boreholes GoHy 600, GoHy 1270, and GoHy 2222.

The Cromerian sediments have thicknesses between 2 m and 24.5 m, the average thickness from 14 boreholes is 9 m. Compared to the older sediments of the Bavelian, the beds show an increase in silt and fine sand, while the structure is similar. An overview of the depths and thicknesses can be found in Table 5.

The most complete profile was found in borehole GoHy 1270. The lowermost eleven metres contain four layers of humous silt or sometimes peat of 0.4 m to 0.7 m thickness, which are separated by highly silty layers of fine sand of up to 4.5 m thickness. The four silt to peat horizons contain interglacial pollen spectra. According to Müller (1992), these are equivalents of the Osterholz, Hunteburg, and Cromerian III (Rosmalen?) Interglacials. The upper fourth horizon is older than the Bilshausen Interglacial and younger than Cromerian III. At the top of the preglacial sediments are 3-m thick humous silts and overlying weakly humous fine sands. These represent cool periods of the Cromerian Complex.

An analysis of heavy minerals from 72 mainly preglacial core samples was performed by Ronschke (1991). This was to test whether the biostratigraphic subdivision was reflected by the heavy minerals. In addition, the results of the gravel analyses and the heavy mineral analyses were compared. Samples were taken from the sandy sediments between the interglacial deposits. As with the results of the petrographic gravel analyses, the heavy minerals showed no significant differences between the Menapian and Cromerian sediments (Table 6).

In contrast to the sudden changes compared to the overlying Elsterian meltwater deposits (high content of hornblende) and the underlying Braunkohlensande of the Miocene (high content of metamorphic heavy minerals), the samples show only weak trends of lower zircon and tourmaline content in the sands of the Menapian Glacial, as well as a lower content of garnet, hornblende, and epidote in the sediments of the Bavelian to Cromerian Complex. Henningsen (1987, 2000) and Müller et al. (1988) concluded from numerous heavy mineral analyses that zircon and tourmaline are minerals that indicate “southern origin" (from the Central German Uplands and the Bohemian Massif), whilst garnet, hornblende and epidote are the main components of Nordic material (of Fennoscandian origin). Thus, the analyses indicate a predominant supply of Nordic material during the preglacial age, with slightly increased addition of southern material during the Bavelian to Cromerian Complex.

Table 5: Base depths [m below sea level] and thicknesses [m] of the preglacial sediments per interglacial episode

GoHy bore-hole	Cromerian Complex					Bavel Complex	
	Bilshausen interglacial	unnamed interglacial	Rosmalen interglacial	Hunteburg interglacial	Osterholz interglacial	Leerdam interglacial	Bavel interglacial
600	–	–	–	118.6/1.2	120.8/1.7	123.9/0.3	124.8/0.4
940	165.1/5.0	–	–	–	–	212.1/9.0	229.1/8.0
1270	–	148.4/0.4	153.6/0.7	155.5/0.6	156.9/0.4	158.7/0.2	160.8/0.4
2222	–	–	132.3/1.8	134.7/1.0	136.6/1.3	–	–
2227	–	69.8/1.0	–	–	–	73.8/1.0	106.0/2.5

In order to supplement the biostratigraphic subdivision of the preglacial beds with precise time marks, paleomagnetic analyses, calibrated by absolute dating procedures, were performed. The objective was to test whether the boundary between the two paleomagnetic epochs "Brunhes" (normal) and "Matuyama" (inverted) – 780 000 years before the present day – could be determined (Fig. 13). The analyses were performed on cores of the boreholes GoHy 603 and GoHy 944 (Fromm 1994). In the first borehole, normal polarity prevailed down to and including the Hunteburg Interglacial; below this a probably inverted polarity (Osterholz Interglacial) is followed by definitely inverted polarity in the time of the Bavelian. In borehole GoHy 944, the evidence for the Jaramillo event in the lower section of the Bavelian Interglacial is of importance. Thus, a time interval between approx. 780 000 years and approx. 1 070 000 years (Fig. 13) before the present day was determined for the sedimentation processes of a part of the preglacial sediments in the Gorleben area. These results allow the interpretation of the subrosion rate during the Early to Middle Pleistocene (Chapter 8.2).

Table 6: Average content (values in percentage of pieces) of the heavy minerals in the preglacial sediments compared to overlying and underlying sediments (fraction 0.036- 0.25 mm; according to Ronschke 1991)

GoHy borehole	zircon	tourmaline	rutile	other stable heavy minerals	garnet	hornblende	epidote	metamorphic Heavy minerals	0ther heavy minerals	∑ garnet. horn-blende. epidote	Sample count	Age
603	6.0	2.0	1.0	4.0	23.0	36.0	21.0	4.0	3.0	80.0	1	Elsterian
2222	4.0	4.0	1.0	1.0	20.0	38.0	17.5	6.0	8.5	75.5	2	Elsterian
603	10.0	11.0	1.0	9.0	20.0	4.0	29.0	17.0	-	53.0	1	Cromerian Complex
1270	46.0	3.0	1.0	4.0	16.00	2.0	15.0	13.0	-	33.0	1	Cromerian Complex
2222	28.0	10.0	3.0	1.0	18.0	1.0	26.0	14.0	-	45.0	1	Cromerian Complex
64	13.0	6.0	3.0	6.0	17.0	19.0	29.0	6.0	1.0	64.0	1	Bavelian to Cromerian Complex
1231	18.7	8.3	4.3	6.7	23.3	4.0	17.0	15.3	2.5	54.3	3	Bavelian to Cromerian Complex
603	17.3	7.7	1.3	5.3	22.3	3.0	26.3	17.0	-	51.6	3	Bavelian Complex
2222	20.2	7.8	2.5	2.2	21.2	4.7	24.2	15.8	1.4	50.1	6	Bavelian Complex
2226	15.5	5.0	2.5	3.2	26.2	10.5	21.8	11.5	3.8	58.5	4	Bavelian Complex
2227	10.8	7.2	3.0	1.0	35.8	7.0	18.2	16.0	1.0	61.0	4	Bavelian Complex
64	4.0	4.0	1.0	3.0	37.0	14.0	15.0	17.0	4.0	66.0	1	Menapian
933	11.0	4.0	2.5	3.0	39.0	6.0	22.0	11.5	1.0	67.0	2	Menapian
1231	6.0	5.6	1.8	3.2	42.2	5.2	15.6	15.6	4.7	63.0	8	Menapian
1270	22.0	2.7	1.0	3.0	32.3	1.0	20.0	17.0	1.0	60.0	3	Menapian
2222	7.5	5.8	1.3	0.8	34.2	9.7	19.5	19.3	1.9	63.4	6	Menapian
2226	8.5	3.8	1.5	2.0	39.2	11.2	18.3	12.2	3.3	68.7	6	Menapian
43	16.2	6.2	1.8	3.5	31.0	0.8	1.5	34.0	4.9	33.3	4	Miocene, Brown Coal Sands

Preglacial age

From the start of the Bavelian Interglacial to the end of the Cromerian Complex and probably during the early part of the Elsterian Glaciation, limnic to fluvial conditions prevailed. Palynological analyses (Müller 1986) showed that muds, silt muds, and peat were deposited in relatively large and shallow perennial freshwater lakes (similar to the Steinhude and Dümmer lakes). This leads to the conclusion that, at the beginning of the Bavelian Interglacial, the ground surface in the wester central area of the Gorleben salt dome consisted of a barely depressed peneplain where the accumulation of sediments and the subrosion-induced subsidence of the lake bottom were in constant equilibrium until the end of the Cromerian Complex.

The exceptions are in the areas of boreholes GoHy 1171 and GoHy 940/944. In the former, sediments of the Bavelian and preglacial gravels were found in the cap rock at depths between 286.7 m and 368.3 m. This occurrence leads to the conclusion that preglacial sediments were originally also present above the northeastern part of the Gorleben salt dome.

Most probably, the ground in the area of the borehole collapsed during the Bavelian, and the preglacial sediments subsided and were preserved in the sinkhole. This is indicated by the following observations:

- The cap rock is very thick, having a thickness of approx. 92 m, and forms a depression in the salt table, which is probably linked to selective subrosion of the Stassfurt potash seam, which crops out in the immediate vicinity of the borehole.
- The anhydrite and gypsum rock is brecciated. Aggregates of jagged anhydrite and gypsum lumps in a clayey-sandy, sometimes muddy matrix occur at varying depths. The structure of the cap rock is atypical.

In the area of boreholes GoHy 940/944, sediments of the Menapian Glacial are significantly thinner and form a silty-sandy facies (subsidence material?). The area was thus a relative upland area during the Menapian Glacial and outside the actual subrosion depression of preglacial time. The thickness of the Bavelian deposits is uncharacteristic at 64 m. The probably subrosion-induced synsedimentary subsidence of the lake bottom was thus significantly larger at this point than in the adjacent western area. In addition, evidence for a salination of the deepest parts of the deposit and the simultaneous absence of shallow-water algae at the same depth indicate that this is the filling of a Bavelian-Interglacial sinkhole.

4.3.2 Elsterian Glaciation

During the Elsterian Glaciation, the Scandinavian ice sheet transgressed the study area for the first time and extended to the Central German Uplands. The glaciers brought a new, fresh (unweathered) component to the sediments (primarily Nordic crystalline, Palaeozoic limestone and flints), so these differ significantly from the older, preglacial and Tertiary deposits.

The sediments of the Elsterian Glaciation occur mainly in the deep Quaternary channels and above the southwestern area of the Gorleben–Rambow salt structure. They reach thicknesses of over 200 m, the maximum is 212.6 m in borehole GoHy 1110, and their lower part consists mainly of outwash sands. Locally, till is interstratified. The final part of the channel filling consists of fine-grained sediments of the Lauenburger-Ton-Komplex, which are partially superposed by upper Elsterian Glaciation outwash sands.

Advance sands

In front of the advancing glacier, outwash sands were deposited. On further advance of the ice, the glacier pushed across the advance sands and they were covered by the Elsterian ground moraine or eroded. Thus, the advance sands can only be discriminated from the younger Elsterian outwash sands where they were separated by the ground moraine. Where the ground moraine is absent, they cannot be distinguished from the upper glaciofluvial (outwash) sands.

The average thickness of the advance sands is 14.5 m. The thickness of the sediments is mostly between 5 m and 20 m, in a few boreholes over 30 m, and the maximum in one borehole (GoHy 10) is 65 m. The sediments were encountered in 51 boreholes. They mainly consist of medium sands with varying fractions of fine sands and coarse sands that are very weakly to weakly gravelly. Only few core samples of the sands exist, so grain-size analyses are only available from the depth range between 203 m and 219 m of borehole GoHy 663. There, the sediments are a silty fine sand that becomes medium sandy and weakly coarse-sandy towards the bottom.

Elsterian till

When the Elsterian age continental ice melted, it left the debris it had carried along as a ground moraine, which usually consists of an unsorted, calcareous cohesive mixture of all grain sizes, ranging from clay and silt through sand grains to gravel, as well as occasional debris of boulder size; this is called till.

The till was originally deposited in the whole area, but in present times it occurs only in major erosional remnants in the Quaternary channels and in some relicts northwest of the Gorleben–Rambow salt structure near Gorleben and Dünsche as well as southeast of the salt structure beneath the Höhbeck and near Lenzen. An occurrence in the Quaternary channel near Gartow has the largest areal extent.

In the study area, Elsterian till was encountered in 100 boreholes and in shafts Gorleben 1 and 2. Usually, only a compact bank was found, which was ascribed to the main ice advance of the Elsterian Glaciation. The Elsterian till reaches its greatest thickness of 72 m in borehole GoHy 130/133. The average thickness is 28 m. The base lies between 292 m below sea level and 47 m below sea level.

The till is from the same time period as the 40 to 50-m thick, relatively homogeneous lower ground moraine of the shaft profiles (Ludwig 1993). In both shafts, a layer of outwash sand with thicknesses of 31 m and 2 m respectively separates the till from a highly sandy till-like material (glacial sands) with thicknesses of 4 m and 7 m respectively. The properties of this sandy ground moraine resemble those of the younger Elsterian ground moraine found in the western Elbe-Weser triangle (Meyer 2000). Indicator stone and fine-gravel analyses do not reveal any distinction from the underlying main ground moraine. Whether the upper ground moraine corresponds to the second (younger) Elsterian ground moraine of Northern Germany cannot be determined based on present knowledge. This horizon was not found in the boreholes (washed over?).

In six core profiles, a 6 m to 12 m thick, sandy interbed splits the till into two banks of 3 m to 13 m thickness each. The stratigraphic record and the gamma ray log show the upper bank as mainly sandier than the lower bank. However, the upper till of these boreholes cannot be correlated with the upper, younger moraine of the shafts, as it lies below the outwash sand of the channels (Fig. 9, cross section B–B', boreholes GoHy 650, 860, and 970).

The petrography of the till reveals a grey to dark grey, weakly clayey, very weakly to weakly gravelly, calcareous silt to sand. Often, streaks and layers of sand and black-brown zones of altered material of the Miocene are embedded. Representative grain-size analyses are available from boreholes GoHy 193, GoHy 472, and GoHy 1542 (Table 7).

The stratigraphic classification of the till as Elsterian Glaciation is often confirmed by sediments of the Holsteinian Interglacial in the upper areas of the borehole profiles. For further confirmation of the lithostratigraphy, numerous fine-gravel analyses were performed on borehole samples and indicator stone counts were performed on material from the shafts Gorleben 1 and Gorleben 2. The spectra of the indicator stones are rather homogeneous and are closely scattered in the northwestern sector of the TGZ diagram ("theoretisches Geschiebezentrum", TGZ method – theoretical pebble stone centre). This exemplifies the general north-south oriented advance of the Elsterian ice sheet.

The method and extent of the gravel analyses can be found in KABEL & SCHRÖDER (1984) and KANTER (1997). The samples of Elsterian till mostly display a characteristic till spectrum that differs from ground moraines of the Saalian Glaciation. Typical features are a high content of flint and a relatively low fraction of Palaeozoic limestone.

Table 8 lists the average percentages of the rock classes from gravel analyses of Elsterian- and Saalian tills in order to illustrate the spread of the analysis results and their interpretation. The table shows that the till from the Elsterian Glaciation and younger Drenthe (Drenthe 2) advance exhibit a similar till spectrum. The same applies for the main Drenthe (Drenthe 1) and Warthe tills, which contain less flint and more Palaeozoic limestone compared to the two tills mentioned above. Thus, the reliable classification of single samples of glacial stratigraphic members based on the gravel spectrum alone is only partially possible. Relative depth and bedding correlation with other stratigraphic members (e.g. Holsteinian sediments dated by palynology) as well as an evaluation of profile sequences that encompass several lithostratigraphic units are necessary to confirm the classification of the sample.

Table 7: Grain-size composition (wt%) of the Elsterian till

GoHy borehole	Depth [m]	Clay	Silt	Fine sand	Medium sand	Coarse sand	Fine gravel	Medium gravel
193	191.0 – 193.0	27.2	18.1	20.0	24.4	9.3	2.5	0.5
472	111.0 – 111.3	28.4	20.0	16.3	20.5	7.1	2.7	5.0
1542	99.1 – 99.2	13.3	22.2	9.5	16.2	17.8	13.2	7.8

Table 8: Per cent fraction of the rock classes (percentage of pieces) of the Elsterian and Saalian tills according to gravel analyses of the 4.0-6.3-mm fraction

GoHy borehole	Depth [m below surface]	K	PK	TU	D	F	KK	S/Q	Q	Sample count
Warthe till										
130	8.0–9.0	38.3	30.2	3.4	2.3	5.7	0.7	18.1	1.3	1
260	36.0–48.0	38.4	32.5	1.3	0.5	8.4	0.5	16.1	2.0	4
600	30.0–39.0	41.0	27.0	1.4	1.7	4.9	0.2	18.5	5.2	2
610	41.8–54.0	48.5	27.5	0.5	1.9	2.7	1.7	13.7	3.5	2
1550	37.8–40.8	41.4	31.1	1.9	2.3	5.5	1.6	10.1	6.0	4
Drenthe(2) till										
130	65.0–85.0	39.4	14.5	0.6	0.1	16.6	0.4	23.3	5.0	6
600	65.7–81.0	39.3	17.6	1.5	–	13.5	2.2	22.4	3.4	3
610	67.5–84.0	45.3	21.8	2.2	–	12.4	1.8	15.7	0.3	3
1550	51.4–53.0	44.5	14.8	0.8	0.6	11.5	6.3	13.4	8.1	2
Drenthe(1) till										
70	64.0–137.0	41.5	34.3	1.2	0.7	4.8	0.3	15.9	1.1	3
610	77.0–105.0	45.0	23.3	1.2	–	8.1	1.3	19.3	1.9	2
1580	67.5–81.3	41.9	30.8	2.6	2.0	6.2	1.6	10.0	4.9	7
Elsterian till										
130	88.4–143.0	37.0	17.5	0.1	–	20.4	2.0	20.4	2.5	4
260	94.0–106.0	41.2	19.8	0.6	–	15.3	0.2	20.1	2.8	4
600	121.0–122.4	31.3	28.0	2.4	–	18.0	1.4	17.6	1.2	3
1550	176.7–185.2	45.8	15.2	0.8	0.1	14.0	0.7	11.5	12.0	4

K = Nordic crystalline rock

PK = Palaeozoic limestone

TU = Palaeozoic shale and siltstone

D = dolomite

F = flint

KK = Cretaceous limestone and residual fossils of chalk

S/Q = sandstone and quartzite, Q = quartz)

Outwash sands in the channels

The deep Quaternary channels, which are found all over Northern Germany and have been described numerous times, were formed during the melting phase of the Elsterian ice. Today, the majority of authors believe that these deep depressions are of subglacial, glacio-hydromechanic origin: Grube (1979) for the Hamburg area, Kuster & Meyer (1979) for northeastern Lower Saxony, Hönemann et al. (1995) for Northeastern Germany, and Eissmann (1975) for Central Germany.

Based on the sedimentary filling, the Gorleben channel (Fig. 14) was mainly formed by erosive meltwater. However, the presence of Elsterian till in subzones south of the Elbe and in the area of borehole GoHy 1550 indicates a simultaneous glacial erosion, which also impacted and modified the channel bottom in large areas of the Gartow channel.

The filling of the deepest parts of the Gorleben channel starts with sand (Fig. 9, cross section A–A', Fig. 10). First, gravelly medium to coarse sands were deposited in the lower part of the channel filling. Cobbles were occasionally embedded (borehole GoHy 1620) and lenses and blocks of till and glaciolacustrine silt were embedded relatively often, e.g. in boreholes GoHy 500 and GoHy 1170 (Pl. 1: Fig. 9, cross section A–A', Fig. 10, cross section B–B'). As the flow velocity decreased, the sand became more fine-grained, starting with deposits of medium sands, followed towards the top by weakly silty, sometimes silty fine sands.

Occasional lignitic silt fragments, local weakly micaceous material and layers of flood-accumulated lignite are reworked materials of the Miocene. Apart from these, the gravel fraction is dominated by Nordic gravel, as numerous debris analyses have shown. These also revealed that there are no significant differences between the till and the outwash sands concerning the composition of the gravel spectrum.

Cores of the sands are scarce, so only few grain-size analyses could be performed. Grain-size analyses over a longer core interval were carried out on samples from borehole GoHy 1534 (Table 9). The grain-size distribution illustrates the sedimentary development from gravelly coarse sand at the channel bottom to fine sandy medium sand in the upper part of the channel.

The filling of the deep channel sections happened directly after they were cut. The time when they were cut, whether during the ice advance or when the glacier disintegrated, cannot be determined. On the one hand, the advance sands mentioned above are present at the channel bottom; on the other hand, the Elsterian ground moraine is overlain by thick outwash sands. However, the till is mostly missing and only a continuous sand complex is present. Thus, the channel filling is heterogeneous, and was deposited partly before and partly after the ground moraine.

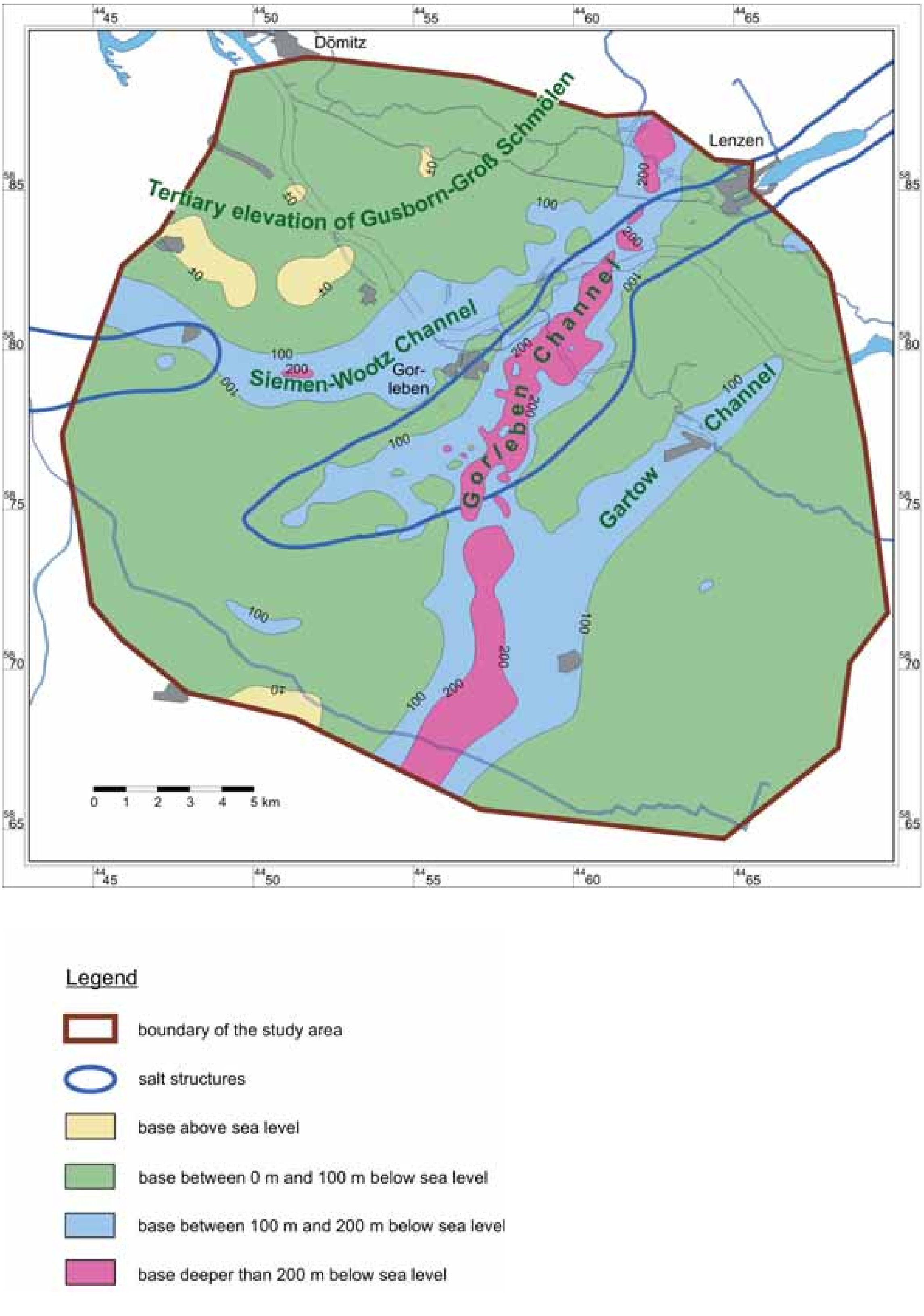


Figure 14: Depth contour of the Quaternary base and Quaternary channels

“Channel sands” were encountered in 105 boreholes, with thicknesses of 3 m to 108 m (borehole GoHy 1240). The thicknesses are mostly between 10 m and 50 m, the average is 32.4 m. The sands present a homogeneous sedimentary body that occurs almost throughout the whole area of the Gorleben channel and the Siemen–Wootz channel. Their base lies below 200 m below sea level in large areas of the Gorleben channel, the maximum depth is 283 m below sea level in borehole GoHy 1240 and the minimum is 58 m below sea level.

In areas where the flow was weaker, fine sandy clays and silts were embedded in the Elsterian channel sands, less so in the advance sands. They are of slight thickness (mostly approx. 2 m to 5 m, rarely more than 10 m) and areally less distributed.

Table 9: Grain-size composition (wt%) of the Elsterian outwash sands (“channel sands”) of borehole GoHy 1534

Depth [m]	Silt	Fine sand	Medium sand	Coarse sand	Fine gravel	Medium gravel
166.4 – 167.4	0.4	25.3	57.8	13.3	3.2	0.0
171.8 – 172.4	1.0	11.3	58.6	29.0	0.1	0.0
181.6 – 182.4	1.4	18.0	40.3	35.2	4.0	1.1
183.6 – 184.4	0.6	3.6	22.5	44.5	14.5	14.3
186.4 – 187.4	1.0	3.7	12.9	36.3	32.2	13.9
197.4 – 198.4	0.5	5.9	24.5	52.3	14.1	2.7

Lauenburger-Ton-Komplex

As described above, the upper part of the channel sands becomes more and more fine-grained until the sediments turn to silts and clays. This sequence is called Lauenburger Ton after the town of Lauenburg due to its typical occurrence in the lower Elbe area, and it is limited to the channel structures. In parts, the Lauenburger Ton occurs in compact homogeneous form as thick clay/silt packages, in other parts it is characterised by rapid lateral and vertical changes between clay, silt, and sand in the facies. Kuster & Meyer (1979) thus coined the term “Lauenburger-Ton-Komplex” (Lauenburg Clay Complex).

Examples of the relatively homogeneous clay-silt basin facies were found in boreholes GoHy 2321 and 2328 (Pl. 1: Fig. 9, cross section A–A’) where massive clay silt sequences with a low fine sand fraction were formed, with a thickness of 122.5 m and 117 m respectively. The beds are mostly dark grey, often also dark brown-grey, due to reworked lignite that occurs finely dispersed and in small fragments. Occasionally a small fraction of mica also occurs. The sediments differ significantly from the Hamburg-Ton of the Lower Miocene, as they generally contain calcium carbonate. Similarly compact bedding was encountered in borehole GoHy 1710, where a monotonous sequence of olive-grey to dark grey, silty, unctuous clay and to a lesser extent clayey silts with a thickness of 127.5 m were deposited. Only rarely, millimetre-thick layers or smears and streaks of fine sand occur. This massive compact bed is interrupted by two highly silty fine sand horizons of 1.6 m and 5.5 m thickness. The lowermost 18.0 m of the borehole consist exclusively of brown-grey to black-brown, clayey and fine sandy, carbonaceous, non-calcareous silts that were reworked from the Hamburg-Ton and were redeposited without any significant Nordic additions or embedded en bloc.

Often, more structured profiles occur, with multiple alternations between glaciolimnic fine sandy clays to silts and sandy gravelly outwash deposits, less often till. This last item should be interpreted as relocated and slipped ground moraines and as drop and drift moraines, which formed when the continental ice melted. These multiple changes in the course of the Gorleben channel between boreholes GoHy 1200 and GoHy 650 are illustrated in Figure 9 (cross section B–B’). Locally, up to four fine to medium sand packages of 3 m to 20 m thickness are embedded in the sequence (e.g. boreholes GoHy 555 and GoHy 1510).

The drilling results of location GoHy 1620 show how much the beds also vary in their apparent thickness. In the three boreholes GoHy 1620, 1622, and 1623, which cover a distance of about 11 m, the apparent thickness of one fine sand layer varies between 5 m and 13 m. This spatial configuration of the sequence explains the dip of beds of 45° to 75°, which was observed in cored borehole GoHy 1623, above and below the fine sand layer. On the whole, the dipping beds, faulting of mm-thin layers by several centimetres as well as bending, folding, and crumpling of layers, which were encountered in cores of the boreholes GoHy 1553/54 and GoHy 1623, indicate submarine slumping and melting processes of buried dead ice rather than compression. This interpretation is confirmed by the superposition of an undisturbed sedimentary sequence of the Holsteinian Interglacial in both drilling profiles.

The marked changes in clay, silt, and sand content are registered in the grain-size analyses that were performed on sediments of the Lauenburger-Ton-Komplex from various depths (Table 10).

Table 10: Grain-size composition (wt%) of the Lauenburger-Ton-Komplex

GoHy bore-hole	Depth [m]	Clay	Silt	Fine sand	Medium sand	Coarse sand	Fine gravel	Medium gravel
472	80.0 – 80.2	48.0	52.0	-	-	-	-	
472	81.5 – 81.7	36.2	49.8	15.2	0.8	-	-	-
472	84.9 – 85.6	58.5	29.7	9.3	1.3	1.2	-	-
514	181.6 – 181.7	68.3	28.4	3.3	-	-	-	-
514	182.9 – 183.0	19.9	10.1	35.3	31.2	3.3	0.3	-
514	184.9 – 185.0	61.4	38.6	-	-	-	-	-
553	140.8 – 142.0	26.2	32.3	16.8	9.2	8.7	3.4	3.4
632	87.0 – 87.2	-	9.8	83.4	6.8	-	-	-
632	89.2 – 89.3	4.7	18.6	70.7	3.5	1.5	1.0	-
721	90.0 – 90.2	40.5	53.2	6.3	-	-	-	-
721	93.5 – 93.7	23.2	22.1	20.9	24.4	8.6	1.8	-
721	94.3 – 94.5	47.3	35.9	4.9	5.4	4.7	1.8	-
1553	82.3 – 82.4	29.1	30.1	9.3	16.8	14.0	0.7	-
1553	88.9 – 89.0	39.0	27.0	12.8	8.0	10.4	2.8	-
1553	99.2 – 99.3	-	2.9	78.1	16.4	2.6	-	-
1553	108.0 – 108.1	28.7	20.8	12.1	10.7	24.7	3.0	-
1554	111.1 – 111.2	-	8.4	66.3	10.6	4.7	-	-
1554	112.5 – 112.9	26.2	23.1	7.9	9.4	17.0	9.0	7.4
1554	122.9 – 123.3	23.2	26.4	9.7	14.3	19.9	7.4	-
1554	144.7 – 144.8	-	8.8	73.0	15.0	2.9	0.3	-

A series of grain-size analyses were performed on cores taken from boreholes GoHy 1553/54. The clay/silt packages are dominated by the two sediments with fractions of 49 % to 64 %. The fine sand layers are very homogeneous, the fine sand content ranges from 66 % to 78 %. The clearly recognisable medium to coarse-sand content and the fine-gravel content in the clayey-silty areas are particularly noteworthy. Apart from the contamination with coarse material (drill cuttings?) that was clearly identified when the samples were taken after the field mapping, the genuine gravel components were also identified with certainty. They are likely to be dropstones and layers of glacial drift, caused by slumping and transport by ice floes. The content of coarser material in the sample from between 107.9 m and 108.3 m is confirmed by a peak of 2.2 g/cm^3 to 2.4 g/cm^3 in the density curve (gamma ray log).

The cored sections of measuring station boreholes GoHy 1553/54 and GoHy 1623 showed a varved deposition of alternating darker clayey-silty and brighter silty fine sandy millimetre-thick layers at irregular intervals in the clay/silt parts. Mostly, however, this layering can only be recognised in larger intervals by centimetre-thick fine sandy layers and streaks.

In some spots, the clayey/silty sediments of the Lauenburger-Ton-Komplex lie directly on top of the Hamburg-Ton. In these cases, it is somewhat difficult to distinguish the two stratigraphic units by description of the beds, due to acquired material of the Lower Miocene (mica content, dark brown colour, some weakly carbonaceous areas). The density log, however, reveals values for the Hamburg-Ton strata that are significantly below 2.0 g/cm^3, due to the higher content of organic matter, while the density values are higher for the Lauenburger-Ton.

The gamma ray log of the Lauenburger-Ton-Komplex displays relatively steady maxima of about 100 API, intersected by minima of 25 API to 50 API, which are caused by the fine sand layers mentioned above. The difference between the gamma ray logs of the Lauenburger Ton and the Hamburg-Ton is most obvious in boreholes GoHy 1260, 1550, and 1620 and GoHy 9002, 9003, and 1700 respectively. Compared to the curve of the Lauenburger Ton, the curve of the Hamburg-Ton is more clearly structured due to the frequent change of facies described in Chapter 4.2.4.

The sediments of the Lauenburger-Ton-Komplex were penetrated in 172 boreholes, where they showed thicknesses between 3 m and 149 m (GoHy 550). The thicknesses are distributed over a wide spectrum, showing maxima between 5 m and 25 m at the edges of the channels and between 50 m and 90 m (an average of 56.7 m) in the centres. The sediments are present as complex sedimentary units throughout the Gorleben channel and the channels of Siemen–Wootz and Gartow. Their bases are at depths between 150 m and 200 m below sea level in large areas of the Gorleben channel, the maximum depth is 205.8 m below sea level in borehole GoHy 1302 and the minimum is 42 m below sea level. In the two shallower channels, the bottom surface drops from approx. 50 m to 60 m below sea level in the outer areas to approx. 130 m to 160 m below sea level in the central areas.

On the whole, the sediments of the Lauenburger-Ton-Komplex form the dominant deposits of the Elsterian Glaciation with respect to thickness and extent, the outwash sands of the channels being in second place.

Upper Elsterian outwash sands (retreat sands)

Between the sediments of the Holsteinian Interglacial and the deposits of the Lauenburger-Ton-Komplex, there are sandy formations in some places that are interpreted as retreat sands of the Elsterian Glaciation. The most frequent occurrences of these outwash sands are above the central part of the Gorleben salt dome in the Quaternary channel and in the Elsterian till, in places where the preglacial sediments occur (Pl. 1: Fig. 9, cross section B–B'). Furthermore, these sands occur in wide areas of the Gorleben channel south of the Gorleben–Rambow salt structure and in the Gartow channel.

Petrographically, they are weakly coarse sandy to coarse sandy, occasionally to weakly gravelly fine to medium sands of normal outwash sand facies. Sometimes coarser parts and less often coarse sands occur. No grain-size analyses are available of these deposits.

The retreat sands were encountered in 78 boreholes, showing thicknesses of up to 50 m (20.1 m on average) except for one borehole (GoHy 1304: 76 m). It is of note that greater thicknesses of 40 m to 50 m are more frequent in areas of deep-lying Holsteinian sediments (boreholes GoHy 1301 to 1305) or proven preglacial subrosion (boreholes GoHy 1170 and GoHy 940). The depth of the base displays considerable variation, between 140 m below sea level in central areas of the Gorleben channel and 28 m below sea level on the edges.

4.3.3 Holsteinian Interglacial

The sedimentary sequences of the Holsteinian Interglacial are very conspicuous due to their greenish colour and sections of fossil content. They are thus an important marker bed for the subdivision of the glacial sequences, especially for the distinction of the glacial deposits of the Elsterian and the Saalian Glaciation. They occur relatively often in Northern Germany.

In the study area, the occurrence of the Holsteinian Interglacial deposits is largely limited to the Gorleben channel. When the Elsterian ice melted, it left a heterogeneous landscape with residual bodies of water of diverse depths, hollows, and buried blocks of dead ice. On top of this landscape, the Holsteinian sedimentary sequence developed either continuously or with a temporal hiatus, depending on local hydrologic conditions, on top of the deposits of the Lauenburger-Ton-Komplex or the glaciofluvial retreat sands of the Elsterian Glaciation. Some deposits contain an almost complete pollen sequence from the beginning to the end of the interglacial. It is of particular importance to the paleogeographic development that a last marine transgression reached the study area approximately at the time of the climatic optimum of the Holsteinian Interglacial. This transgression originated from the Lower Elbe area and expanded towards south-western Mecklenburg, eastern Lower Saxony, and to a lesser extent to Saxony-Anhalt and northwestern Brandenburg.

Sediments from the Holsteinian Interglacial were encountered in 97 boreholes, with thicknesses between 2 m and 33 m (borehole GoHy 1251). The thicknesses are mostly between 3 m and 10 m, the average is 11 m. The occurrences, depths, and thicknesses of the layers are shown in Figure 15 and Figure 16 on Plate 2.

The deposits of the Holsteinian Interglacial consist mostly of conspicuously olive-green to dark olive-green, mostly non-calcareous, in layers humous, highly clayey silts. Sections of silty muds and decimetre-thick layers of peat occur, and sometimes the beds are weakly micaceous and/or contain shells and organic matter. Rarely, thin fine sand layers were found. In some boreholes, fine to medium sand layers of up to a few metres thickness were embedded. Palynological analyses of numerous samples (511) revealed that the described petrography mainly represents the middle to upper part of the Holsteinian Interglacial sedimentary sequence.

The history of the Holsteinian Interglacial can be divided into three sections, due to the brackish-marine transgression of the Holsteinian Sea that occurred during the Middle Holsteinian Interglacial. The comprehensive palynological analyses showed that the distribution and thickness of the sediments are rather different in the three sections.

Two division methods were used in the palynological analyses of the samples: The division according to Meyer (1974) and Müller (1974), which is obligatory for Lower Saxony, and the division according to Erd (1973), which is commonly used in Eastern Germany. The last one was used due to the good comparability with profiles of neighbouring areas in Mecklenburg and Brandenburg. Figure 17 shows the correlation of the two divisions. The interval of brackish-marine impact is highlighted in yellow.

The sediments of the **Early Holsteinian Interglacial** (before the marine transgression) were found only in few boreholes, ten times in undisturbed bedding, twice in a compressed position. In the study area Gorleben-Süd, the occurrence was evidenced exclusively by discrete samples and no precise thickness information is available. The analyses of continuous core intervals of two boreholes in the Dömitz-Lenzen study area (GoHy 1553 and GoHy 1623) revealed a continuously limnic sedimentation in the residual channel waters that have been in existence since the Late Elsterian Glaciation (Strahl & Zwirner 2002). In both boreholes, which are situated in the Gorleben channel northwest of the salt structure, the transition from Lauenburger-Ton-Komplex to Holsteinian Interglacial is gradual. The clay content decreases in favour of silt content, and organic matter in the form of streaks, smears and layers is increasingly embedded. The boundary between the two stratigraphic units could not be defined by core inspection, but was defined by palynological analysis instead. The 2.5 m to 4.3 m thick, weakly fine to medium sandy,

Pollen zones and their duration according to MEYER (1974) and MÜLLER (1974) *(Lower Saxony - former West Germany)*			Pollen zones according to ERD (1973) *(former GDR)*	
500 – 1000 a	XIV	pine age	7	herb, alder, pine, birch age
1000 – 1500 a	XIII	age of oak and alder decline *(Pterocarya, Celtis)*	6	(pine, alder) fir age *(Pterocarya)*
3000 – 4000 a	XII	oak and fir (pine, alder) age		
300 – 500 a	XI	late pine/birch advance	5	(pine, alder) hornbeam, fir age *(Celtis)*
1600 a	X	hornbeam (alder, pine) age		
≥1000 a	IX	hazel, spruce (alder, pine) age	4	(pine, alder) hornbeam, hazel age
200 – 400 a	VIII	early pine/birch advance		
2500 a	VII	yew, hazel, spruce (pine, alder) age	3	(pine, alder) spruce, yew, hazel, oak age
1500 – 2000 a	VI	spruce, alder (pine, birch) age		
1000 a	V	elm, pine age	2	pine, alder, birch, spruce age
600 a	IV	pine, birch age		
500 a	III	birch, pine age	1	pine, birch age
500 – 1000 a	II	birch age		
late Elsterian Glaciation	I	early reforestation phase		

Figure 17: Correlation of the palynologicalal divisions of the Holsteinian Interglacial (highlighted in yellow: period of brackish marine influence)

occasionally coarse sandy silts and silty muds, which follow above the Lauenburger-Ton-Komplex, are calcareous, contain fossils (gastropods, pelecypods and ostracods) and smears and layers of organic matter (e.g. vessel residues of up to 5 cm in length). Some sections emit a smell of H_2S. The colours vary between dark olive-grey, sometimes bluish-grey, and light olive-grey. The sediments were deposited in deep waters, as the content of algal flora that is indicative of shallow waters (various species of *Pediastrum*) is very low compared to the content found in the younger Holsteinian sediments.

The **interval of brackish-marine impact** north of the Elbe starts in the upper part of pollen zone 3. During this pollen zone, the transgression of the Holsteinian Sea from the area of the Lower Elbe to the study area started, with the deep Elsterian age Gorleben channel evidently acting as a transgression channel. Marine medium sands, alternating between fine and coarse sandy, (GoHy 1623) or silty, medium sandy fine sands were deposited (GoHy 1553). The sands in borehole GoHy 1623 frequently contain shells of *Cardium* and thick-shelled hinge and shell fragments of other marine pelecypods. Marine sedimentation continued into the younger section of pollen zone 5. The greatest thickness of the sands of 7.0 m was encountered in borehole GoHy 1623.

South of the Elbe, the oldest evidence of marine Holsteinian was contemporaneous with pollen zone VIII in borehole GoHy 642 northeast of Gorleben. Additional evidence of beginning marine conditions is scarce and cannot be found beyond the area southeast of Gorleben (boreholes GoHy 840 and GoHy 1160). Not until the middle of the pollen zone XII were large areas of the Gorleben channel and its continuation south of the salt structure flooded, due to the extensive transgressive rise of the seawaters. Clayey olive-green silts were deposited, with local intercalations of fine and medium sands. Beside the marine facies indicators (marine dinoflagellates, shell fragments), freshwater algae and considerable amounts of sporomorphs can be found in the sediments. Also, some boreholes (e.g. GoHy 1210) show changes in the sedimentary conditions within pollen zone XII, and clayey silts of limnic, brackish, and marine origins lie more or less on the same level, tightly spaced on top of and next to each other. Thus, the sediments must be near-shore formations that were deposited under the influence of freshwater as well as ocean water.

Palynological analysis found the layers of brackish to marine origin in 43 boreholes, 37 of which contained only the upper part that was deposited during pollen zone XII. In the study area Gorleben-Süd, the occurrence was generally evidenced by spot samples and not by major core sequences so no precise thickness information on the marine sediments is available. Compared to the results of the Dömitz-Lenzen study area and the palynological analyses of samples from borehole GoHy 1251, the thicknesses should reach approx. 7 m to 12 m.

During the interval **after the transgression of the Holsteinian Sea**, a progressive formation of perennial shallow waters occurred in the upper part of pollen zones XII and 5 (Fig. 17), as the waters of the Holsteinian Sea retreated. When this happened, previously peripheral areas of the Gorleben channel and sections of the Gartow channel (boreholes GoHy 470 and 1540) were included in the sedimentation area. Silty muds and silts with characteristics similar to those described above for the other intervals were deposited. The beds are alternatingly fine sandy, mostly non-calcareous, in some parts layered, and often contain layers, smears, and streaks of organic matter. Vivianite stains occur frequently. Limnic conditions are indicated by embedded shells of *Valvata piscinalis* and lids of *Bithynia tentaculata* as well as shells of freshwater ostracods (boreholes GoHy 1553 and 1623). The deposits of this interval have the greatest thicknesses within the Holsteinian sedimentary sequence, in some parts 15 m to 18 m, and the widest distribution. They were found by palynological analyses in 54 boreholes. Figure 18 compares the thicknesses of the sediments of the three intervals and the pollen zones. It must be noted that the boreholes GoHy 1553 and GoHy 1623 underwent detailed analyses with sampling intervals of 10 cm, compared to five and ten discrete samples in boreholes GoHy 200 and GoHy 1251 respectively.

Sedimentological analyses were performed on samples from boreholes GoHy 1542 and GoHy 1623, and one grain-size analysis each on boreholes GoHy 542 and GoHy 1261. Table 11 summarises the results of the sedimentological analyses for the sediments of the Holsteinian Interglacial and Fuhne Glacial. The grain-size analysis of the Holsteinian Interglacial revealed a comparatively uniform character of the silts and silty muds with a pelite content of over 80 %. The content of organic carbon remains relatively small; the average of nine samples is 3.4 % TOC, with a variation between 2.9 % and 4.1 % TOC. In borehole GoHy 1623, the analyses of calcium carbonate content produced average values of 2.1 % for the zone above the marine sands, 3.5 % for the marine sands, and up to 16.3 % for the underlying calcareous silts and muds.

The base of the Holsteinian Interglacial beds displays large depth variation. These differences in the depth of the bottom surface were caused by the relief of the sedimentation area at the beginning of the Holsteinian Interglacial, subsidence of the underlying sediments, synsedimentary deepening, glacigenic dislocation during the Saalian Glaciation or synsedimentary to postsedimentary subrosion. The greatest depths are above the central part of the Gorleben salt dome in an area called “Weißes Moor”. In this area, the base of the Holsteinian sediments sinks below 120 m below sea level (137 m below sea level maximum, borehole GoHy 840). In the majority of the boreholes, the depth of the bottom surface varied between 25 m and 60 m below sea level. The uppermost base depth that was not impacted by glacigenic compression (see below) was 20.8 m below

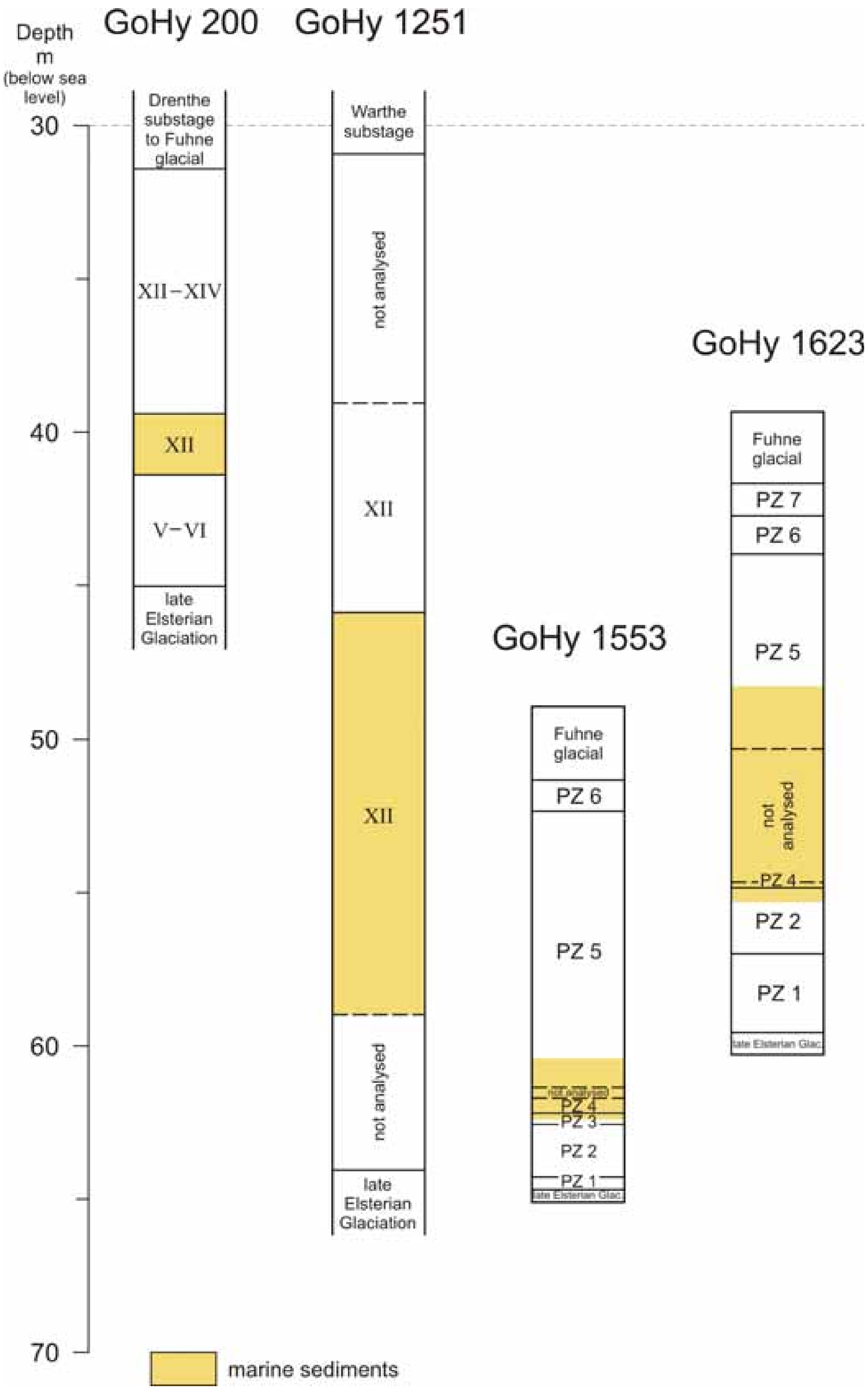


Figure 18: Thickness of the Holsteinian deposits and detected pollen zones

Table 11: Grain-size composition (wt%), $CaCO_3$ and C_{org} content [wt%, sample count in brackets] of the Holstein Interglacial and Fuhne Glacial sediments

GoHy borehole	Depth [m below survace]	Grain-size distribution [%]							$CaCO_3$ content	C_{org}- content	Stratigraphy
		C	S	FS	MS	CS	FG	samples			
183	39.5 – 42.0	8.1	6.6	28.0	49.3	6.0	2.0	2	n.a.	n.a.	qsFN–qD1
642	60.2 – 61.5	7.5	15.3	28.2	44.5	4.5	0.0	2	n.a.	n.a.	qsFN–qD1
1542	23.60 – 26.65	0.0	1.1	46.4	47.9	4.3	0.3	2	n.a.	n.a.	qsFN(B)
1542	30.35 – 30.45	19.2	42.3	16.4	10.8	11.3	0.0	1	n.a.	0.88 (1)	qsFN(B)
1623	51.78 – 56.18	24.9	50.3	17.6	7.2	0.0	0.0	3	5.9 (4)	1.54 (4)	qsFN(B)
1542	32.30 – 32.40	47.6	32.7	6.9	6.5	6.3	0.0	1	n.a.	0.99 (1)	qsFN(A)
1623	57.78 – 60.05	16.8	73.4	3.8	4.6	1.4	0.0	2	2.2 (2)	1.41 (2)	qsFN(A)
1542	57.78 – 60.05	21.8	58.1	8.6	6.7	3.6	1.2	2	n.a.	3.02 (2)	qhol; PZ 5–7
1623	61.78 – 66.05	25.1	59.8	9.3	5.1	0.7	0.0	3	2.1 (6)	3.37 (6)	qhol; PZ 5–6
1623	67.78 – 72.05	0.0	1.4	22.9	67.8	7.2	0.7	3	3.5 (7)	n.a.	qhol; PZ 4–5
1623	73.78 – 78.05	25.6	56.8	9.1	6.7	1.8	0.0	3	16.3 (5)	n.a.	qhol; PZ 1–2
543	62.65 – 62.90	42.0	58.0	0.0	0.0	0.0	0.0	1	n.a.	n.a.	qhol: PZ XII
1261	86.00 – 89.50	12.4	87.6	0.0	0.0	0.0	0.0	1	0.0	4.13 (1)	qhol; PZ XII–XIII

Stratigraphic abbreviations:

qD1 = Saalian Glaciation, Drenthe 1 substage
qsFN (A or B) = Fuhne Glacial, substage A or B
qhol = Holstein InterGlacial
PZ = pollen zones
1–7 according to Erd (1973) or XII–XIII according to Meyer (1974) and Müller (1974)

n.a. = not analysed
petrographic abbreviations for Tables 11-14:
C = clay, S = silt, FS = fine sand, MS = medium sand, CS = coarse sand, FG = fine gravel, MG = medium gravel, GG = coarse gravel

sea level (borehole GE_2734). Beyond the limits of the Gorleben–Rambow salt structure, Holsteinian sediments were found only in a few boreholes, predominantly in the Gorleben channel northwest and southeast of the salt structure. Northwest of the Gorleben–Rambow salt structure, the average depth of the bottom surface is 66.4 m below sea level, the maximum is 91.8 m below sea level (borehole GoHy 1520). Southeast of the salt structure, the average depth is 38.4 m (maximum depth 52.2 m below sea level, borehole Brk Grs 6/61).

The surface of the Holsteinian beds became very complicated during the following Saalian Glaciation. In some locations, the Holsteinian sediments were eroded or glacitectonically compressed. Glacigenic deformation was found in 27 boreholes. Some profiles display multiple repetitions of the same pollen zone sequence (e.g. in borehole GoHy 1301); in other boreholes, the upper Holsteinian beds were truncated (e.g. borehole GoHy 1553).

4.3.4 Saalian Complex

Between the glacial sequences of the first Saalian ice advance and those of the Holsteinian Interglacial, the time interval of the Lower Saalian Complex is located, which comprises the beds of the Fuhne Glacial and the Dömitz Interglacial in the study area (Fig. 12).

Lower Saalian Complex

In the study area, only deposits of the Fuhne Glacial were found.

Towards the end of the Holsteinian Interglacial, not all sedimentation areas had silted up. In the remaining sedimentation areas, limnic and limnic-fluvial sedimentation continued without apparent major recession under the glacial conditions of the Early Saalian Glacial.

According to Erd (1973), the Fuhne Glacial is divided into

- Fuhne phase B
- Pritzwalk interstadial A/B
- Fuhne phase A

Evidence for continued sedimentation into the Early Saalian Glacial by means of coherent core sequences is only available from the area around Lenzen. The most complete record of sediments of the Fuhne Glacial is available from boreholes GoHy 1623 and GoHy 1542. In the area of borehole GoHy 1553, the transition from Fuhne phase A to Pritzwalk interstadial A/B is missing. Due to its slight thickness (0.2 m to 0.6 m) the

Pritzwalk interstadial A/B is only identified in a few palynologicalal samples per borehole and can not be established with certainty (Strahl & Zwirner 2002).

In boreholes GoHy 1542, 1553 and 1623, the silt sedimentation of the upper part of the Holsteinian Interglacial continues without any macroscopically recognisable lithological hiatus. During the Fuhne phase A, increasingly fine to medium clastic sediments were embedded, which led to alternatingly limnic-fluvial to fluvial sedimentation conditions. In the upper part of Fuhne phase B in boreholes GoHy 1542 and GoHy 1553, the sandy-fluvial facies with light grey to grey, quartz-rich, well-rounded, non-calcareous fine to medium sands prevail. Occasionally, thin green, non-calcareous clay-silt layers of only a few centimetres are interstratified. The sands have a thickness of 6.4 m (GoHy 1542) or 3.6 m (GoHy 1553) and are superposed by meltwater deposits of the Drenthe substage.

The sediments of the Fuhne Glacial mainly consist of weakly coarse sandy, in parts weakly gravelly fine to medium sands with thin interstratified non-calcareous, greenish clay to silt layers. In the lower parts, the sands are quartz-rich and non-calcareous; towards the top, the proportion of Nordic components increases significantly. Stratigraphic classification was based on the occurrence of the clay to silt layers mentioned above, several samples of which (boreholes GoHy 180, 190, 642, and 720) revealed pollen zones XV to XVII, which lie above the Holsteinian Interglacial. As the upper boundary to the overlying outwash sands of the Saalian Glaciation is gradual, the beds were mostly dated as Fuhne Glacial to the Drenthe substage of the Saalian Glaciation.

The results of the sedimentological analyses of the Fuhne Glacial deposits are listed in Table 11. The silts of Fuhne phase A display a grain-size spectrum similar to that of the bottom Holsteinian sediments but contain less organic carbon. In Fuhne phase B, the silts become significantly more sandy and towards the top of borehole GoHy 1542 they turn into a homogeneous fine to medium sand. The sands of the interval from the Fuhne Glacial to the Drenthe substage are coarser and less homogeneous.

Sediments of the Fuhne Glacial were found in 22 boreholes. Their occurrence is limited to areas containing Holsteinian deposits. They are irregularly distributed in the study area. The average thickness is 10.8 m (minimum 1.5 m, maximum 24 m). A slightly larger occurrence is situated near Lenzen.

Upper Saalian Complex (Saalian Glaciation in the narrower sense)

The glacial deposits of the Saalian Glaciation are the most widespread of the Quaternary beds. Compared to the Quaternary sediments described above, which are mostly bound to the Quaternary channels, they are present throughout almost the whole study area. They only crop out at the surface near the Elbe in the area of the push moraine of the Höhbeck and the Langendorfer Geest, and further south, in the edges of the Öring and Lemgow uplands.

During the Saalian Glaciation, the Scandinavian glaciers transgressed the study area three times. Two glacial advances belong to the Drenthe substage. Thus, two lithostratigraphic ground moraine horizons, and tills of the older (Main Drenthe) and of the younger Drenthe substage can be found. The subsequent Warthe substage, however, produced only one ground moraine. Between these banks of ground moraines, outwash sands and glaciolacustrine deposits are interstratified. The structure of the Saalian bedding complex as a whole is dominated by outwash sands. Ranked by thickness and distribution, the tills take second place. Glaciolacustrine deposits are interstratified relatively often.

Drenthe substage

The beds of the Drenthe substage were encountered in 356 boreholes, 299 of which were penetrated completely. The glacial sedimentary sequence is intricately structured, with multiple changes, caused by deposition and erosion, between outwash sands, glaciolacustrine deposits and tills, in combination with large variations in thickness and quick wedging-out of the beds. The base of the Drenthe deposits is very heterogeneous, as it is formed by the lithostratigraphically and petrographically most diverse sediments of the Drenthe substage. The greatest depth of the bottom surface is at 152.6 m below sea level in borehole GoHy 370. The average thickness of the Drenthe sequence is 47.2 m, the greatest thickness is 142 m (borehole GoHy 370). Only the two tills of the older and younger Drenthe phases could be clearly differentiated by pebble analyses.

Outwash sands were deposited in front of the advancing Drenthe glaciers, as with the Elsterian ice advance. Thus, both Drenthe advances began with widely spread advance sands. As the glaciers of the main Drenthe advance as well as the younger Drenthe glaciers ran over their advance sands, these are covered by till. This repeated sedimentary sequence, however, is the exception, as the ground moraine banks, which serve as marker beds, were partially destroyed again in large areas due to erosion and exaration within the Saalian Glacial age. Thus, the two outwash sands of the Drenthe substage often cannot be differentiated. They will be discussed as a single unit below.

The **outwash sands** at the bottom of the older Drenthe till (Drenthe 1 advance sands) can only be clearly identified where they were superposed by the Drenthe 1 ground moraine. This is the case in 41 boreholes. The sands are mostly fine to medium-grained, weakly coarse sandy to coarse sandy, very weakly gravelly and of grey, sometimes brownish-grey colour. In the case of larger thicknesses, zones of coarse sands and gravelly areas can be found. The calcium carbonate content and red feldspars prove the predominance of Nordic material. In some boreholes, the quartz content increases towards the bottom, which indicates a blending with fluvial sands of the Early Saalian Glacial or the Fuhne Glacial. The average thickness of the advance sands is 19.5 m. Maximum values of up to 57 m were recorded (borehole GoHy 3030). An area of larger thicknesses is situated in the area of the Höhbeck (e.g. boreholes GoHy 650 and GoHy 1070, Pl. 1: Fig. 9, cross section B–B').

As the intervening ground moraines are frequently missing or only one ground moraine was formed, most of the deposits of the Drenthe outwash sands cannot be ascribed directly to either the older or the younger Drenthe phase. They are thus called Drenthe outwash sands. Among the stratigraphic members of the Drenthe substage, these are the most widely distributed – they were found in 312 boreholes – and are most often located at the level between the two Drenthe ground moraines.

The Drenthe outwash sands are weakly calcareous to calcareous, alternatingly coarse sandy and in parts weakly gravelly, grey to brownish-grey fine to medium sands. The bedding is outlined by thin, weakly gravelly layers, in parts also by millimetre to centimetre-thick, dark grey to black-grey layers of flushed-in and relocated carbonaceous-silty material of the Miocene.

The average thickness of the outwash sands is 28.6 m. This is only of statistical value, more interesting is the enormous variation in thickness between 2 m and 129 m. This documents the complex structure and the frequently abrupt discontinuance of the sedimentary units. The greatest thicknesses of the sediments are located in the area of the Höhbeck (boreholes Hy 52_2934 = 128.7 m and Hy 65_2934 = 102 m) and its environs (boreholes Hy 53_2934 = 90.1 m and Hy 54_2934 = 95.2 m). There is a repeated change of fine to medium sands, medium sandy coarse sands, and weakly gravelly to gravelly coarse sands within these thick sand sequences. Occasionally, thin glaciolacustrine silt banks are interstratified. In the area southeast of Gorleben (Weißes Moor and environs), boreholes also revealed considerable thicknesses between 80 m and 124 m (borehole GoHy 840 Pl. 1: Fig. 9, cross section B–B'). In borehole GoHy 840, there is a glacigenically imbricated, 26 m thick package of Holstein-Ton (Holsteinian Clay) and Lauenburger Ton. This indicates that the great thicknesses of the Drenthe outwash sands were mainly caused by glaciotectonic imbrication and compression.

The base of the Drenthe outwash sands is at depths between 132 m below sea level and 35 m above sea level (boreholes GoHy 840 and Hy 75_2934 respectively).

In some spots, **glaciolacustrine silts and clays** are interstratified in the glaciofluvial deposits. They occur sporadically and their thickness (20 m on average) is significantly smaller compared to that of the glaciofluvial deposits. The glaciolacustrine silts and clays are divided into many individual units. They are mainly located between the two Drenthe ground moraines, sometimes also above the younger one and less often below the lower one. The glaciolacustrine deposits were found in 129 boreholes. Like the other Drenthe sediments, they display considerable variation in thickness. The greatest thicknesses were encountered in the Saalian compression complex of the Höhbeck (boreholes Hy 76_2934 = 111.7 m and Hy 88_2934 = 98 m). These are multiple alternating sequences of fine sandy silts and silty clays. In borehole Hy 88_2934, one 10.5 m thick and one 7.5 m thick layer of medium- to coarse-grained glaciofluvial deposits are interstratified.

In most boreholes, the glaciolacustrine deposits are described as fine sandy to clayey, calcareous silts, less often silty clays. This corresponds to the results of the grain-size analyses. Sometimes, the silts to clays are layered in the millimetre to centimetre range, sometimes they have a uniform appearance. They are occasionally micaceous and are mostly light grey to grey compared to the darker silts and clays of the Lauenburger-Ton-Komplex.

The bottom of the glaciolacustrine silts and clays of the Drenthe substage is at depths between 102 m below sea level and 12 m above sea level (boreholes BKN 90 and IG 60_2933 respectively).

The **till of the older ground moraine** (**Drenthe 1**) was encountered in 122 boreholes. Originally, it had probably been present throughout the whole study area but was eroded in wide areas, as already indicated for the glaciofluvial deposits. Thus, the ground moraine is almost completely absent in areas where the Tertiary is at shallow depths. Large contiguous deposits are situated northwest and southeast of the Gorleben–Rambow salt structure, whilst only sporadic occurrences of limited extent can be found above the salt structure.

The grain-size composition is the typical blend of clay, silt, and sand with small to occasional additions of gravel. The sand fraction often dominates the composition. In boreholes GoHy 1563 and GoHy 1584, the till is described as a highly sandy, clayey silt with slight to low gravel content. Till of up to cobble size is rarely embedded. Locally, the till is very homogeneous, e.g. in the upper 14.5 m of borehole GoHy 1584 and in borehole GoHy 610. Frequently, however, blocks and lenses of acquired outwash sand, Lauenburger Ton, and material of the Hamburg-Ton are embedded. These can reach thicknesses in the range of decimetres to several metres. The colour changes from mainly brown-grey to dark grey, in parts dark brown-grey due to reworked Miocene sediments.

The lithostratigraphic classification was based on gravel analyses (chapter 4.3.2) taking the bedding conditions into account. The Drenthe 1 till contains a high proportion of Palaeozoic limestone and a very small proportion of flint (Table 8).

The thickness of the Drenthe 1 till is mostly between 1 m and 30 m (90 % of the boreholes). The average thickness is 17.3 m. Exceptionally large thicknesses of 104 m, 75 m, and 60 m were found in boreholes GoHy 370, GoHy 70, and Hy 87_2934, respectively. The base of the till displays great variation, between 4.5 m above sea level and 152.6 m below sea level, but is in large areas at around 60 m below sea level.

Above the glaciofluvial and glaciolacustrine deposits of the Drenthe substage, less often directly on top of the older Drenthe ground moraine, **Drenthe 2 till** follows. This sediment, which was encountered in 127 boreholes, is less thick and more sporadic than Drenthe 1 till. The distribution areas of the two till banks are partially similar. In 42 boreholes, both tills were encountered. In some areas, however, there were differences. Drenthe 2 till occurs more often above the Gorleben–Rambow salt structure, but it is missing in large areas towards the south, approximately from Trebel southwards and westwards.

In the normal facies, there are no macroscopic differences between Drenthe 1 till and Drenthe 2 till to be found in the petrographic structure. Drenthe 2 till is also a cohesive silt to sand with occasional gravels and rarely cobble-sized debris. In some spots, highly sandy sections up to single blocks of medium to coarse sand occur. Other places contain blocks of glaciolacustrine silts with thicknesses of several metres, e.g. in borehole GoHy 830. In other boreholes, the till contains some smears and some blocks of greenish clays and silts, which are indicative of incorporated Holsteinian sediments. In borehole GoHy 1563, a compact, up to 40 cm thick block or shingle of interglacial sediments is embedded in the base of the ground moraine. These silts are clayey, olive-green, non-calcareous and contain plant residues. Palynological analysis dated them as Holsteinian Interglacial, pollen zone 5. The presence of reworked Holsteinian sediments in the Drenthe 2 till, which was encountered in several boreholes, supports the interpretation that the frequent shingles and blocks of Holsteinian material inside the Drenthe sediments are correlated with the glacial advance of the younger Drenthe substage.

The lithostratigraphic classification of the Drenthe 2 till was again based on gravel analyses, taking the bedding conditions into account. The Drenthe 2 till is characterised by a higher proportion of flint and a lower proportion of Palaeozoic limestone compared to the older

Drenthe 1 till. Additionally, the proportion of limestone of the Upper Cretaceous is slightly increased in the Drenthe 2 ground moraines (cf. Meyer 1998).

The thickness of Drenthe 2 till is mostly between 1 m and 25 m. The average thickness is 15.3 m. Greater thicknesses of 52 m, 47 m, and 47 m were found in boreholes GoHy 130, GoHy 830, and GoHy 3050, respectively. The base of the till is between 26 m above sea level and 90 m below sea level. The occurrences above sea level are in boreholes on the geest uplands of the Höhbeck, Öring, and Lemgow. In wide areas, the base is between 20 m and 40 m below sea level and is thus approx. 30 m above that of the Drenthe 1 till.

Warthe substage

The sediments of the latest Saalian ice advance, the Warthe substage, lie above the beds of the Drenthe substage. The maximum extent of the Warthe continental glacier remained significantly behind that of the Elsterian and Drenthe ice advances. The glaciers of the Warthe substage advanced to some tens of kilometres beyond the study area and extended approximately to the edge of the Uelzen basin (Caspers et al. 1995). The sediments of the Warthe substage are not as widespread as those of the Drenthe substage, as large parts of their distribution area fell prey to erosion in the sandy valley plains. In the ranking of the extent of the sediments, the outwash sands come first, the ground moraine second, and the glaciolacustrine deposits lag far behind. The sequence of strata of the Warthe substage is very heterogeneous, similar to the Drenthe substage, with continuous vertical and lateral changes of sedimentary units. Frequently, only one bed of outwash sand or till was preserved.

The sediments of the Warthe substage were encountered in 296 boreholes, with an average thickness of 16.8 m (58 m maximum).

The drilling results revealed that the **outwash sands** are mainly weakly calcareous to calcareous medium sands with a smaller fine sand and greater coarse sand fraction; they rarely occur as medium sandy coarse sands. The gravel content is mostly low and alternates between very weakly gravelly and weakly gravelly. Occasionally, higher gravel content occurs. Due to the prominently Nordic spectrum of the material, the sands are light grey to multicoloured grey.

The outwash sands of the Warthe substage were found in 183 boreholes. The thicknesses are mostly between 5 m and 20 m, the average is 10 m, according to drilling results. The maximum thickness is 40 m (borehole GoHy 1750). Predominantly, only one sedimentary unit was found (119 boreholes), whose stratigraphic position could not be determined (advance or retreat sands) because the ground moraine was missing. In another

43 boreholes, the outwash sands of the Warthe substage overlie the Warthe ground moraine. This indicates that a major part of the outwash sands of the Warthe substage was deposited after the retreat of the Warthe glacier. In some parts, these sands are widely distributed underneath the sediments of the Lower Terraces (Pl. 1: Fig. 9, cross section A–A'; Fig. 10, cross section B–B'). Their top surface is relatively level, at a few metres above sea level. In addition to the dominating Nordic spectrum of the gravel content, quartz and milky quartz as southern components occur increasingly (approx. 5 % to 15 %) towards the top. Thus, it is highly probable that meltwater already drained through the Elbe ice-marginal valley of the Weichselian Glaciation in the late Warthe substage. MEYER (1983) had already arrived at the same conclusion with analyses on gravel samples of the Langendorfer Marsch, as had BUNDROCK & GROSS (1994), following supplementary debris analyses of GoHy boreholes.

The base of the sands is mainly on a level between 10 m above sea level and 15 m below sea level, but sinks locally to less than 40 m below sea level (boreholes GoHy 610 and GoHy 1750) and reaches heights of over 30 m and 40 m above sea level on the upland of the Höhbeck.

Grain-size analyses of the outwash sands of the Warthe substage are available from borehole groups GoHy 270 and GoHy 320. They are listed in Table 12 together with the other sediments of the Warthe substage.

In 60 boreholes, **glaciolacustrine silts and clays** were found that were dated as Warthe substage, based on the underlying Warthe ground moraine in 22 boreholes (e.g. GoHy 300, GoHy 350, GoHy 700, and GoHy 1550) and the geological situation in the close vicinity.

The stratigraphic records and the grain-size analyses of cored borehole s GoHy 352 and GoHy 1602 (cf. Table 12) revealed that the glaciolacustrine sediments are weakly to highly sandy, clayey, occasionally micaceous, calcareous to highly calcareous, grey to brownish-grey silts. The calcium carbonate content in borehole GoHy 1602 is 10.2 wt% to 12.8 wt%. The layering changes from millimetre to centimetre intervals. In some boreholes (GoHy 1520, 1770, 2424), the silts are more fine sandy and weakly clayey with larger layer intervals, or turn into silty to clayey fine sand in the upper sections (borehole GoHy 350). A highly sandy facies with highly fine sandy, weakly silty medium sands with millimetres thick clayey/silty layers was encountered in borehole GoQ 16.

The thicknesses are mostly between 3 m and 20 m (9.6 m on average). In seven boreholes, the thicknesses are greater, the maximum is 35 m (borehole GoHy 210).

The glaciolacustrine sediments of the Warthe substage are preserved in many irregularly scattered small to medium areas throughout the whole study area.

The **till** of the Warthe substage is about as widely distributed in the part of the study area south of the Elbe as the older ground moraines of the Drenthe substage. A nearly unbroken expanse extends from the area Dünsche-Gorleben across the salt dome into the area southeast of Prezelle-Gartow. Gaps due to erosion exist in the Gorleben channel. The Warthe till crops out at some spots in the upland areas. In large areas of the western part of the Höhbeck, it forms the surface as a so-called cover moraine.

The Warthe till was encountered in 150 boreholes. The thicknesses are mostly between 2 m and 30 m (16 m on average). Due to heavy erosion and weathering, only a few metres have remained on the Höhbeck. In parts, only a 2 m to 3 m thick cover of drift loam or only a thin blanket of drift cover sand is present. The greatest thickness of the Warthe till of 58 m was encountered in borehole GoHy 900, above the Groß Heide–Siemen salt dome.

The base is mainly between 10 m above and 10 m below sea level. Depending on the thickness of the bed, the bottom sinks to depths of 20 m to 40 m below sea level; the maximum is 52.5 m below sea level in borehole GoHy 900. In some spots on the Höhbeck upland, the bottom was encountered at more than 60 m above sea level (borehole Hy 88_2934).

The petrographic entries in the stratigraphical records and grain-size analyses (Table 12) show that the clay content of the Warthe till is higher than that of the ground moraines of the Drenthe substage. Thus, it is a clayey to highly clayey, weakly fine sandy to fine sandy, medium sandy, weakly coarse sandy to coarse sandy, very weakly gravelly to weakly gravelly calcareous silt of a grey to brownish-grey, in parts dark brown colour. The ground surface samples of the Höhbeck are also reported to have reddish-brown hues. The Warthe till occurs mainly as a compact bank. Occasionally, outwash sands or glaciolacustrine silts of up to 2 m thickness are embedded. Acquired blocks of older material are rare.

The gravel analyses showed that the Warthe till contains low proportions of flint and high proportions of Palaeozoic limestone and thus has a till spectrum similar to that of the Drenthe 1 till. In contrast to the latter, the Warthe till is supplemented by a noticeable fraction of dolomite, which rises to 8 % in some samples (KABEL & SCHRÖDER 1984).

An east-Baltic dominance as strong as reported for the adjoining area to the northwest (CASPERS et al. 1995; GAUGER & MEYER 1970) could not be identified. The results of the gravel analyses have already been listed in Table 8. As previously indicated, similar till spectra reoccur within the glacial sequence of strata (Elsterian till and Drenthe 2 till: rich in flint and poor in limestone; Drenthe 1 and Warthe till: less flint content and rich in limestone). Hence, the stratigraphic subdivision was never based on the results of the gravel analyses alone. It is an aid, but other criteria are also taken into account (biostratigraphic marker beds, assessment of multipartite profile sequences, bedding relations). For example, the samples of borehole GoHy 1553/1554, on which gravel analyses had been performed, were lithostratigraphically dated as belonging to the Warthe substage as a result of the classification of the underlying ground moraine as younger Drenthe substage, which in turn was based on the significantly lower content of Palaeozoic limestone and higher proportion of flint and Cretaceous limestone (Table 8). The lower Elsterian ground moraine is confirmed by biostratigraphic analyses of overlying Holsteinian deposits.

Table 12: Grain-size composition (wt%) of the outwash sand, glaciolacustrine deposits, and tills of the Warthe substage

GoHy borehole	Depth [m]	C	S	FS	MS	CS	FG	MG	Sample count	Genesis
271	29.0 – 30.0	0	2.4	5.3	82.3	8.3	1.7	0	2	outwash sands
271	31.0 – 32.0	0	2.3	13.2	55.1	27.9	1.5	0	2	
321	25.0 – 28.0	0	5.6	10.2	28.9	50.9	4.4	0	1	
352	19.2 – 19.3	23.2	22.2	51.9	1.6	1.1	0	0	1	glacio-lacustrine deposits
352	24.0 – 24.1	28.3	35.2	35.7	0.8	0	0	0	1	
1602	25.1 – 31.4	23.9	68.0	0.7	0.8	0.3	0	0	2	
301	14.0 – 15.0	19.2	30.1	16.4	20.1	10.4	3.8	0	1	till
352	53.0 – 53.1	30.6	26.6	7.4	14.7	7.6	7.3	4.8	1	
702	43.9 – 44.0	24.3	30.2	20.9	18.2	5.2	1.2	0	1	
1553	37.0 – 37.4	31.8	24.4	5.3	14.6	21.0	2.9		1	

4.3.5 Eemian Interglacial

The only sediments to be found of the Eemian Interglacial were in two boreholes beyond the limits of the Gorleben–Rambow salt structure. In borehole GoHy 620, palynological analysis dated a sample of fine sandy, 4 m thick silt that contained occasional organic matter as belonging to the Early Eemian Interglacial. The borehole probably penetrated a relict of a very limited local hollow because the measuring station boreholes in the vicinity did not penetrate this bed. The second occurrence is allochthonous debris within the sediments of the Lower Terraces in borehole GoHy 312.

4.3.6 Weichselian Glaciation

The last glaciation, the Weichselian Glaciation, lasted about 100 000 years. Only at the height of the glaciation, at approx. 15 000 to 20 000 years before the present day, did the Scandinavian continental ice cover Northern Germany. The glaciers did not advance beyond the Elbe. The outer edge was approx. 40 km northeast of the study area. Thus, glacial sediments are missing. In the periglacial environment, the mainly vegetationless area experienced erosion and relocation processes on the geest plateaus and the accretion of the Lower Terrace in the Elbe valley. According to Meyer (1983), the Elbe ice-marginal valley was created during the Warthe substage at the latest and was largely imprinted by drainage of Weichselian meltwater. In the study area, the Elbe ice-marginal valley has a width of 20 km to 25 km.

Glacial cover sand

On the uplands of the Höhbeck and the Langendorfer Geest and the geest areas reaching into the south of the study area, the Saalian till and outwash deposits are superposed by a thin layer (approx. 1 m) of glacial cover sand. Due to the former permafrost conditions, this product of congelifluction, scouring, and destratification consists mainly of heterogeneous sands with a varying gravel content. The main raw materials were probably weathered ground moraines of the Warthe and Drenthe stages, from which the fine-grained fraction had been scoured.

Lower Terraces

The sediments of the Lower Terraces are distributed throughout the whole study area with the exception of the geest uplands. In wide areas, they constitute the ground surface in the form of Weichselian sandy valley plains or lowland sands (Chapter 3.2, Fig. 5). The Lower Terrace consists of materials of Nordic and southern origin, which were brought in by meltwater of the Weichselian Glacial or waters of the Elbe and its southern tributaries.

According to the results of a great number of gravel analyses (>500) of boreholes of different exploration programmes (Duphorn 1980, 1983; Meyer 1983; Schröder 1988), the sands and gravels of the Lower Terrace are not to be viewed as a uniform sedimentary unit. There is a petrographic differentiation into an older (lower) and a younger (upper) Lower Terrace. Due to this bipartition, Duphorn (1983) referred to the deposited sequence conjointly as Lower Terrace Complex.

The older unit of the Lower Terrace contains a higher proportion of southern material (porphyry, touchstone and milky quartz) than the lower glacial sediments of the Saalian Glaciation. These materials were brought in by the Elbe and its southern tributaries when, after the melting of the continental ice of the Warthe substage, the upper course of the Elbe was connected to the present Elbe estuary (Ehlers 1978).

The stratigraphic differentiation of the Weichselian Lower Terrace sediments and the underlying Saalian sands proved to be difficult, due to the mixed petrographic facies of the sands and gravels of the Lower Terrace and especially due to the missing Eemian sediments. Only one borehole (GoHy 620) penetrated and biostratigraphically confirmed the autochthonous layers of the Eemian Interglacial. There, the Eemian beds lie under 32 m thick Lower Terrace sands. Underneath the Eemian beds, 4 m thick sands follow, which display no petrographic difference to the sands of the older Lower Terrace above. According to the investigations of Meyer (1983) and the debris analyses of Bundrock & Gross (1994), it must hence be concluded that lower sections (especially those that contain a significant amount of Palaeozoic limestone) of the older Lower Terrace may originate from the Warthe age.

The bulk of the Lower Terrace is certainly of Weichselian age. The older Lower Terrace was formed mainly during the Early Weichselian Glaciation, which was proven by evidence of thin Early- Weichselian silt layers below the younger Lower Terrace in borehole GoHy 902 and between the older and the younger Lower Terrace in borehole GoHy 1080.

During the height of the Weichselian Glaciation, the younger Lower Terrace was accumulated, which contains an even higher proportion of southern material (Duphorn 1983; Schröder 1988).

The sediments of the Lower Terrace consist of a weakly fine sandy, in parts fine sandy, weakly gravelly medium to coarse sand. The sands contain layers of fine and medium gravel, the gravel layers occurring more frequently towards the bottom. Occasionally, a coarse gravel layer containing cobbles was encountered at the bottom. In sections, the beds contain lignite and even alluvial layers of lignite of up to decimetre thickness. The sediments are usually free of humous components, plant matter, and silt or mud layers. On the whole, there is a tendency towards increased grain sizes with increasing depth. The upper 6 m of the younger Lower Terrace consist mainly of fine to medium sand. The grain-size analyses performed on core sequences from measuring station boreholes confirm the increasing coarseness towards the bottom that was described in the stratigraphical records (Table 13).

Table 13: Grain-size composition (wt%) of sands of the older (qN1) and younger (qN2) Lower Terrace

GoHy borehole	Depth [m]	C	S	FS	MS	CS	FG	MG	CG	Strati-graphy
172	3.5 – 3.55	0	16.1	77.1	4.6	1.2	1.0	0	0	qN2
172	4.95 – 5.00	0	51.8	44.9	2.3	1.0	0	0	0	qN2
172	6.50 – 6.55	0	2.4	81.2	14.6	1.8	0	0	0	qN2
172	9.00 – 9.05	0	1.0	11.6	79.1	7.4	0.9	0	0	qN2
172	9.95 – 10.00	0	2.5	22.9	68.2	6.1	0.3	0	0	qN2
172	10.95 – 11.00	0	0.8	15.1	38.8	29.6	13.9	1.8	2	qN2
142	6.25 – 6.38	0	1.0	21.3	74.9	2.8	0	0	0	qN2
392	5.20 – 5.25	0	0.5	3.6	77.1	17.6	1.2	0	0	qN2
392	14.30 – 14.40	0	2.2	3.2	24.9	44.9	17.6	6.7	0.5	qN1
392	15.00 – 16.00	0	3.3	2.4	2.4	10.4	53.1	27.9	0.5	qN1
392	17.40 – 17.45	0	3.7	3.9	35.8	39.5	12.4	4.7	0	qN1
392	17.60 – 17.65	17.8	6.9	45.8	27.6	1.9	0	0	0	qN1
392	18.30 – 18.35	0	3.8	1.5	9.4	22.8	11.1	22.9	28.5	qN1
142	18.70 – 18.90	0	9.5	4.2	10.5	17.6	22.5	33.4	2.3	qN1

Depending on thickness and bedding position, the sands and gravels of the older Lower Terrace are either calcareous (lower position) or non-calcareous (higher position). The colour of the sediments is mainly grey to multicoloured grey.

The younger unit of the Lower Terrace is generally non-calcareous. Only when it directly overlies older calcareous sediments can a calcium carbonate content be found in the lower part. The transition from the older to the younger Lower Terrace is often accompanied by a change in colour. The sands of the younger Lower Terrace are mainly brownish to brownish-multicoloured.

Sediments of the Lower Terrace were encountered in 400 boreholes. The average thickness is 15.9 m. The maximum thickness of 32 m was encountered in borehole GoHy 620 (above an occurrence of Eemian beds!). The average base depth is 2.9 m above sea level, the greatest depth is 14.9 m below sea level (borehole GoQ 14). Debris analyses of 166 boreholes revealed that the sediments of the older Lower Terrace are less thick than those of the younger Lower Terrace. Their average thickness is 7.6 m, the maximum thickness is 21.5 m. The average base depth is 0.8 m above sea level. The sediments of the younger Lower Terrace were encountered in 242 boreholes, their average thickness is 11.3 m. The base depth is correspondingly higher, on average 8.8 m above sea level.

Debris analyses

As mentioned above, the subdivision of the Lower Terrace into an older and a younger unit was based on comprehensive debris analyses, especially by Duphorn (1980, 1983) and Schröder (1988). Both units consist of a debris-petrographic blend of Nordic and southern components that can be assigned to four different types based on origin:

1. Nordic material from the meltwater of the Weichselian Glaciation
2. Nordic and southern material from old geest cores of the immediate and intermediate environs
3. Nordic material from the local subsoil of the study area
4. Southern material from the fluvial waters of the Elbe and its southern tributaries

The debris spectra of both Lower Terrace units are mostly dominated by Nordic rock. Other characteristic features are the polish, which is displayed by the flint, quartzite and porphyry specimens and the stronger weathering that are both indicative of relocated former surface material.

The fluvial sands and gravels of the **older Lower Terrace** contain a high proportion of southern components, in contrast to the underlying glacial sediments: porphyry up to 12 %, brown sandstones and quartzites up to 33 %, milky quartz up to 35%, and residual quartz up to 20 % (values according to Duphorn 1983).

In the gravel spectrum of the **younger Lower Terrace**, an even greater influence of southern components can be observed. The following maximum values were determined according to Duphorn (1983): Southern porphyry 23 %, brown sandstones and quartzites 59 %, milky quartz 46%, and residual quartz 27 %.

At first glance it may seem illogical that, despite the solely fluvial processes during the Early Weichselian Glaciation, the southern influence on the older Lower Terrace is weaker than in the fluvial/glaciofluvial environment at the height of the Weichselian stage, when the younger Lower Terrace was deposited. The larger proportion of Nordic material in the older unit is probably due to the fact that the uneven glacial relief had to be flattened at the beginning of the deposition of the Lower Terrace and thus more Nordic material was reworked. The increase in southern debris in the younger Lower Terrace can be explained by the intense solifluction during the height of the Weichselian Glaciation and the correlated increased load in the Elbe and its tributaries.

Aeolian sand

During the Late Weichselian Glaciation, starting approximately 14 500 years before the present, large parts of the Lower Terrace surface outside the Elbe floodplain were exposed until a complete vegetation cover formed in the Holocene. The wind could take full effect. Sand drifts, wind-scoured hollows, and stone plateaus were formed. South of the Elbe in the area of the Gartower Tannen (Fig. 4), a coherent area of aeolian sand was formed. Outside this area, the sandy valley plains were scattered with fields of aeolian sands.

The aeolian sands consist of uniform, mostly micaceous, non-calcareous fine to medium sands that seldom contain additions of silt and occasional coarse sand. The results of a grain-size analysis are listed in Table 14. The colour of the sands varies from light brown to yellowish to yellow-brown. The thickness of the aeolian sands is approx. 0.5 m to 2.0 m. In the area of the Gartower Tannen, the drifts can reach greater thicknesses.

Organogenic deposits

The warming during the late glaciation caused a more or less complete vegetation cover to form slowly. Drainless hollows in the surface of the Lower Terrace gradually silted up and locally muds and peat were formed. These were only encountered during the mapping of the Quaternary geology (DUPHORN 1980) and in shallow boreholes during earlier projects (LESEMANN 1969). Figure 19 provides an overview of the subdivision of the Late Weichselian Glaciation and the Holocene.

The greatest thickness of late-glacial muds was reported by LESEMANN (1969: 494 ff.) of a bog approx. 1 km southwest of Siemen. The bog was bore sounded in a north–south profile. The hollow is filled with a maximum of 9 metres of muds and peat. In the centre, there is a steep-walled basin that previously contained a lake. The shallower edges of the hollow contain only peat of the Holocene. In the interval from the Early Dryas to the Late Dryas, a clayey, occasionally sandy, fine-detrital mud of 5.9 m thickness was deposited in the centre of the hollow. According to palynological results, these lacustrine sediments must have accumulated very quickly. It is possible that the hollow is a result of subsidence. This is indicated by the shape (funnel-shaped sink) and by the fact that it is situated above the salt dome of Groß Heide–Siemen.

Table 14: Grain-size composition (wt%) of meadow sand, meadow loam, aeolian sand, and dune sand profiling excavation (Hennings & Duijnisveld 1997)

Profile no.	C	S	FS	MS	CS	Sample count	Depth [m]	Lithol. unit
10	1.6	3.1	43.8	51.3	0.1	3	0.5–1.1	floodplaine sand
11	3.7	6.3	18.7	69.8	1.5	3	0.4–1.5	floodplaine sand
14	1.6	1.6	29.0	66.6	1.2	1	0.4–1.3	floodplaine sand
12B	5.1	6.1	41.8	46.9	0.1	1	0.7–1.0	floodplaine sand
12B	46.8	40.4	7.8	3.2	1.7	2	0.3–0.7	floodplaine loam
8	57.8	36.4	3.6	1.9	0.4	3	0.3–1.1	floodplaine loam
12	63.1	27.4	7.1	2.0	0.4	3	0.4–1.0	floodplaine loam
2	1.1	1.5	48.2	49.0	0.2	2	1.0–1.4	aeolian sand
Klein Schmölen dune	0.0	0.0	19.4	78.5	2.1	2	ca. 0.5–1.5	dune

Another bog was described also by Lesemann (1969) near the valley floodplain of the Elbe, approx. 0.5 km southwest of Laase. The bog has an almost circular shape (200 m diameter) and originated from a silted-up lake. The thickness of the organogenic sediments is approx. 2 m. At the bottom, there is a dark brown, calcareous fine-detrital mud of 0.3 m thickness that becomes increasingly more sandy towards the bottom. The age of this mud was dated as Allerød to Early Dryas.

Duphorn (1980: 23) described further deposits of late-glacial muds. Two manual drillings in the zone of aeolian sands southwest of Gartow encountered thin muds below the sands at a depth of 2.2 m, which were dated by palynological analyses as Late Allerød to earliest Holocene. Near Kapern at the edge of the Elbe floodplain, a channel of late-glacial origin was penetrated (Duphorn 1980: 24), the bottom filling of which consists of fine to coarse detrital mud that was deposited during the Younger Dryas.

Age	Stratigraphy climatic subdivision					Pollen zones according to FIRBAS	Lithogenesis and petrography	
0.25	HOLOCENE			Sub-Atlantic	late	Xb	aeolian sand, dunes, floodplain sand, muds, peat	younger floodplain loam
						Xa		
0.8					early	IXb		
						IXa		
2.4				Subboreal	late	VIIIb		older floodplain loam
3.3					early	VIIIa		
5.7				Atlantic	late	VII		
					early	VI		
9.2				Boreal	late	Vb		
					early	Va		
10.6				Pre-Boreal		IV		
11.6	PLEISTOCENE	WEICHSELIAN GLACIATION	late Weichselian	Younger Dryas		III	aeolian sand, muds	
12.7				Allerød interstadial		II		
13.3				Older Dryas		Ic		
				Bölling interstadial		Ib		
				Oldest Dryas		Ia		
14.4			main Weichselian				glacial cover sand	younger Lower Terrace
25			early Weichselian					older Lower Terrace
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Figure 19: Stratigraphic subdivision of the Late Weichselian Glaciation and the Holocene (ages according to MERKT & MÜLLER 1999)

4.3.7 Holocene

The Holocene comprises the interval of the last 11 600 years (MERKT & MÜLLER 1999). In this interval, predominantly fluvial sediments, floodplain loam, and floodplain sand were deposited in the Elbe lowland. Muds and peat are less common in the silted-up areas and in the river valleys of the Löcknitz River and the Alte Elde River. The accumulation of aeolian sands, which started in the Late Weichselian Glacial, continued into the Holocene, and individual dunes and dune fields were formed, particularly at the edge between the Elbe floodplain and the Lower Terrace and on the aeolian sand blanket.

The description of the sequence of strata of the Holocene is based mainly on the reports of the mapping of the Quaternary geology (Chapter 2.2.3).

Fluvial deposits

In wide areas of the Elbe lowland, fluvial deposits of the Holocene crop out at the surface and superpose the Weichselian sediments of the Lower Terrace. The sediments inside the dikes are subdivided into floodplain sand and floodplain loam and into outwash masses in depressions and channels, and into deposits of natural levees outside the dikes along the Elbe. The fluvial deposits mostly display a tight dovetailing and contain intercalations of and transitions to limnic sediments such as muds and low-moor peat. CASPERS & SCHWARZ (1998) described similar conditions of multiple facies changes in the area between Dannenberg and Boizenburg (Amt Neuhaus).

Floodplain sand

The floodplain sand occurs in wide areas mainly beneath the floodplain loam (SCHULTE 1905; DUPHORN 1980, 1983). Often, it also occurs intercalated in the floodplain loam or less often at the ground surface as an erosion window within the floodplain loam.

The floodplain sand consists of a mainly uniform, weakly humous to humous, weakly silty fine to medium sand with subordinate proportions of coarse sand and rare occurrences of fine gravel. Often, clay and silt bands occur and rarely mud layers as well. The grain size increases towards the bottom. The sand is always non-calcareous and of light brown to grey, near the surface also of yellow colour. Grain-size analyses are available for the topmost 2 m of the profiling excavations from the pedological mapping Dömitz-Lenzen. Selected representative results are listed in Table 14.

The thickness of the sands varies from a few decimetres to over 2.0 m. The greatest thicknesses were registered in channel fillings or within depressions. The transition to the underlying Weichselian sands is difficult to determine. Mostly, the boundary was established where a slight increase in grain size towards the bottom or a discontinuation of the organic content was registered. The investigations of the Elbe lowland between Dannenberg and Boizenburg by Caspers & Schwarz (1998) show that the floodplain sand, which was deposited by the meandering Elbe, can attain thicknesses between 5 m and 10 m. Palynological analyses of boreholes GoQ 5, GoQ 6, and GoQ 7 dated mud intercalations from depths of 5 m to 7 m as belonging to the Atlantic phase. Sands of thicknesses of up to 4.5 m were interstratified between these organogenic layers or followed on top. These investigations, and the channel profile of Kapern (Duphorn 1980), prove that floodplain sands have been accumulated since the Atlantic phase and can reach thicknesses of 4.5 m in the study area.

Floodplain loam

The deposits of floodplain loam cover the largest part of the valley floodplain in the study area and form large uninterrupted surfaces north and south of the Elbe. The floodplain loam, which was called sludge in older works (Schulte 1905), was deposited as a high-flood sediment before the dikes were constructed. It overlies mostly floodplain loam. According to Duphorn (1983) and Caspers & Schwarz (1998), the floodplain loam was deposited in two periods, one being the Atlantic stage and the Subboreal stage (older floodplain loam), the other being the late Sub-Atlantic stage (younger floodplain loam). The formation of the latter has been helped by human impact on the landscape since the early Middle Ages (deforestation and correlated soil erosion). Palynological analyses of samples of the Quaternary shallow boreholes detected the younger floodplain loam down to a maximum depth of 2.6 m (GoQ 15). The older floodplain loam was detected by palynological analyses from a depth of 3.4 m (GoQ 6) down to 4.0 m maximum (GoQ 15). Frequently, a layer of floodplain sand of average thicknesses between 0.5 m and 1.0 m was found between the younger and the older floodplain loams.

The floodplain loam occurs mostly as a clayey, highly silty, weakly fine sandy high-flood sediment. The sediment is always non-calcareous, occasionally micaceous and often contains humous components or plant matter. Locally, thin layers of increased fine sand proportions occur. Often, iron specks and concretions of secondary origin occur. The colour of the floodplain loam varies from blue-grey to dark grey, near the surface from brown to red-brown, due to oxidation of the iron. The results of the grain-size analyses can be found in Table 14.

In the study area, the floodplain loam reaches thicknesses mainly from a few decimetres to approx. 3 m. The average thickness is approx. 2.5 m. At some locations, however, greater thicknesses of over 6 m were encountered, e.g. northeast of Besandten in borehole GoHy 1590 and approx. 2 km northwest of Wootz in older exploration boreholes. These only locally occurring large thicknesses are restricted to channel locations on the surface of the Lower Terrace (Duphorn 1980). The floodplain loam being a high-flood sediment levelled the relief that was previously present at the floodplain sand surface.

Natural levee

There is little information available on the areas between the Elbe and the outer dikes commonly named “Uferwall” (natural levee) in the study area. Even the early geological maps of Schulte (1905) and Weissermel (1901) did not include these areas in the survey. Deeper drillings of the area of the levee do not exist. The only information available is in the stratigraphic records of the up to 2 m deep auger drillings that were performed during the pedological survey. According to these, the levee sediments usually consist of floodplain loam overlying levee sands. The floodplain loam layers have thicknesses of 0.3 m to 1.8 m; underneath, sand was always encountered. Three boreholes southwest of Wootz were the exception, where only sand was encountered down to 2.0 m depth. As these boreholes are situated on the slip-off slope of the northwesterly turning Elbe, the sediments are most probably river bank sand.

Redeposited masses

In the area of the former depressions and channels in the Elbe lowland as well as on the slopes of the Höhbeck and at the foot of the dune ranges, small patches of redeposited masses were encountered. The formation of the redeposited sediments was rather diverse. On the slopes of the dunes, dune sands were washed down by run-off rainwater, which transported the material to the foot of the dunes. In the Elbe lowland, the redeposited sediments in the channel and depressions were mainly formed by long-term relocation of material due to inflowing surface water, or occasionally by man-made filling with surrounding material. From the 17th century on, dike bursts with large-scale flooding of the hinterland occurred repeatedly. This was accompanied by the flushing-out of potholes directly at the dikes and an adjoining formation of sedimentary fans on top of the existing floodplain sediments. Some of the potholes are still water-filled, outwash sediments are widely distributed at their edges. These water-filled potholes are called “Bracks”, the largest “Brack” in the study area is the Johannes Brack just west of Wootz.

The outwash masses occur mostly as fine sandy medium sands with low silt content and rarely also with gravel content. They are poorly sorted and often contain a high amount of humus in the upper part. The thicknesses are mostly under 2 m.

Organogenic deposits

Within the whole sequence of the Elbe floodplain sediments, peat and muds often occur at varying depths and in varying thicknesses. The peat may either be an indicator of a generally slight or absent sedimentation, or it was formed in detached channels or lakes when the river bed had moved.

Numerous boreholes found muds that, as explained above, are dovetailed with fluvial sediments. These muds were also encountered in the shallow Quaternary boreholes, so depth-oriented samples could be gained for palynological analysis.

The muds mostly consist of a weakly fine sandy, in parts clayey silt with a varying proportion of organic detritus. The muds are always non-calcareous and of dark grey-brown to black-brown colour. The thickness is usually a few decimetres, muds of over 0.5 m were rarely encountered. The dating of the muds always produced an age of the Holocene between the Atlantic (pollen zone VI after Firbas 1949) and Sub-Atlantic (pollen zone X).

South of the Elbe, on the edge of the Elbe floodplain near Kapern, an older, late-glacial age (Late Dryas) was detected as the start of the mud formation (Chapter 4.3.6). In the channel profile near Kapern, an almost uninterrupted formation of muds and peat since the latest late glacial has been documented. Only during the Boreal warm stage, was sedimentation interrupted. Up to the end of the Atlantic stage, exclusively limnic sediments (fine and coarse detritus muds) were deposited. Subsequently, the lake silted up and peat was formed, which is now covered by floodplain loam. The sequence of strata of the Holocene reaches a thickness of 5 m in this area.

In the bogs near Siemen and Laase, mentioned in Chapter 4.3.6, sedimentation continued in the Holocene. Near Siemen, low-moor peat of approx. 2 m thickness was deposited from the Boreal warm stage to the late Sub-Atlantic, after an interval of reduced peat growth at the beginning of the Holocene, which proves an uninterrupted sedimentation.

Further organogenic formations have been reported by Lesemann (1969) from the area of the Gartower Tannen. Between Gorleben and Gartow, a series of bogs and fens lie in a Holocene dune landscape. The bogs and fens have formed in more or less large depressions that were probably created by wind scour. In places where the water could not run off, the basis for peat formation was laid. The peat in the bogs has a thickness of 0.25 m to 2 m. Peat growth took place from the pre-Boreal to the late Sub-Atlantic.

Aeolian deposits

Aeolian deposits show a relatively wide distribution in the study area. They are concentrated in the valley sand areas north of the Löcknitz and south of the Elbe, especially in the area of the Gartower Tannen. The deposits consist of aeolian sands and morphologically distinctive dunes. Traditionally, their formation is dated as belonging to the ending phase of the Weichselian Glacial and to the Holocene. According to the overview mapping in the adjoining area to the northwest by Caspers & Schwarz (1998), however, the aeolian sediments overlie fluvial Holocene sands, muds and peat in large areas. Correspondingly, it can be assumed that a large proportion of the aeolian sediments originate from the Holocene, only the cores of the large dune ranges are probably of Late Weichselian age.

North of the Löcknitz River, thin layers of aeolian sands and large individual dunes and dune fields, which in parts form a west-east-striking band, cover the valley sands of the Weichselian Glaciation. The aeolian sands consist of consistently uniform, mostly micaceous, non-calcareous fine to medium sands, which seldom contain additions of silt and sporadically of coarse sand. Occasionally, root or wood charcoal residues were detected; the colour of the sands varies from light brown to yellowish to yellow-brown. The results of a grain-size analysis are listed in Table 14. The thickness of the aeolian sands is approx. 0.5 m to 2.0 m, though it is often difficult to determine the boundary to the underlying lowland sands. Distinguishing them from the dunes can only be achieved based on surface morphology and thickness of the sediments. The dunes also consist of homogeneous fine to medium sands and only occasionally contain coarse-grained fractions. Root and wood charcoal residues are also rare, and the colours vary from bright yellow to yellow-brown. The dunes reach considerable thicknesses of several metres to over 10 m in the study area. The greatest height of 44.5 m above sea level is reached by a dune range southeast of Dömitz in the Weiße Berge (White Mountains). This complex of inland dunes at Klein Schmölen, which is approx. 600 m wide and 2 km long, rises to approx. 30 m above the valley floor. The dunes are still moving in present times (Bülow & Krienke 1993).

South of the Elbe lies a large area of aeolian sands, the Gartower Tannen. According to Duphorn (1980), the thicknesses of the aeolian sand cover are mostly between 0.5 m and 1.5 m. In the dune ranges, the accumulations can attain heights of up to 10 m. The highest dune tops are in the Hahneberge southwest of Gartow. In that area, aeolian sands and dune sands of up to almost 15 m thickness were deposited. Archaeological finds and old chronicles, indicate that the formation of aeolian sands and dunes continued into the 18th century and was only stopped by modern afforestation in the mid-19th century.

5 Regional structure of the deeper subsurface

As the deeper subsurface was not explored in the Gorleben study area, generally data acquired outside of the Gorleben study area had to be used. This area, called “sheet section”, comprises the TK 100 sheets C2730, C2734, C3130, and C3134. The Gorleben study area is approximately in the middle of this sheet section.

Preliminary notes on the deeper subsurface

The knowledge on the stratigraphic structure, the lithofacial development, and the tectonic characteristics of the deeper, pre-Zechstein underground of the North German Basin has been considerably expanded during the last 20 years, especially while prospecting for oil and gas. This knowledge is also the basis for the geological assessment of the structure of the Zechstein and post-Zechstein overburden, their temporal-spatial activation processes, and the correlated paleogeographic-lithofacial and tectonic development.

However, significant differences exist, depending on the thickness of the overlying overburden. While numerous boreholes have encountered the pre-Permian strata in the outskirts of the basin and the geophysical survey data can be interpreted with sufficient accuracy, information on the central areas, where depths of burial of over 7 km to 8 km exist, is nonexistent or insufficient and limited to sections of the Upper Carboniferous. The situation is different for the Permian red beds (Rotliegend), the main target horizon for the gas prospecting activities. Several boreholes in the centre of the basin have penetrated these strata, or at least their sedimentary section.

In the area of the Altmark ridge, the northern part of which is in the sheet section, numerous boreholes have penetrated the Permian red beds, some even completely, so that the derived isopach maps, particularly those of the sedimentary Permian red beds, are very accurate.

According to present-day knowledge on the structure of the crystalline crust – and the lithofacial and tectonic development during the pre-Zechstein largely controlled by this structure – the basement of the North German Basin can be assumed to be an autonomous unit (East Avalonian terrane) between two geotectonically important sutures: To the north the southwestern edge of Baltica (Avalonia-Baltica suture) and to the south, the Armorican terrane (Avalonia-Armorica suture) at the northern edge of the Central German crystalline zone (Fig. 20).

There is an ongoing lively debate (Franke 1992; Onken & Weber 1995; Franke et al. 1996 among others) about the extent to which subduction processes and/or extensive lateral movements took place at these sutures during the Caledonian orogeny (Cambrian-Silurian) and the Variscan orogeny (Devonian-Carboniferous) that have led to the present co-location of such markedly different lithofacial and structural deep geological formations in some crust areas. Thus, the presented views are largely of model character.

5.1 Mohorovičić discontinuity

Hoffmann et al. (1996) and Hoffmann & Brink (2004) performed a detailed analysis of the long recording time, steep-angle seismic surveys available for Northern Germany, which had been carried out by the German oil and gas industry while prospecting for deposits. They revealed that strong reflections occurred in the time interval of approx. 10 s to 12 s, which can be ascribed to the Mohorovičić discontinuity, in short the Moho. Based on the velocities determined by seismic refraction surveys, the depth of the Moho varies between approx. 29 km and 34 km in the area of the sheet section (Fig. 21).

In the area of the Gorleben–Rambow salt structure, the depth of the Moho is approx. 31 km. This area is characterised by the centroclinal strike of a marked Moho elevation that strikes from the Weser Hills to the Wendland region (SSW to NNE), on the eastern flank of which the Altmark ridge is located, which was partially active in the Permian red beds and the Mesozoic. In the central section of the Moho elevation is the Braunschweig-Gifhorn fault zone (Fig. 20), a segment of the Mediterranean-Mjøsa rift system described by Stille. Thus, it belongs without doubt to the important fault zones of Northern Germany, but passes west of the sheet section.

The genesis of the Moho is a subject of controversy in literature. According to Hoffmann et al. (1996), it is closely correlated with the temporal and spatial development of the North German Basin. Thus, the Moho was influenced by magmatic underplating and mantle diapirism during the initial stage of the formation of the basin (Upper Carboniferous/ Stephanian-Lower Permian red beds). Its present-day structure with marked monoclines and synclines is probably caused by isostatic compensatory movements from the Upper Permian red beds onwards that are correlated with tectonic events. Here, especially transtension and inversion movements have influenced the structure and relief of the Moho. Thus, the contour of the Moho reflects important tectonic events that are expressed in the later activation of fracture faults and in the facies distribution, particularly in the Mesozoic and Cenozoic.

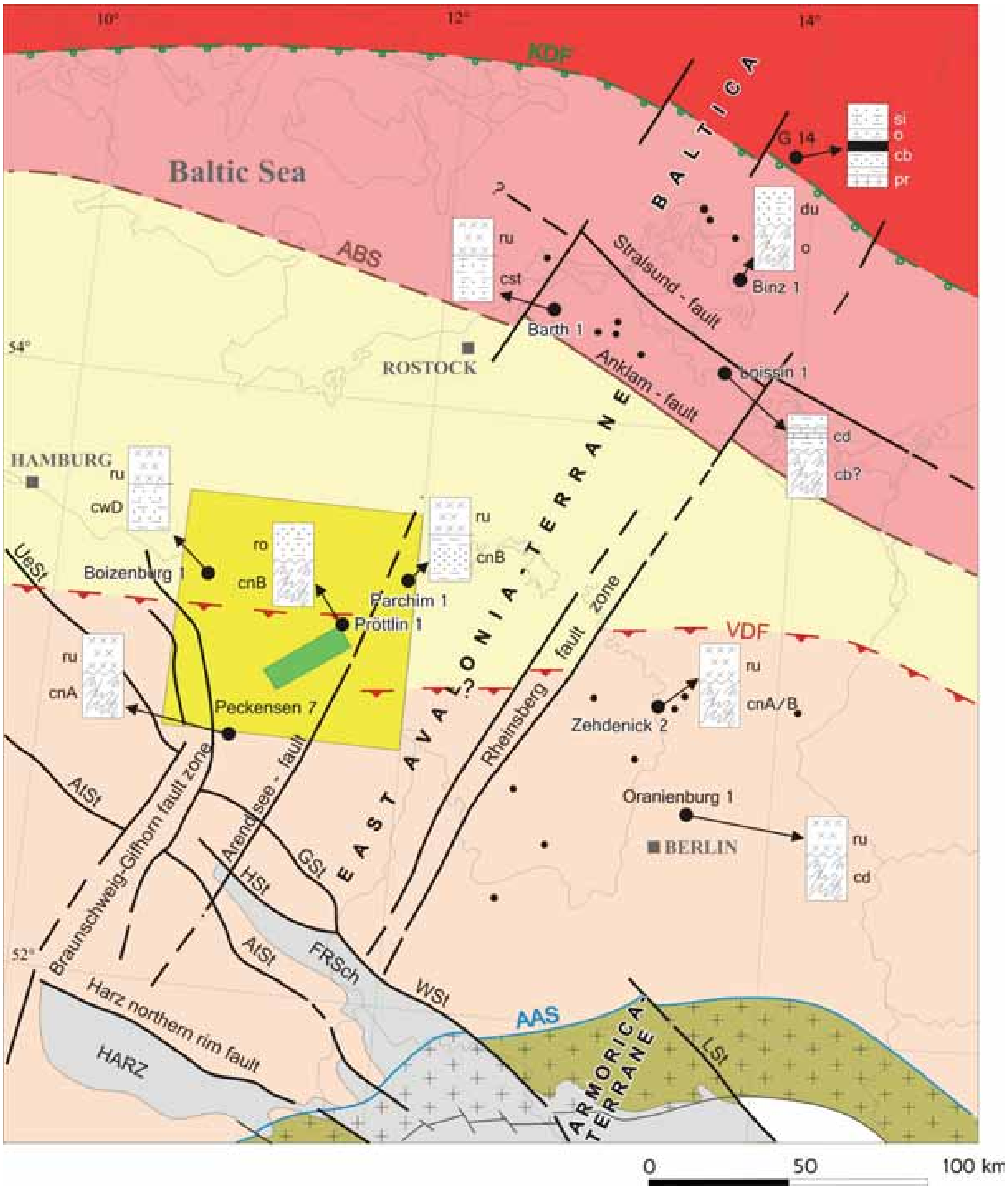


Figure 20: Tectonic systems of the deep subsurface of Northern Germany (Legend see right page)

Legend

Plate tectonic division of the deep subsurface (according to HOFFMANN et al. 1985, extended and supplemented)

Baltica continent (Precambrian consolidated)

- Eastern European platform
- Caledonian (Cambrian - Silurian) folding and faulting bed

East Avalonia Terrane (Precambrian to Caledonian consolidated)

- Variscan foreland (Devonian - Carboniferous)
- Variscan (Devonian - Carboniferous) folding and faulting belt

Armorica-Terrane

- Central German Crystalline zone (mainly Variscan deformation)

tectonic lines

- ABS Avalonia Baltica suture
- AAS Armorica Avalonia suture
- KDF Caledonian deformation front
- VDF Variscan deformation front

sheet section

area of the Gorleben-Rambow salt structure

Important faults (according to FRANKE et al.1989, BALDSCHUHN et al.1996)

GSt - Gardelegen fault

HSt - Haldensleben fault

WSt - Wittenberg fault

LSt - Lausitz fault

AtSt - Allertal fault

UeSt - Uelzen fault

FRSch - Flechtingen-Roßlau block

basement cropping out or beneath thin Cenozoic cover

Boreholes

- Pre-Permian boreholes with lithologic profile
- other Pre-Permian boreholes

Stratigraphy

ro	Upper Permian Red Bed
ru	Lower Permian Red Bed
cst	Upper Carboniferous (Stephanian)
cwD	Upper Carboniferous (Westphalian D)
cnA/B	Upper Carboniferous (Namurian A/B)
cd	Lower Carboniferous
du	Lower Devonian
si	Silurian
o	Ordovician
cb	Cambrian
pr	Precambrian

Lithology

- tectonically deformed sediments
- sandstone
- claystone
- alternating beds of sandstone/claystone
- limestone
- black shale
- crystalline basement
- volcanic rock

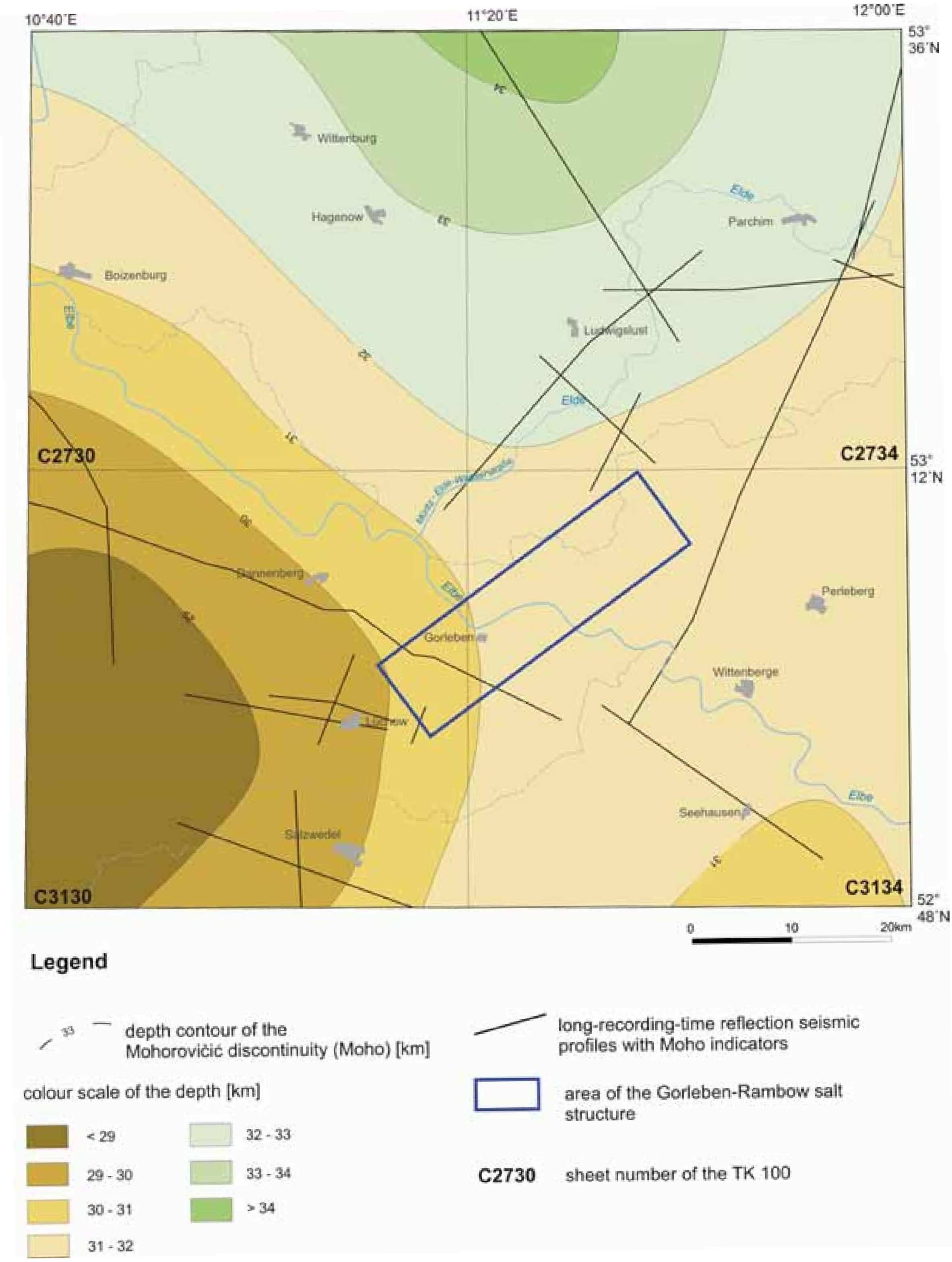


Figure 21: Depth contours of the Mohorovičić discontinuity in the sheet section

5.2 *Crystalline surface*

Only little, reasonably reliable information on the depth of the crystalline surface is available at present. This is mainly due to the great depth of more than 10 km of this boundary and thus the lack of drilling results. The existing data originate from different geophysical methods. The numerous deep seismic soundings provided relatively little but quite reliable data. This is especially due to the general absence of impedance differences. Comprehensive data can thus mainly be expected from potential field methods, i. e. magnetics and gravity.

As a first measure, Geophysik GGD Leipzig, under contract of the BGR, calculated the relief of the magnetically effective crystalline (Lindner et al. 2002). Here, the procedure proposed by Hahn (1965), which explains the regional magnetic anomalies as variation in relief of a homogeneously magnetised underground (crystalline surface), was rejected and a model of considerably differing magnetic conditions (changes in magnetic susceptibility) was used that corresponds to current geological knowledge. The map thus produced shows a relatively strongly structured depth relief of the top of the crystalline basement of < 10 to < 13 km in Northern Germany, which is geologically quite plausible (Lindner et al. 2004; Seidel et al. 2004; Scheibe et al. 2005). What remains to be determined is which stratigraphic and regional geological interpretation is accurate for the crystalline surface.

In the sheet section, the crystalline surface is mainly at approx. 12 km to 12.5 km depth (Fig. 22). It shows only little relief so an indication of deep fracture faults cannot be deduced directly. The markedly elevated position in the Moho (Fig. 21) is not present to such a significant extent in the crystalline surface. However, there is an indication for such a zone that results from isolated, approximately NNE to SSW-oriented elevations, which are usually surrounded by the 12 km contour line, as can be seen in maps of smaller scale (Lindner et al. 2002). This may be caused by the problem of stratigraphic and thus tectonic interpretation of the magnetic indicators already mentioned above.

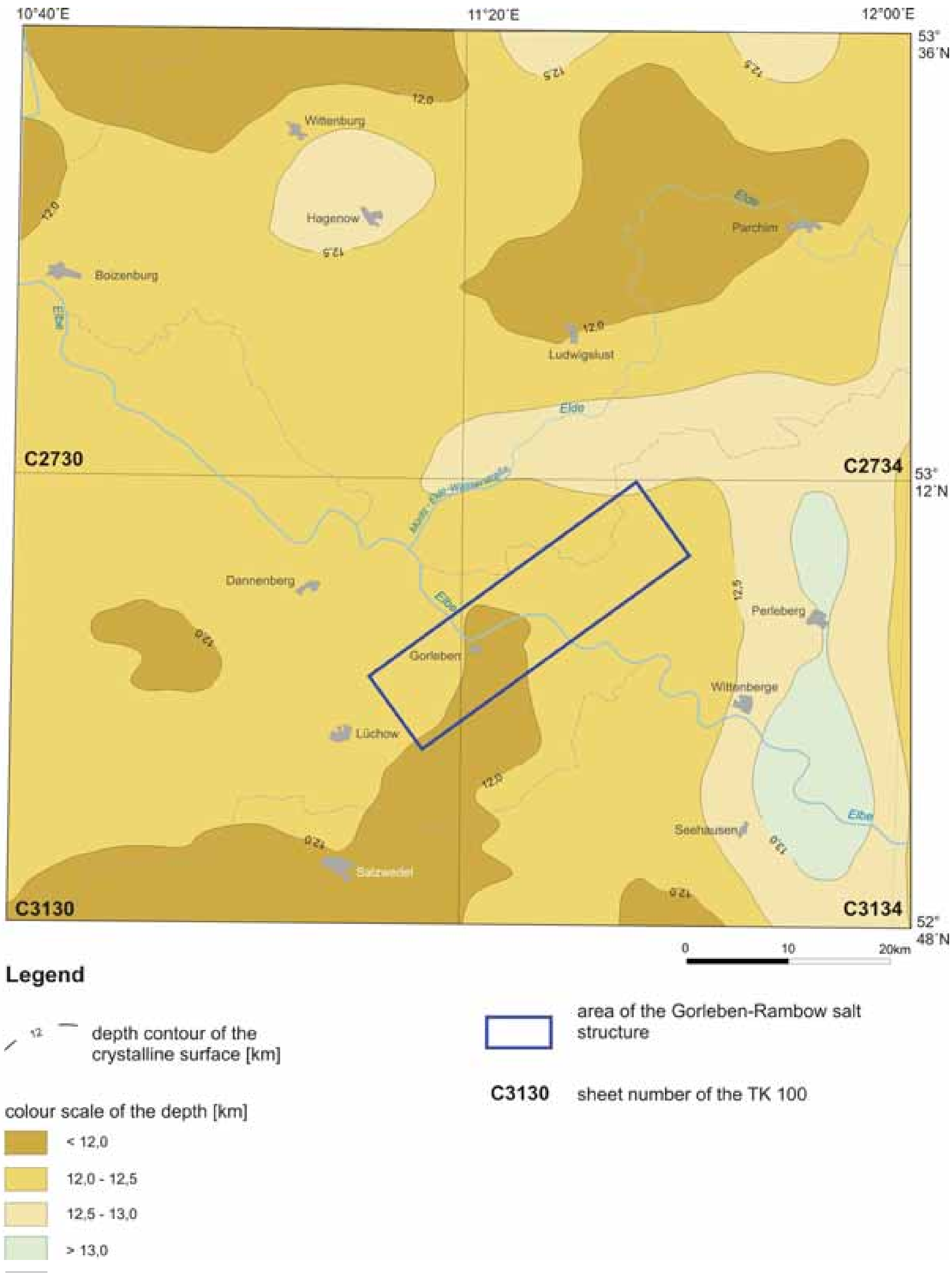


Figure 22: Depth contours of the crystalline surface in the sheet section

5.3 *Pre-Permian surface*

The pre-Permian surface is the first structurally significant boundary below the base of the Zechstein. It separates the Variscan basement in the broader sense from the Late Palaeozoic overburden and usually constitutes a distinct unconformity. In the sheet section, it was encountered in eight boreholes (Fig. 23). At the top of the Altmark ridge, it lies at a depth of < 4 500 m and drops to > 7 000 m in the centroclinal strike towards the north. It should be noted that this coincides well with the elevated zone of the Moho (Fig. 21). Numerous faults of relatively minor displacement values that strike predominantly from NNW to SSE or nearly N-S dominate the course of the isolines. The locations of the fracture faults were taken from the Zechstein base map, as seismic reflection data do not allow a mapping of faults in the depth interval of the pre-Permian surface due to missing indicators. It is reasonably probable that other directions, especially the faults striking from NNE to SSW, may contribute to the modification of the derived structural view. The faults that may occur in the potential field maps (gravimetry, magnetics) as gradient bundles in the deeper underground are situated outside the sheet section.

The age of the Altmark ridge, i.e. its formation, is of interest. Based on available data, it can be concluded that the ridge was formed in its present-day shape during late Variscan movements (Franconian–Asturian, Upper Westphalian to lower Stephanian) (Fig. 23). It is presumed that these events are correlated with the evolution of the present-day Moho and the North German Basin. Comparisons of regional geological analogies in similar geological regions provided no indication that this ridge was present in the Variscan (FRANKE & HOFFMANN 1997).

In the area of the sheet section, the pre-Permian surface is located between approx. 4 500 and 5 000 m below sea level (Fig. 23). Significant fracture faults seem to be mostly absent. The northeastern spurs of the Rhenish-striking (NNE to SSW) Altmark ridge are crossed by the approximately E-W-striking Variscan deformation front (FRANKE et al. 1995, 1996). Its confirmed course is south of boreholes Boizenburg 1 and Parchim 1 with unfolded sediments of the Upper Carboniferous. Upper Carboniferous showing Variscan folding, however, was encountered in boreholes Sellien 3Z, Pröttlin 1 and Peckensen 7. Seismic sections (FRANKE & HOFFMANN 1997) and interpretation of magnetotelluric data (HOFFMANN et al. 1998) show that the area south of the Variscan deformation front is characterised by shear planes that dip relatively gently towards the south and are at depths between approx. 7 500 m and approx. 9 000 m in the area of the sheet section. The shovel-like shear planes are presumed to be stratigraphically in the Lowest Namurian and Upper Visean 3 and are thought to be correlated with the Rhenish-Hercynian alum shale (HOFFMANN et al. 2005). On these shear planes, the molasse of the Upper Carboniferous was thrusted northwards over undeformed or slightly deformed Lower Carboniferous and older strata during the Variscan compression.

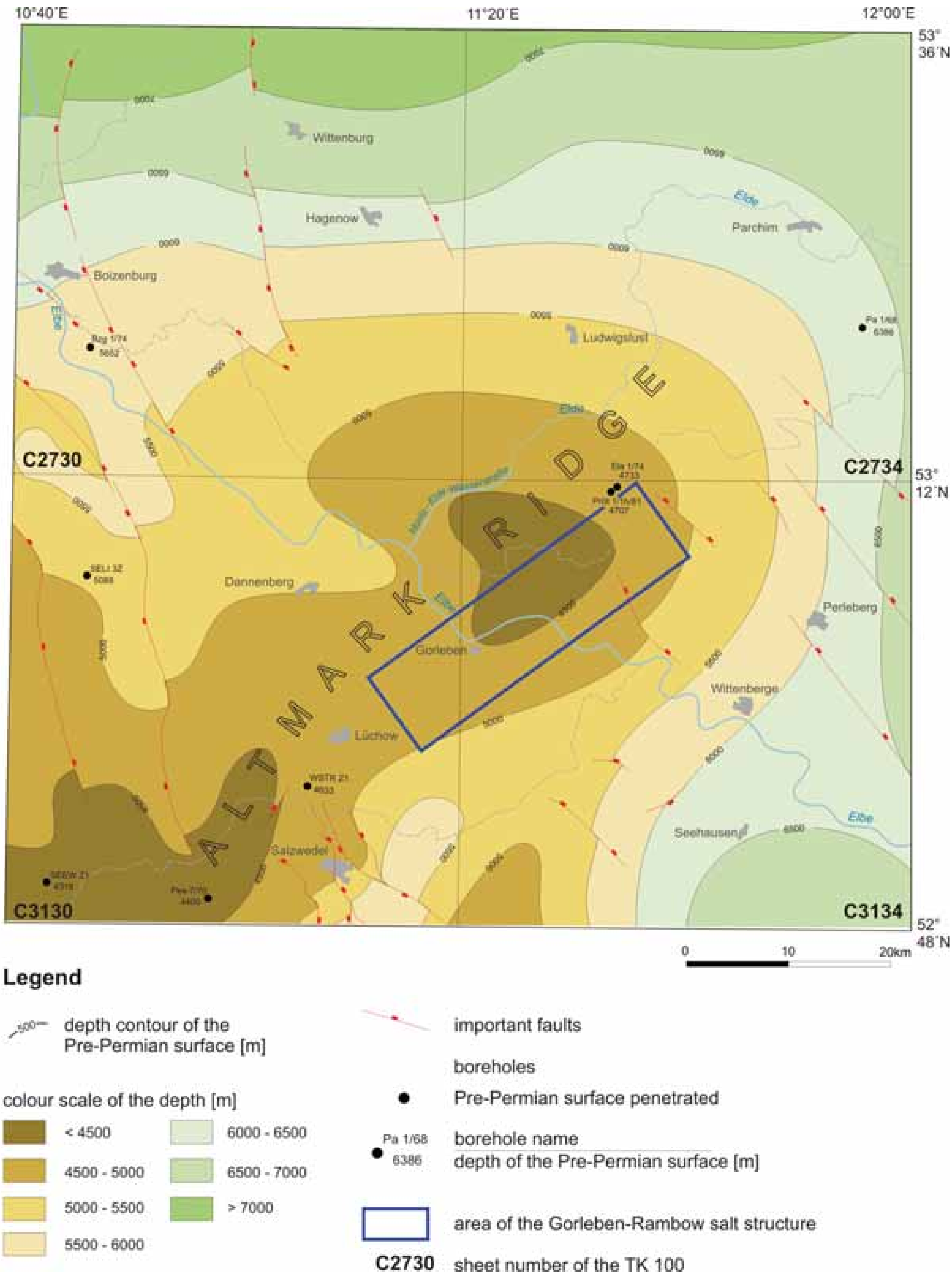


Figure 23: Depth contours of the pre-Permian surface in the sheet section

The sheet section lies in this overthrust belt, i.e. such shear planes, which can be reasonably assumed to be preferential unconformity planes for later, mainly Saxonian impulses, are to be expected in the pre-Permian underground.

5.4 Elbe lineament

Tectonically, the region of the Gorleben study area is situated in a zone of marked NW to SE-striking lineament fault zones (Fig. 24), which are often subsumed as the “Elbe lineament” in the literature. After comprehensive literature study and assessment of the geological-geophysical data, FRANKE & HOFFMANN (1999a, b) presented the results of a detailed assessment and interpretation of the “Elbe lineament”. According to their assessment, there are two fundamentally different interpretations regarding the course of this tectonic element.

The “classic” (southern) alternative (STILLE 1949) uses the Elbe valley in the area of Dresden as point of origin. Its continuation north of Meissen is partially via the deep fractures of Haldensleben and Gardelegen (KÖLBEL 1954; WATZNAUER 1964) or via the Südflechtinger and Weferlinger faults (SCHMIDT et al. 1977), where an extension to the northwest via the Wittenberg and Gardelegen fault to the NNE to SSW-striking (Rhenish) Braunschweig-Gifhorn fault zone and evidently even beyond (Uelzen fault) is established (KOCKEL 1998). Other points of discussion are possible connections to the Aller valley fault and the fault on the northern edge of the Harz mountain range. This southern “Elbe lineament” (“Elbe zone”) is south of the sheet section and is of no importance for the site assessment.

According to a second (northern) alternative, the “Elbe lineament” runs from the Elbe estuary northwest of Hamburg along the Lower Elbe via Central Brandenburg onwards along the southern Oder River to the southeast of Kraków. Thus, this northern “Elbe lineament” is also called Hamburg-Kraków lineament (Fig. 24). The north-western section, which is termed “Lower Elbe line” in the literature, is to be subjected to a detailed analysis with regard to its temporal and spatial development due to its possible importance for the Gorleben site. The establishment of its course is primarily based on geophysics. The distribution of the gradient bundles at the gravimetric (e.g. BRINK et al. 1994) and magnetic anomalies (e.g. LINDNER et al. 2002) in the area of the so-called “Ostelbisches Massiv” (East Elbe Massif), which extends from Schleswig-Holstein to Northern Brandenburg, and the interpretation of seismic refraction (e.g. EUGEMI Working Group 1990) and reflection (e.g. ABRAMOVITZ et al. 1998) deep soundings revealed that the Lower Elbe line is probably an important boundary in the lower crust. Its geological interpretation is a subject of controversy in the literature. At present, the following interpretation is favoured: the heavier part, which shows higher seismic velocities and is northeast of the Lower Elbe line, is a mainly mafic to ultramafic crust residue of the former Tornquist Ocean (Cambrian-Silurian) or of a curved East Avalonian Caledonian insular system. The lighter southeastern section, which shows lower seismic velocities, is a mainly acidic crust residue of the East Avalonia Terrane (e.g. Rabbel et al. 1995; Tanner & Meissner 1996; Hoffmann & Franke 1997). All interpretations have in common that the Lower Elbe line is considered an important pre-Variscan (Caledonian) terrane boundary, which was formed during the transition from Silurian to Devonian at the latest in the context of the closing of the Tornquist Ocean and the attachment of East Avalonia to Baltica.

Fundamental ruptures are often characterised by a certain longevity. When considering the presented geophysical data, it must be concluded that the Lower Elbe line is situated especially in the crystalline basement. The question is whether and how the presumed deep-lying geofracture impacted the overlying crustal sections, i.e. the Variscan and post-Variscan levels. As there are no deep-reaching boreholes, the evaluation of the character of the Lower Elbe line has to be based on comparisons with regional analogies.

During the Early Devonian, the zones on both sides of the rupture definitely belonged to the large Northern European Old Red Continent. This is indicated by the paleogeologic conditions in the Rhenish-Hercynian trough of the Variscan and by results from boreholes Schleswig Z1 and Flensburg Z1 in Schleswig-Holstein. The few drilling results available from the more distant environs (Münsterland, Schleswig-Holstein, Rügen) suggest that mainly marine carbonate is to be expected in the Upper Devonian. The first indication that the Lower Elbe line significantly influenced the paleogeographic conditions occurs in the Lower Carboniferous. The results of magnetotelluric surveys (Hoffmann et al. 1998; Hoffmann et al. 2005) indicate that the sapropelic limnic facies of the outer zone of the Variscan (boreholes Münsterland 1, Versmold 1, Pröttlin 1) seems to taper off as Rhenish-Hercynian alum shale in the area of the Lower Elbe, to be replaced by carboniferous limestone of the Lower Carboniferous that is common to the north (e.g. boreholes Schleswig Z1, Loissin 1, and the boreholes of Rügen).

In the Upper Carboniferous, however, such a marked facies differentiation cannot be detected. The facies boundaries rather cross the Lower Elbe line and mainly follow the Variscan orogenic belt, as the paleogeographic reconstructions of Ziegler (1990) and Gerling et al. (1999) illustrate.

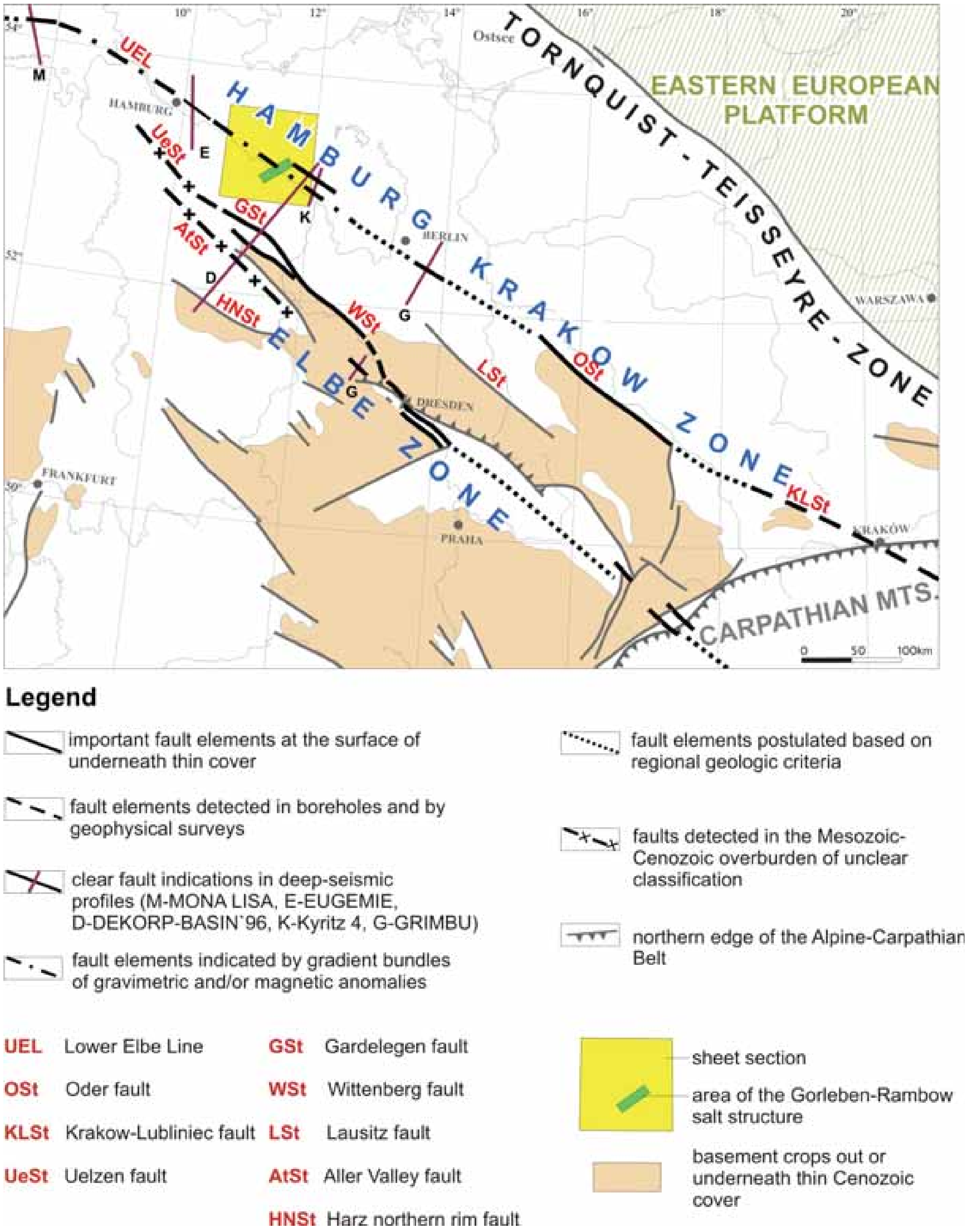


Figure 24: Variants of defining the Elbe lineament

The paleogeography of the Permian, i.e. of post-Variscan developments, does not show any further correlation with the Variscan bedding. The lithofacies boundaries partially run across the Variscan structures. The lower part of the Permian red beds, consisting of thick beds of volcanic rock, is dominated by marked, NNE to SSW-striking structures (pull-apart basins) (Bachmann & Hoffmann 1995). The NW-SE-oriented Lower Elbe line is crossed by these structures nearly at right angles and it has no impact on the volcanogenic facies and their thickness. The Rhenish-striking, isolated synclines in the Permian red bed I still display a close relationship to the volcanic stage.

The paleogeographic situation changes fundamentally in the Permian red bed II. During the Altmark impulses (Hoffmann et al. 1989), the approximately NW-SE-oriented North German basin was formed where sediments from the Early Palaeozoic to the Cenozoic with a maximum thickness of approx. 5 000 m were deposited in the area of the sheet section. The northwest–southeast strike as the dominating element of the basin configuration allows a better integration of the NW-SE-striking Lower Elbe line and its accompanying potential field anomalies into the general structural pattern. According to Bachmann & Grosse (1989), it is an important dextral shear zone that approximately marks the southern boundary of the Permian red bed deposition centre (Holstein-Southwest-Mecklenburg syncline). Though the northwest–southeast orientation is of great importance for the sedimentation processes and especially for the thickness development of the Permian red beds, Zechstein, and Bunter, the Lower Elbe line has no part in this, e.g. as a facies boundary. The tectonic atlas of northwest Germany (Baldschuhn et al.1996) shows that this is all the more valid for the Muschelkalk series (Muschelkalk = Triassic limestone formed from shells). Due to the expansion of the marine sedimentation area, the NW-SE-striking structures are almost completely lost. In the Upper Permian red beds, Zechstein, Bunter, and Keuper, directions become dominant even in the area of the Glückstadt Trench that run crosswise to the strike of the Lower Elbe line, i.e. they strike NE to SW and cross the Lower Elbe line at more or less right angles. This is also valid for the halokinetic structures. Sedimentation during the Jurassic and Cretaceous also offers no correlation with the Lower Elbe line. In the Tertiary, the deep troughs of Hamburg and Westholstein strike approximately orthogonally (NNE to SSW) to the Lower Elbe line. On the other hand, the gross configuration of the Tertiary in the North German Basin in general, and the subsidence zone of Cuxhaven-Gorleben in particular (which approximately follows the Lower Elbe line), show the typical NW-SE direction.

For the marked photo lineation that can be traced on satellite imagery (Krull 1979; Krull & Schmidt 1990), which that follows the Lower Elbe and the Berlin floodplain, no indication of a fracture-tectonic marking can be detected in the seismic reflection data of the post-Zechstein overburden. Surveys of recent crust movements (Bankwitz 1976;

Ludwig 1995), which revealed slightly higher subsidence rates and a shallow subsidence of the Quaternary base, may indicate the beginning of a renewed epeirogenic subsidence in this zone.

The temporal-causal interrelations of the Lower Elbe line are variable and partially contradictory, as the unquestionably incomplete list of geological criteria from the Palaeozoic and Cenozoic development shows. Far-reaching conclusions about current and future tectonic activity of the Lower Elbe line are fraught with great uncertainty, as the root causes, among which are tectonic, epeirogenic, and halokinetic factors, are yet scarcely explored and can temporally and spatially overlap.

5.5 Zechstein base

The seismic reflector for the construction of the Zechstein base is the surface of the basal anhydrite and can mostly be safely correlated. Exceptions are areas of salt formations and highly disturbed suprasalt. The base of the Zechstein as defined by biostratigraphy and lithostratigraphy is about 50 m to 60 m below, at the bottom of the Kupferschiefer (copper shale) seam or the base of the Zechstein conglomerate.

The construction of the Zechstein base map (Fig. 25), especially the tracing of the faults, was accomplished using data of the depth contour map of horizon Z_1 of the "Regionales Geophysikalisches Kartenwerk" (regional geophysical atlas) of VEB Geophysik Leipzig and the depth map of the Permian red bed surface for the Altmark area (Ludwig et al. 1988; Lungershausen & Twarok 1999). As continuous profiles were not available, the connection to the geotectonic atlas of Northwest Germany was achieved mainly by interpolation. In most cases, the connection of the isobaths was easily accomplished. In case of larger deviation, e.g. southeast of the Gorleben salt dome, the depth of selected profiles was recalculated using an adjusted base velocity.

The Zechstein base generally dips to the north towards the centre of the North German basin to depths of more than 5 100 m below sea level. Its most significant structural geologic element is the Altmark Ridge – as illustrated in the map of the pre-Permian surface (Fig. 23) – whose summit is at depths of less than 3 200 m below sea level. Towards its edges, the ridge divides into finger-like ridges and depressions, which outline the paleogeographic image of the Permian red bed basin in this area and finally subside in the surrounding depression zones. This also comprises the Gorleben–Rambow salt structure.

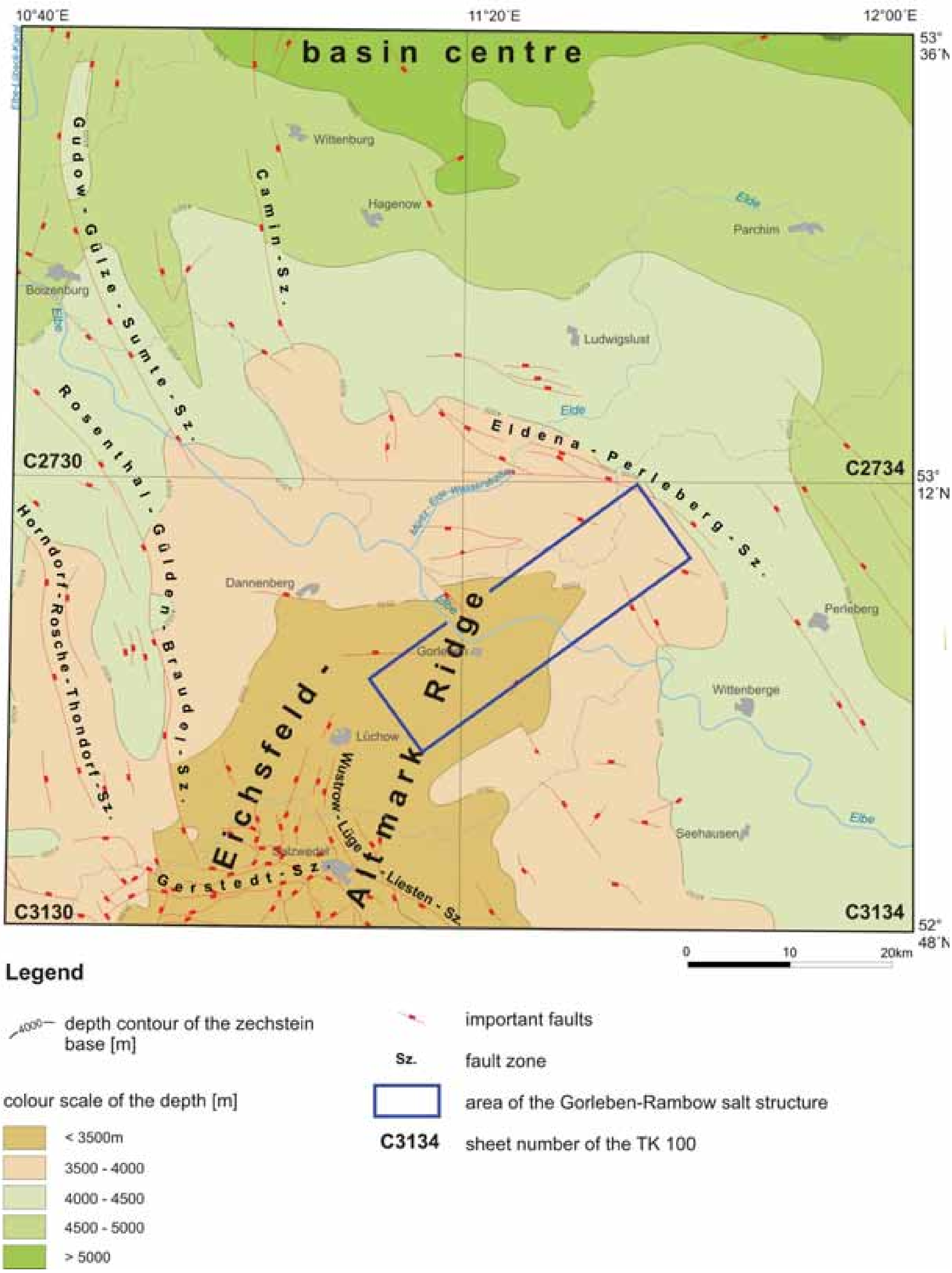


Figure 25: Depth contours of the Zechstein base in the sheet section

An outstanding element of the fault pattern is that the far-reaching faults that enter the sheet section from the NW (fault zones Horndorf – Rosche–Thondorf, Rosenthal – Gülden–Braudel, Gudow – Gülze–Sumte and Camin) terminate at the edge of the Altmark ridge.

Above the top of the Altmark ridge in the Altmark region and in southern Wendland in the area of the Wustrow structure, several boreholes and extensive seismic surveys mapped a tightly spaced fault pattern, which shows strikes of mainly SSW to NNE, E-W, and less often NW-SE. BENOX et al. (1997) note, however, that the multiple changes of orientation in the area of the Zechstein base often prevent the detection of significant displacements and thus hinder or even prevent their mapping. Possible regional fault correlations and connections are only perceptible when viewing the fault pattern in the level above the salt formation. Thus, it remains questionable whether the fault zone Rosche–Thondorf, which marks the crest of a high in the Zechstein base at approx. 3 800 m below sea level, reaches to below the salt domes Bonese and Waddekath. There is a decline to more than 4 150 m below sea level from the fault zone Rosche–Thondorf to the fault zone Rosenthal – Gülden-Braudel. The higher block that is east of the fault zone Rosenthal – Gülden-Braudel shows a displacement of more than 250 m and forms the northwestern flank of the Altmark ridge. It remains unclear whether this fault zone, too, reaches below the Peckensen salt dome as BENOX et al. (1997) assume.

The most significant E-W-striking element in the area of the Altmark ridge is the Gerstedt fault zone. Among the most important northwest-southeast-striking fractures are the fault zones Pretzier - Meßdorf (Wustrow - Lüge-Liesten - Meßdorf) and Apenburg - Wernstedt (in Fig. 25 only discernible in the northwestern section). The latter terminates at the fault zone Ristedt - Poppau - Apenburg, which strikes from NNE to SSW. The northern flank of the ridge, which plunges towards the centre of the basin, comprises the Wendland and North Altmark block and is significantly less fragmented (Fig. 26). The E-W-striking elements with relatively small displacements dominate the relatively few mapped faults. KAPUSTIN (1971) and GLUSCHKO et al. (1976) postulated the existence of a Rambow-Marnitz fault, based on geophysical potential field surveys and also based on the elongated shape of the Gorleben–Rambow salt structure. This fault was thought to have penetrated the pre-Permian basement but its existence could not be confirmed by more recent seismic reflection surveys of the post-Permian overburden. Even undershooting the Gorleben salt dome provided no indication for a fault (ZIRNGAST 1991).

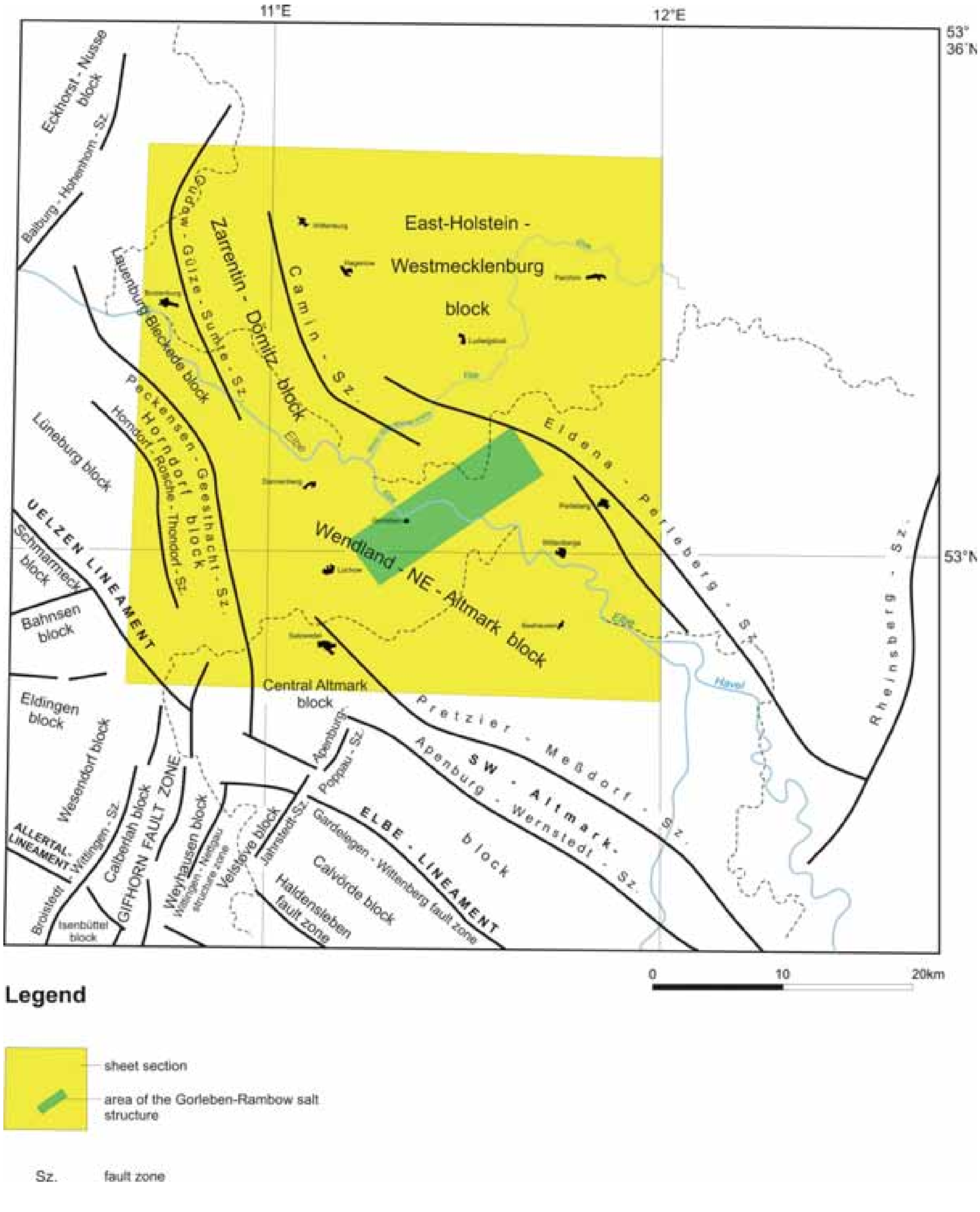


Figure 26: Subsalt fault pattern of the extended region of the sheet section (supplemented according to BRÜCKNER-RÖHLING et al. 2002: App. 2.1)

The fault zone Gudow-Gülze-Sumte shows the greatest displacement, with a displacement of 150 m in its northern section at the base of the Gudow salt pillow. The displacement decreases below the Gülze-Sumte salt dome. The Zechstein base forms a level high plain with depths between 4 200 m and 3 900 m below sea level in this area. The displacement value of approx. 50 m of the Camin fault zone is within the margin of error of the seismic reflection method that was used. Evidently, this fault zone does not continue below the Lübtheen salt dome, as no indications of a fault could be found on the southern side of the salt dome.

6 Geological structure of the environs of the Gorleben salt dome

6.1 Mesozoic structures

The faults and fault zones depicted in Figure 26, which divide the basement into a mosaic of blocks, were formed essentially in the Early Mesozoic and were moved in sections during the Late Mesozoic and partially in the Tertiary as well, often in the opposite direction to the initial movement. Only few of them coincide with the Permian rift valley rim faults. The depicted lineaments are mostly not individual faults but fault bundles with inserted lath-shaped and rhomboid blocks.

The movements at these basement joints during the Mesozoic and the Tertiary were often – if not always – the cause of the formation processes in the superstructure of the post-Zechstein (salt structures, troughs, inversion structures). The tectonic impulses generated by these basement moves were filtered and buffered by the Zechstein and Permian red bed salt in between before they reached the overburden. Thus, it is not easy to discern and date the extent and movement patterns at the basement joints from the overburden morphology. Many overburden structures, especially inversion structures with and without participation of salt, but also many salt domes, were incited by movements in the basement. This is particularly obvious in areas where the Zechstein salt is of slight thickness and thus remained passive instead of generating structures.

In the Mesozoic, periods of dilatational deformation (downfaulting, formation of trenches) and periods of compression (upfaulting, overthrusting, inversion) can be differentiated.

The first dilatational movements in Northern Germany formed trenches already in the earliest period of the Middle Bunter during the deposition of the Quickborn Formation and are evidenced below the “V” unconformity (Röhling 1999).

The large rift systems that cross northwest Germany in northerly directions and the large lineaments that strike from WNW to NW were formed before the “H” unconformity (base of the Solling sequence). The dilatational movements at these basement lineaments continued during the Upper Bunter and Muschelkalk, as differences in thickness on both sides of the major faults prove (Kockel 1999). The greatest rift movements above the basement faults along the N to NNE-striking rift edges and the NW-striking lineaments took place during the interval of the Middle Keuper (Frisch & Kockel 1997, 1999). This phase of rifting ended before the formation of the Steinmergelkeuper unconformity (Late Triassic).

In the Lias and Dogger (Early and Middle Jurassic), the dilatational movements affected mostly the NW to WNW-striking lineaments, although the meridional rift systems were also still moving. These movements were the precursors of the formation of the west-northwest- to east-southeast-striking basin of Lower Saxony, formed in the Late Jurassic to Lower Cretaceous, whose periphery touches the sheet section (for the definition of sheet section, see Chapter 5).

The Upper Jurassic was the interval of the greatest trough subsidence and thus the largest dilatation in the basin of Lower Saxony. This trough formation continued into the Early Cretaceous and faded out in the Late Aptian age. The Albian, Cenomanian, and Turonian ages were tectonically mostly quiet.

From the Bunter to the Aptian, the basement joints experienced only dilatation. This changed in the Late Cretaceous, more precisely in the Late Turonian. The interval of approx. eight million years from the Coniacian to the Middle Campanian was characterised by general compression and inversion (Baldschuhn et al. 1991). The basement was shortened, upfaulting and overthrusting occurred, which can be proven with the results of seismic surveys and boreholes. Due to this shortening of the basement, an inversion deformation occurred in the superstructure. The depth and the fault pattern in the Upper Cretaceous at the end of the Mesozoic development are illustrated in Figure 27.

Due to geophysical and coalification anomalies, it is assumed that intrusive bodies of basic or neutral chemical composition thrusted upwards in the central areas of the Lower Saxony basin during or shortly before the inversion. In the environs of the Gorleben–Rambow salt structure, however, no indication of this can be found.

The compression and inversion declined during the Santonian, the fracturing deformation was concluded in the Middle Campanian. Yet, small upward movements of the inversion structures occurred until the beginning of the Maastrichtian age. Movements at the subsalt basement faults have not been detected and cannot be detected in the study area as the Maastrichtian is mainly not present.

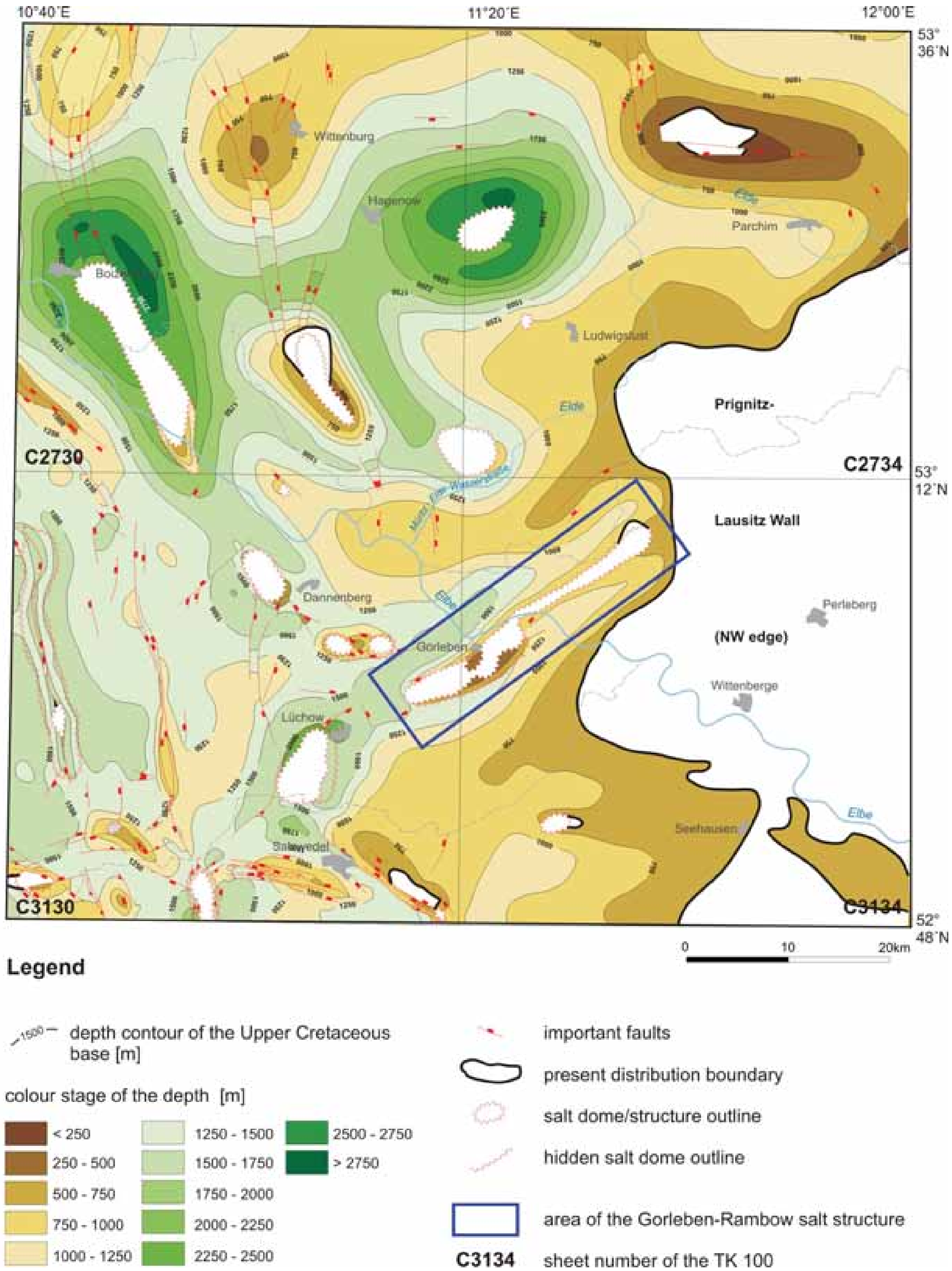


Figure 27: Depth contours of the Upper Cretaceous base in the sheet section

The Wendland-Northeast-Altmark block (Fig. 26) remained mostly undisturbed during the Mesozoic - except for faults caused by halokinesis. Immediately east of the Gorleben–Rambow salt structure, the inversion structure that was formed in the Late Cretaceous, the western edge of the Prignitz-Lausitz ridge, becomes effective. At this NW to SE-striking area of uplift, large areas of Lower Cretaceous and local structures of the Jurassic, Triassic, and Zechstein crop out in the northwestern section, and large areas of the Triassic crop out in the southeastern section. Their development ends at the transgression of the Nennhausen beds of the Upper Maastrichtian. The Gorleben–Rambow salt structure was no longer significantly affected by the development of this structure.

The dilatation movements, especially during the Middle Keuper until the start of the Steinmergelkeuper, were so strong that the sedimentary cover above the salt accumulations was torn and the salt was able to flow to the surface in the shape of **salt domes** (diapirs). Three out of four salt domes in Northern Germany went through their first stage of diapirism during this interval (Kockel 1999). The sheet section, however, is dominated by salt domes that formed in the Early Cretaceous (mainly Wealden), among them the Gorleben–Rambow salt structure (Table 15). It is unclear whether the breakthrough of this salt structure already started in the Late Jurassic, as the dating of the oldest sediments in the secondary rim syncline is problematic. The Rambow salt dome most probably started its breakthrough in the Malm (White Jurassic). However, an overlap of the area of influence of the Werle salt dome is to be expected in the northern rim syncline (Fig. 28).

The second most common salt domes in the sheet section are Triassic salt domes, some of which had already broken through the overlying strata in the Late Bunter and had concluded their breakthrough in the Muschelkalk or in the Keuper age. There are also salt domes that achieved breakthrough in the Early Jurassic, Middle Jurassic, Late Cretaceous, and the Cenozoic (Tables 15 and 16). All efforts to derive patterns for the distribution of the structures of different ages, e.g. according to the direction of the strike, have failed so far.

In addition to diapirs which pierced the sedimentary cover unconformably, several **salt pillows** occur in the sheet section where the salt formation, whose thickness was highly increased due to lateral flow, did not penetrate the primary sedimentary cover. Mature salt pillows are characterised by high tops, steep flanks, and the occurrence of crestal faults or crestal trenches and half trenches. The Camin salt pillow that belongs to this group has a degree of maturity of 90 % according to Althen et al. (1973).

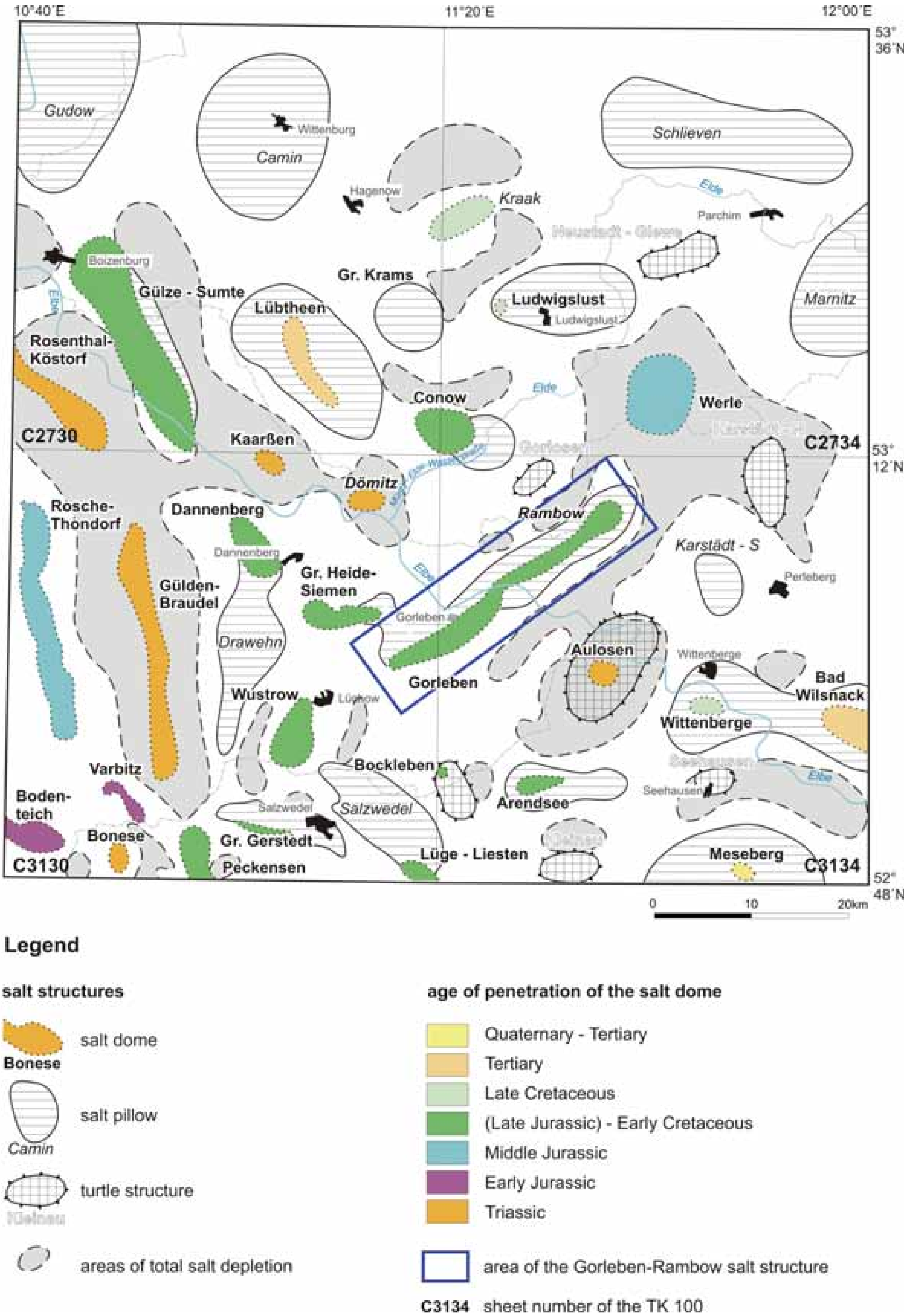


Figure 28: Position and age of the salt structures in the sheet section

Table 15: Salt structures in the vicinity of the Gorleben-Rambow salt structure active in the Mesozoic

Name	Present type	sm	so	m	k	ju	jo	kru	kro
Arendsee	SST	no	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	1. diapir st.	1. diapir st.
Aulosen	SST + SK	no	pillow stage	pillow stage	1. diapir st.	afterthrust	afterthrust	no	no
Bad-Wilsnack	SST m. SK	no	no	no	pillow stage	pillow stage ?	pillow stage ?	pillow stage ?	pillow stage
Bockleben	SST	no	pillow stage	pillow stage	1. diapir st.	afterthrust	afterthrust	afterthrust	afterthrust
Bodenteich	SST	no	pillow stage	pillow stage	pillow stage	pillow stage	afterthrust?	afterthrust	2. diapir st.
Bonese	SST	no	1. diapir st.	1. diapir st.	1. diapir st.	no	2. diapir st.	afterthrust	afterthrust
Camin	SK	no	no	no	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage
Conow	SST	no	no	no	no	pillow stage	pillow stage	1. diapir st.	1. diapir st.
Dannenberg	SST	no	pillow stage	pillow stage	pillow stage	pillow stage	1. diapir st. ?	1. diapir st.	1. diapir st.
Dömitz	SST	no	1. diapir st. ?	1. diapir st.	1. diapir st.	1. diapir st.	no	no	no
Drawehn	SK	no	no	no	no	pillow stage	no	no	no
Gorleben	SST	no	pillow stage	pillow stage	no	no	1. diapir st. ?	1. diapir st.	1. diapir st.
Gr. Gerstedt	SST	no	no	no	no	no	no	1. diapir st.	afterthrust
Gr. Heide-Siemen	SST	no	pillow stage	pillow stage	no	no	1. diapir st. ?	1. diapir st.	1. diapir st.
Gr. Krams	SK	no	no	no	no	no	no	no	pillow stage
Gudow	SK	no	no	no	pillow stage	pillow stage	pillow stage	no	pillow stage
Gülden-Braudel	SST	no	pillow stage	pillow stage	pillow stage	no	no	no	afterthrust
Gülze-Sumte	SST	no	no	no	pillow stage	pillow stage	pillow stage	pillow stage	1. diapir st.kruo
Kaarssen	SST	no	1. diapir st. ?	1. diapir st.	1. diapir st.	1. diapir st.	no	no	no
Karstädt-Süd	SK	no	no	no	no	pillow stage	pillow stage	pillow stage	pillow stage
Kl.Kühren	SST	no	no	no	pillow stage	pillow stage	pillow stage	pillow stage	1. diapir st.kruo
Kraak	SST	no	no	no	pillow stage	pillow stage	pillow stage	pillow stage	1. diapir st.
Lübtheen	SST m. SK	no	no	no	no	no	no	pillow stage	pillow stage
Ludwigslust	SST m. SK	no	no	no	no	no	pillow stage	pillow stage	1. diapir st.
Lüge-Liesten	SST	no	no	no	pillow stage ?	pillow stage ?	pillow stage ?	1. diapir st.	1. diapir st.
Marnitz	SK	no	no	no	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage
Meseberg	SST m. SK	no	no	no	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage
Peckensen	SST	no	no	no	pillow stage ?	pillow stage ?	pillow stage ?	1. diapir st.	1. diapir st.
Rambow	SST	no	no	no	pillow stage	pillow stage	1. diapir st.	1. diapir st.	1. diapir st.
Rosche-Thondorf	SST	no	no	no	pillow stage	pillow stage	afterthrust	afterthrust ?	afterthrust
Rosenthal-Köstorf	SST	pillow st.	pillow stage	pillow stage	1. diapir st.	1. diapir st.	afterthrust	afterthrust	afterthrust
Schlieven	SK	no	no	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage
Varbitz	SST	no	no	1. diapir st.	1. diapir st.	1. diapir st.	pillow stage	pillow stage	pillow stage
Werle	SST	no	no	pillow stage	pillow stage	pillow stage	1. diapir st. jmcl	1. diapir st.	afterthrust
Wittenberge	SST	no	no	no	no	no	pillow stage	pillow stage	1. diapir st.
Wustrow	SST	no	pillow stage	pillow stage	pillow stage	no	1. diapir st. ?	1. diapir st.	1. diapir st.

SST = salt dome
SK = salt pillow
st. = stage
jm = Middle Jurassic
jo = Upper Jurassic
ju = Lower Jurassic
jutco = upper Toarcian
k = Keuper
kro = Upper Cretaceous
kru = Lower Cretaceous
kruo = upper Lower Cretaceous
m = Muschelkalk
sm = Middle Bunter
so = Upper Bunter

Table 16: Salt structures in the vicinity of the Gorleben-Rambow salt structure active in the Cenozoic (supplemented according to Brückner-Röhling et al. 2002)

Name	Present type	Pre-Cenozoic	tpao-teou	teom-teoo	tolR-tolo	tmiu	tmiR-tpl	qp
Arendsee	SST	Wd	1. diapir stage	1. diapir stage	1. diapir stage	afterthrust	afterthrust	afterthrust
Aulosen	SST + SK	k	no	no	no	no	no	no
Bad-Wilsnack	SST m. SK	pillow stage	1. diapir stage	1. diapir stage	1. diapir stage	1. diapir stage	1. diapir stage	afterthrust
Bockleben	SST	k	no	no	no	no	no	no
Bodenteich	SST	ju	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?	no
Bonese	SST	tr	afterthrust	afterthrust	afterthrust	afterthrust?	afterthrust?	no
Camin	SK	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage
Conow	SST	Wd	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust 2.diapir stage ?	afterthrust
Dannenberg	SST	jo, Wd	afterthrust	afterthrust	afterthrust	afterthrust	2.diapir stage ?	afterthrust?
Dömitz	SST	so?, mu	no	no	no	no	no	no
Drawehn	SK	pillow stage	no	no	no	no	no	no
Gorleben	SST	jo?, Wd	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?
Gr. Gerstedt	SST	kru	afterthrust	no	no	no	no	no
Gr. Heide-Siemen	SST	jo?, Wd	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?	afterthrust?
Gr. Krams	SK	pillow stage	no	no	no	no	no	no
Gudow	SK	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage?
Gülden-Braudel	SST	so	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?	no
Gülze-Sumte	SST	Wd	1. diapir stage	afterthrust	afterthrust	afterthrust	afterthrust?	afterthrust
Kaarssen	SST	so?, mu	no	no	no	no	no	no
Karstädt-Süd	SK	pillow stage	no	no	no	no	no	no
Kl.Kühren	SST	kro	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?	no
Kraak	SST	kro	afterthrust	afterthrust	afterthrust	2.diapir stage ?	2.diapir stage ?	afterthrust
Lübtheen	SST m. SK	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	1. diapir stage tmiMA	afterthrust 2.diapir stage ?
Ludwigslust	SST m. SK	kro?	1. diapir stage	1. diapir stage	afterthrust	afterthrust	afterthrust	afterthrust
Lüge-Liesten	SST	kru	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust
Marnitz	SK	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage?
Meseberg	SST m. SK	pillow stage	1. diapir stage	1. diapir stage	1. diapir stage	1. diapir stage	1. diapir stage	2.diapir stage ?
Peckensen	SST	kru	1. diapir stage	1. diapir stage	afterthrust	afterthrust	afterthrust	afterthrust
Rambow	SST	jo?, Wd	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust
Rosche-Thondorf	SST	jm	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?	no
Rosenthal	SST	k	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?	afterthrust?
Schlieven	SK	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage	pillow stage?	pillow stage?
Varbitz	SST	ju	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?	no
Werle	SST	jmcl	no	no	no	no	no	no
Wittenberge	SST	kro	1. diapir stage	1. diapir stage	1. diapir stage	1. diapir stage	afterthrust	2.diapir stage ?
Wustrow	SST	jo?, Wd	afterthrust	afterthrust	afterthrust	afterthrust	afterthrust?	no

SST = salt dome
SK = salt pillow
jm = Middle Jurassic
jmcl = Callovian
jo = Upper Jurassic
ju = Lower Jurassic
k = Keuper
kro = Upper Cretaceous
kru = Lower Cretaceous
mu = Muschelkalk
qp = Pleistocene
so = Upper Bunter
teom-teoo = Middle to Upper Eocene
tmiR-tpl = Miocene (Reinbekian) to Pliocene
tmiu = Lower Miocene
tolR-tolo = Rupelian to Chattian
tpao-teou = Upper Paleocene to Lower Eocene
tr = Triassic
Wd = Wealden

The third structural category comprises the **turtle-structure anticlines**. These are anticlinal structures in the Mesozoic overburden, which can be explained as sediments that originally filled a primary rim syncline of two or more salt pillows. When these salt pillows developed into salt domes with secondary rim synclines, the filling of the primary rim syncline remained as a relative dome after the migration of the salt formation. Such turtle structures in the vicinity of the Gorleben–Rambow salt structure are the structures of Gorlosen, Karstädt-Nord and probably also Aulosen (Wambach 1966).

6.2 Cenozoic structures

During the Cenozoic, the tectonic activity in the North German Basin declined considerably. The detected movements in the Tertiary superstructure were caused by movements in the basement, which even pressed through the salt into the superstructure, and by halokinesis, subrosion, and subsidence. The formation of basement faults that were only active in the Tertiary was not detected. According to Brückner-Röhling et al. (2002), a maximum of 10 % of all charted basement faults in the whole North German Basin were active in the Tertiary. The movements during the Tertiary occurred preferentially at the same basement faults, though often at different segments of the same fault zone. The Tertiary dilatation movements occurred preferentially at those fault zones that had experienced the greatest compressional movements during the inversion of the Late Cretaceous.

In areas where inversion movement had not taken place, e.g. in the area of the Ems estuary, in the southwestern part of the German North Sea, and in Schleswig-Holstein, old rift rim faults, particularly those that had been active in the Middle Keuper and in the Middle Bunter (pre-Solling), were reactivated in the Tertiary.

In the sheet section, a reanimation of old faults that had been altered by compression in the Late Cretaceous was only detected in some sections of the fault zones in the Altmark (Fig. 29). In these areas, movements took place again in the interval from the Late Paleocene to the Early Eocene. The last movements in the Early Miocene can be detected in some segments of the fault zones Rosenthal – Gülden-Braudel, Gudow – Gülze–Sumte, and Camin. The crestal trench of the Camin salt pillow can be traced to the beginning of the Miocene (Petzka 2002). In the environs of the Gorleben–Rambow salt structure, no Tertiary movements of the basement faults could be identified.

The majority of the faults in the superstructure that moved in the Tertiary are linked to halokinesis and/or subrosion, which means that they did not move for endogenic-tectonic reasons. This includes the crestal trenches and half trenches that were formed during the formation of the pillow or due to the salt uplift compensating the dilatation above the diapir. Faults due to subrosion also developed as overlying strata of the Tertiary partially fractured and sank into the hollow that had been created by leaching of the salt at the top of the salt structure. In the sheet section, these two groups comprise, for example, the faults in the eastern top section of the Gorleben–Rambow salt structure and the crestal faults of the salt dome Groß Heide–Siemen.

Not only the fault structures but also the salt structures in the North German Basin developed further (uplift of the pre-Cenozoic salt domes due to re-supply; breakthroughs of diapirs in the southern North Sea, at the southern edge of the Western Schleswig block, on the eastern bank of the Glückstadt trench, in subzones of the Pompeckj Block, in the northern Altmark, and in the western Prignitz).

As the strata of the Lower Pleistocene and the lower Middle Pleistocene (Pretiglian to base of Elsterian Glaciation) are largely missing in the onshore areas of Northern Germany, there is little to report on the structural development of this interval of approx. 2.1 million years. In the central North Sea Basin, where this interval is represented by sediments, it is known that cases of considerable epeirogenic subsidence of more than 800 m occurred, while the fault activity declined considerably compared to the Middle Miocene (Brückner-Röhling et al. 2002). The blocks of the Central German Uplands show evidence of considerable uplift.

The interval from the Middle Pleistocene to present day started with an extensive formation of channels by mainly subglacial erosion, probably in the melting phase of the Elsterian glaciers (alteration of the pre-Elsterian Quaternary base). Occasionally, diapirism (in parts primary, in parts secondary phase of breakthrough) as well as movements caused in the basement or by halokinesis occurred in the North Sea (displacements sometimes cropping out at the seafloor).

There are no reliable data available on the distribution of sediments of the Early Tertiary and Late Quaternary in the sheet section. It is known from seismic profiles of the North Sea that a broad fan of imbricate debris advanced from the east and southeast into the German Bight in the period from the Neogene to the Lower Pleistocene. The hinterland served as a region of denudation, except for depressions caused by halokinesis, such as the rim syncline of the Lübtheen salt dome.

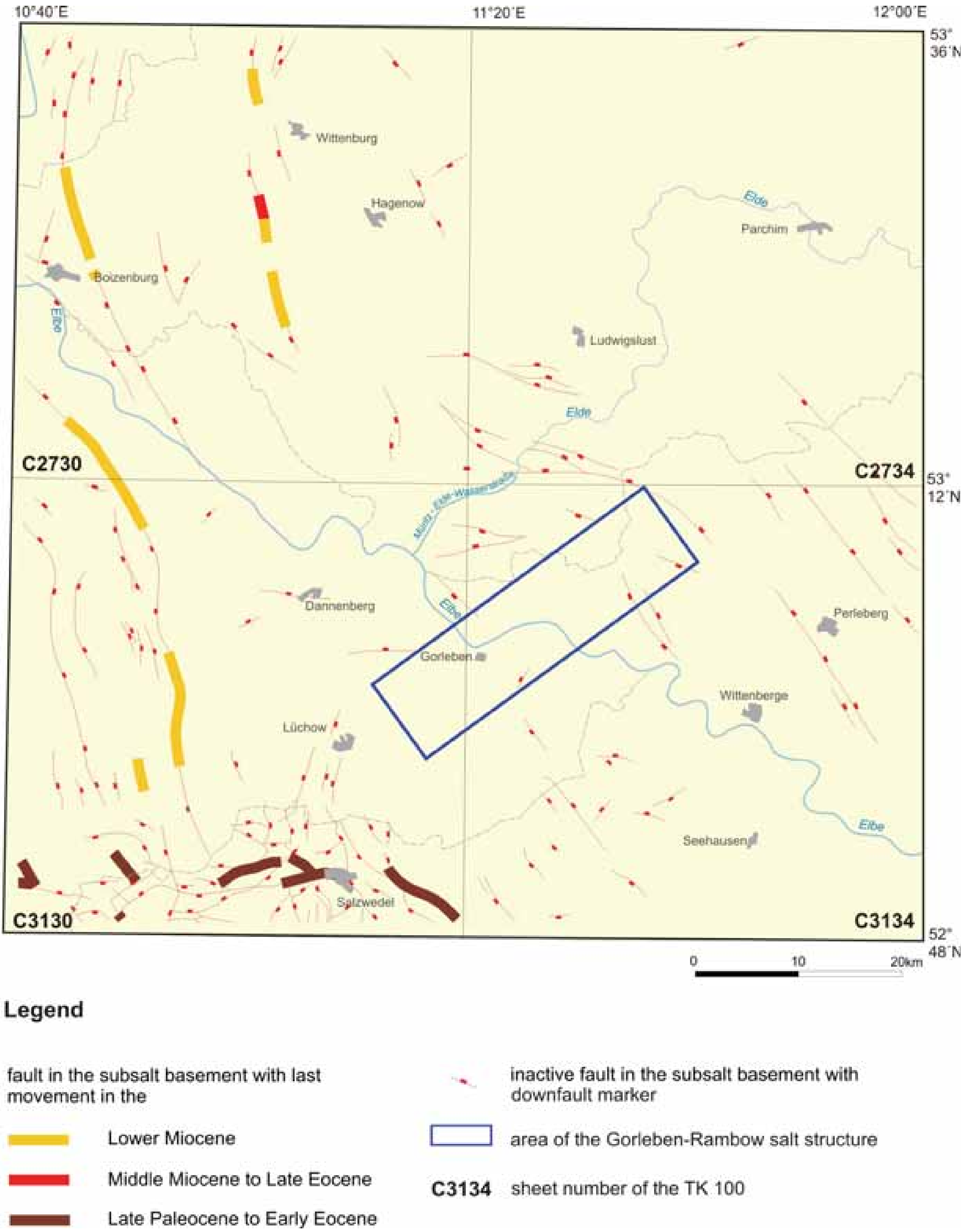


Figure 29: Last movements of basement faults during the Tertiary in the sheet section (detail from Brückner-Röhling et al. 2002: App. 4.12)

At least since the Late Pliocene, the North German-Polish Basin was no longer an area of accumulation but of denudation, which was intersected by river systems. Relicts of this river system (Baltic River System), which existed through the Early Pleistocene, are the Loosen beds (gravel beds) in southwest Mecklenburg (Bülow 2000b), which were deposited in the Late Pliocene at the turn to the Pleistocene and which lie unconformably on flattened older Pliocene, as well as the pre-Elsterian age (Menapian until Cromerian) limnic-fluvial sediments southwest of Gorleben.

The halokinetic formation of the structure in the sheet section happened in different stages. Paradoxically, the most recent stage, the Pleistocene development phase, is difficult to assess. Table 16 shows that the development of the diapirs in the pre-Cretaceous salt domes (e.g. Dömitz, Rosche–Thondorf, Werle) had come to an end before the beginning of the Tertiary. In the Tertiary, only afterthrusts of varying intensity occurred, which are evidenced by subsidence of the rim synclines caused by afterthrusts, which continued to occur through the Pleistocene. But in some of the salt domes that had risen during the Early Cretaceous (e.g. Lüge–Liesten, Gorleben–Rambow) and the Late Cretaceous (e.g. Kraak), the primary diapir stage also ended before the beginning of the Tertiary, as the strata of the Paleocene to Lower Eocene overlying the sediments of the cap rock prove.

In most cases, however, only the end of the diapir development can be established. Evidence for interruptions is mostly lacking, as the overlying strata were eroded upon renewed breakthrough and slight variations in thickness in the sediments of the rim synclines frequently cannot be determined due to insufficient stratigraphical resolution.

There are very few salt domes that entered their first diapir stage as late as the beginning (e.g. Bad Wilsnack, Meseberg) or during the Tertiary (e.g. Lübtheen) (Fig. 28). The Lübtheen salt dome, which is the youngest in Northern Germany, achieved its breakthrough at the end of the Early Miocene when the Malliss beds were deposited. At the end of the Pliocene, the development of the diapir was mostly concluded. Only east of the town of Lübtheen, the gypsum cap rock crops out at the surface and thus proves that a partial breakthrough happened during the Pleistocene, probably after the melting of the Elsterian age glacier.

The salt domes Bad Wilsnack, Meseberg, and Wittenberge apparently were in the diapiric stage during the whole Tertiary. The salt domes of Meseberg and Wittenberge probably experienced a renewed – maybe even decisive – breakthrough of the salt after the melting of the Elsterian age glacier and the corresponding pressure relief (Poblotzki 1969). The Miocene bed that is registered in the stratigraphic record of the salt dome top borehole Wittenberge 1/53 is probably from the Pleistocene, according to Poblotzki (1969). On the Meseberg salt dome, the thick Quaternary sequence might even indicate the formation of secondary rim synclines during the Pleistocene, which, however, is overlapped by a channel depression.

7 Gorleben–Rambow salt structure

7.1 Differences in the development of the Gorleben and Rambow salt domes

The structure of the adjoining rock of the Gorleben–Rambow salt structure displays different rim syncline formations in the structures of Gorleben and Rambow, which indicate a different development of the two salt domes.

In all salt structure areas, the oldest secondary rim synclines were formed in the Early Cretaceous, i.e. the breakthrough occurred during the uplift phase in the Malm (White Jurassic).

The thickest rim synclines of the Lower Cretaceous confine the salt structure in the northeastern part of the Rambow salt dome whilst the Upper Cretaceous shows only small thicknesses in that area. Towards the southwest, the rim syncline proportion of the Upper Cretaceous steadily increases and that of the Lower Cretaceous decreases. The conclusion is that the greatest salt uplift in Rambow occurred in the Early Cretaceous, while the greatest uplift rates in the Gorleben salt dome occurred in the Late Cretaceous. It is of note that the pillow bases in the transition area between the Elbe and Lenzen are more markedly developed than the bases of the Rambow and Gorleben salt domes. This indicates a weaker salt dome development in this area. The small structural cross section in this zone also indicates that the salt migration from this area occurred preferentially towards the northeast and southwest into the Gorleben and Rambow salt domes, which is why the salt supply in the catchment area of this diapir section is smaller. The interpretation of a smaller uplift rate in the zone between the Elbe and Lenzen is supported by the thin cap rock and the structure of the overburden.

The exploration results, too, show a difference in the structure of the overburden above the Gorleben salt dome and the transition zone towards the Rambow salt dome in the Dömitz-Lenzen area. Above the flanks of the Gorleben salt dome, the Tertiary is dragged steeply upwards and forms the so-called ring wall, where the beds reach their highest position (Pl. 1: Fig. 10, cross section A–A‘; Fig. 30, profile 0010). In the central part above the Gorleben salt dome, the beds of the Tertiary are highly disturbed, making an identification of single beds by seismic reflection methods impossible. The drilling results reveal, however, that the beds display a fluctuating but relatively level bedding in this zone. Crestal faults can only be detected in the steep flank area where they show only minor displacement.

The overburden in the transition zone towards the Rambow salt dome displays a completely different structure (Pl. 1: Fig. 10, cross section B–B‘; Fig. 30, profile 9502). Above a domed salt dome top, the beds of the Tertiary are dragged up and display an intact stratigraphic sequence that is displaced at crestal faults. Only below the central zone of the crestal graben, the salt dome surface, which comprises the cap rock, displays a regressive flattening due to subrosion. In this area, the Paleocene, the Lower Eocene, and the Middle Eocene are missing, which indicates that the salt dome was probably exposed at the seafloor in this period and was thus subjected to erosion and subrosion.

The schematic illustration of the development of the overburden above the salt structure (Fig. 30, A to C) explains the different bedding above the Gorleben salt dome and the transition zone towards the Rambow salt dome. In the crestal graben area above the transition zone towards the Rambow salt dome, there is a faulted but otherwise intact Tertiary blanket, which prevents major subrosion of the salt dome. As it continues to rise, an updoming of the salt dome surface occurs (Fig. 30, A). This state represents the primary stage of the salt dome top formation of profile 0010. Due to the significantly stronger salt uplift and the corresponding subrosion, an extensive movement of the thin overburden occurs in Gorleben at former crestal faults (Fig. 30, B), which leads to an extensive fracturing, deformation, and loosening of the overlying strata of the Tertiary. The degree of faulting is so high that it cannot be resolved by the shallow seismics (Fig. 30, C). This loosened zone is preferentially eroded by glacial processes so that Quaternary channel sediments directly overlie the structure‘s surface in some places.

Exactly above the top of the Rambow salt dome, which is situated outside the study area, there is a depression between 16 m and 20 m above sea level with two lakes and marshy meadows and in parts thicker organogenic sediments. According to Hurtig (1965) and Reinhard (1967), this depression was formed by recent subrosion processes. According to Hurtig (1965) und Reinhard (1967), the symmetric elevations of the rims between 40 m and 55 m above sea level indicate a recent (after the Warthe substage) uplift of the Rambow salt dome including the drag zone on the salt dome edge. The morphological findings are not as clear. The geomorphologic rim elements on the northwestern side are barely significant, too broad and evidently of glacial origin. The morphology on the plane table sheet Rambow is dominated by a northeast–southwest orientation and apparently displays a drainage network that was already formed in the Saalian age and coincidentally conforms with the depression that was formed by subrosion.

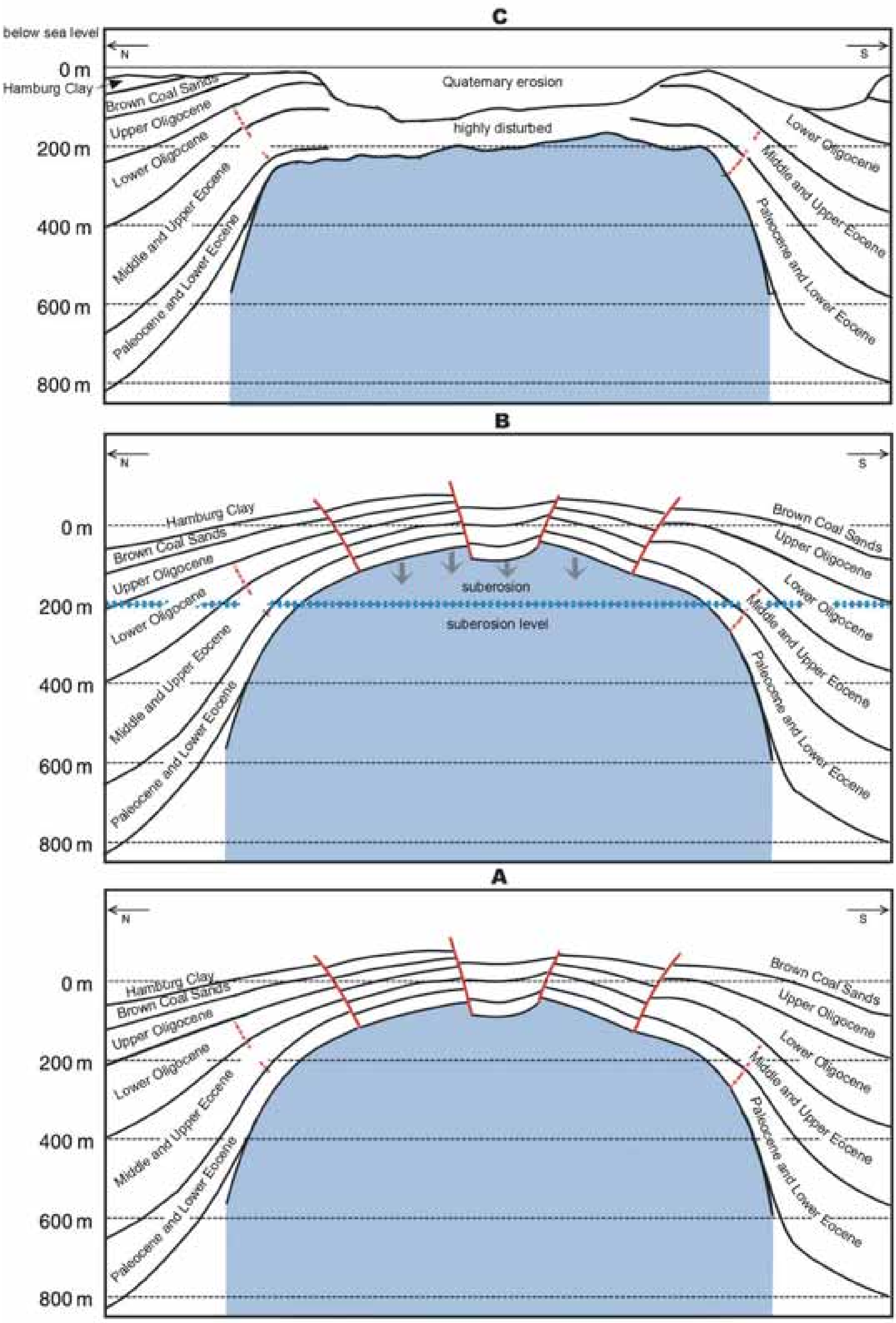
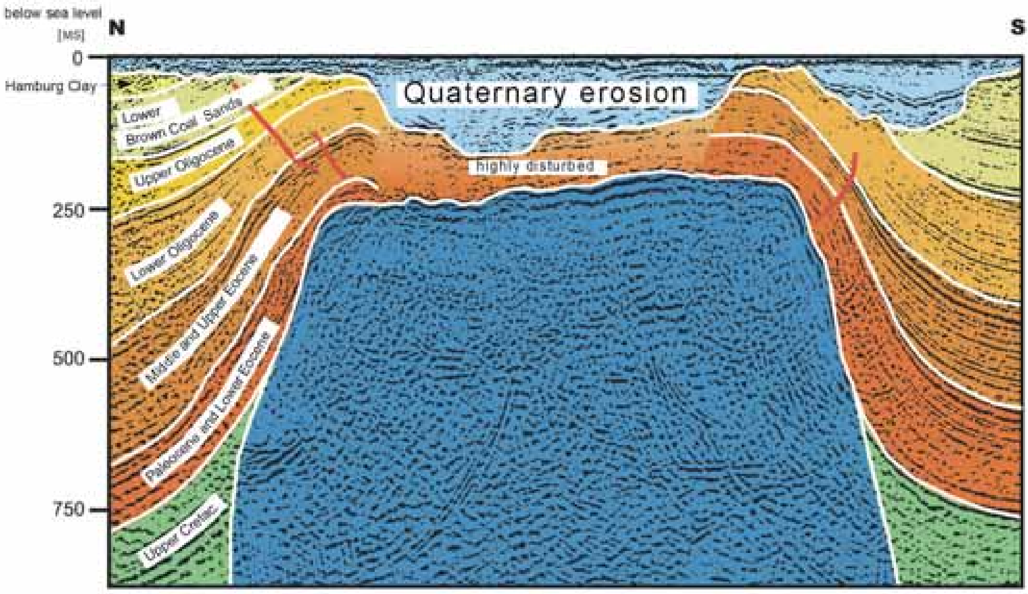


Figure 30: Development of the Tertiary overburden above the Gorleben salt dome

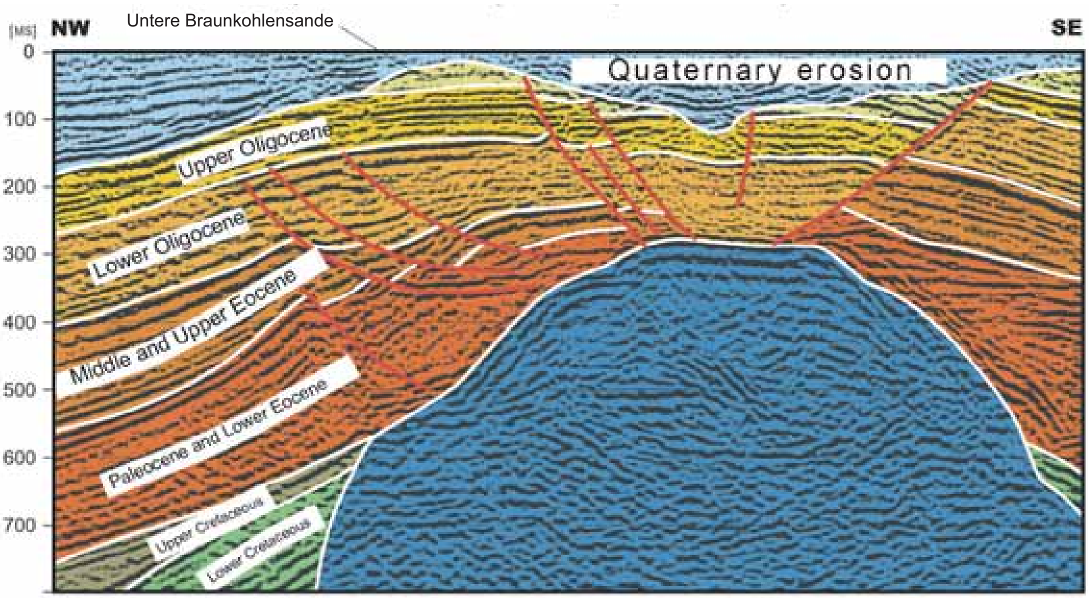
A: Conditions before Quaternary subrosion. Corresponds roughly to the present-day structure of the overburden in profile 9502 in the transition area towards the Rambow salt dome between Lenzen and the Elbe

B: Subsidence of the Tertiary overlying strata during the Quaternary due to increased subrosion

C: Present-day structure of the Tertiary overburden in profile 0010



shallow seismic profile 0010 (detail) with interpretation



shallow seismic profile 9502 (detail) with interpretation

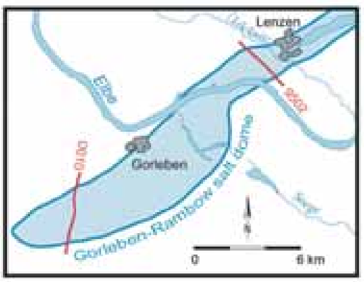


Figure 30: continued

A shallow borehole northeast of the Rambow Lake revealed sands, probably of the Warthe substage, beneath 7.7 m of organogenic sediments. The shallow-water sedimentation began in the Late Weichselian age and was dated by palynological analysis as the end of the Allerød. The available findings indicate that the Rambow salt dome had a different subrosion history in the Quaternary compared to the Gorleben salt dome. For example, there is no Elsterian age channel but mostly only a reduced Quaternary cover. The relatively thick Quaternary above the northeastern salt dome summit cannot be reliably identified either, as boreholes and shallow seismic surveys are missing for this zone and the profiles of boreholes E RmwL 101/64 and E RmwL 17/70 allow various interpretations. The geomorphological shape of the depression and the late-glacial to Holocene sequence of strata that was drilled northeast of the Rambow lake indicate recent subrosion at the Rambow salt dome, possibly through the Holocene, but do not reveal the age of the most recent or recent movements.

7.2 Bedding of the Zechstein and the Mesozoic

The description of the bedding of the Zechstein and the Mesozoic layer complexes refers to the area of structural analysis (Chapter 3.1).

Zechstein

In the area of structural analysis, the Zechstein base lies between 4 450 m below sea level in the northeast and 3 100 m below sea level in the southwestern part of the Gorleben salt dome. The depth contours trace the northeastern spurs of the Altmark ridge, which strikes from the southwest into the area of structural analysis (Brückner-Röhling et al. 2002) and causes an elevation of the Zechstein base in that area.

In contrast to the areas southwest and west of the area of structural analysis where marked fault zones displace the Zechstein base (fault zone of Gerstedt and Gülden–Braudel, cf. Fig. 25), only one continued fault in the north to northeast of the area of structural analysis can be attributed to a major fault zone (fault zone Eldena–Perleberg, cf. Fig. 25). However, the single faults show only a small displacement of less than 50 m. The other faults in the area of structural analysis have no preferential strike. They reach a longitudinal extent of 10 km maximum and displace the Zechstein base by less than 100 m.

The thickness of the Zechstein is between 4 000 m in the area of the Wittenberge salt dome and 100 m in the centre of the salt migration areas northwest and southeast of Rambow and on the outskirts of the Dömitz and Aulosen salt domes, which were formed in the Keuper age.

In the area of the primary rim synclines southeast and northwest of the Gorleben–Rambow salt structure, residual salt pillows occur, with a thickness of approx. 500 m. An even thicker residual salt pillow with up to 900 m thickness of the Zechstein is located south of Karstädt and is connected to the large pillow bottom of the Wittenberge salt dome. More pillows have formed on the outskirts of the salt domes of Gorleben (northwestern edge), Rambow, and Groß Heide–Siemen (southeastern edge). In the northwestern corner of the area of structural analysis, the thickness of the Zechstein increases to 1 900 m. This accumulation of salt belongs to the large pillow base of the Lübtheen salt dome, which is situated outside the area of structural analysis. Figure 31 displays the depth contours of the Zechstein surface. Within the salt dome outlines, the diapirs are shown without overhangs. Their top surface is defined by the top of the cap rock. Despite the salt movements, the Altmark ridge can be recognised outside the salt domes as an elevation even in this image (zone above 3 200 m below sea level southeast of Gorleben). The different levels of the salt dome top surfaces are clearly recognisable. The salt domes Dömitz and Aulosen have the smallest heights at 1 100 m and 900 m below sea level, respectively. The Werle salt dome rises slightly higher. Its top surface is at approx. 700 m below sea level. The cap rock surfaces of the other salt domes reach heights of less than 200 m below sea level. The salt domes of Wittenberge and Conow possess the highest peaks of less than 50 m below sea level. Above the salt domes of Gorleben, Rambow, and Groß Heide–Siemen, isolated cap rock eminences of less than 100 m below sea level were found.

Lower and Middle Bunter Sandstone

The depth of the base of the Lower and Middle Bunter is strongly influenced by salt movements in the underlying strata, which covered the morphology of the subsalt basement. Only in the salt migration zones outside the salt domes can the elevation of the Altmark ridge be recognised. Thus, the deepest area of the Bunter base is situated southwest of the area of structural analysis at approx. 3 000 m below sea level, and at the northern and southern boundaries at approx. 3 800 m below sea level. It plunges down to 4 300 m below sea level towards the northeast. In the flank zones of the salt domes of Gorleben, Rambow, Groß Heide–Siemen, Wittenberge, and Lübtheen, the base of the Bunter is inclined above the pillow bases at a medium-steep angle. At 1 400 m below sea level, the base of the Bunter reaches it greatest height in the drag zone of the northwestern flank of the Gorleben salt dome and on the southwestern edge of the Wittenberge salt dome.

Faults occur preferentially in the flank zones of the salt domes with drag zones and are of halokinetic origin. Thus, they do not show a link to the fault pattern in the Zechstein base.

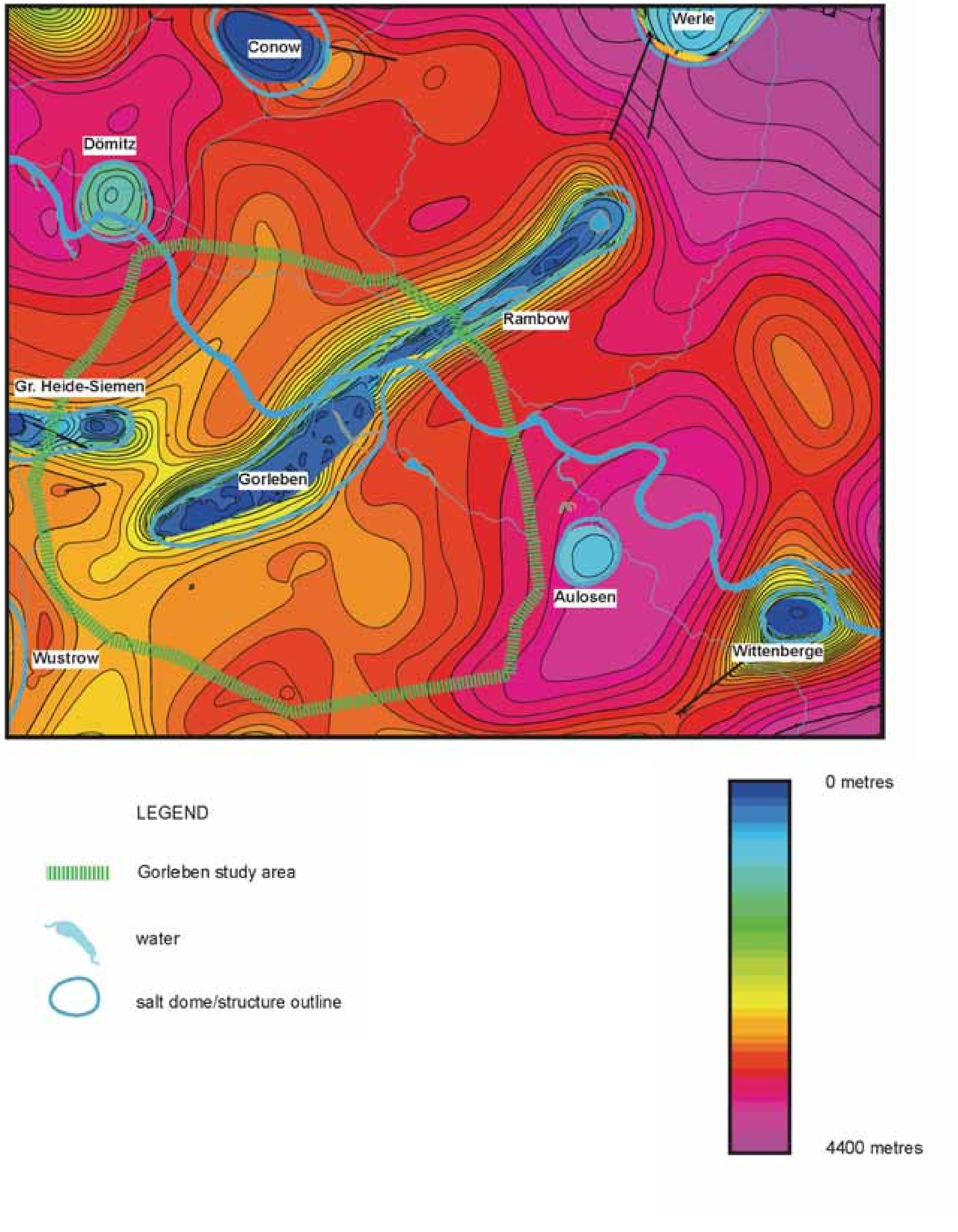


Figure 31: Depth contours of the Zechstein surface in the area of structural analysis

The average thickness of the Lower and Middle Bunter is between approx. 500 m in the southwest of the area of structural analysis and approx. 800 m at the eastern and northern boundaries. The presence of the Altmark ridge is evident in the slightly lower thicknesses around Gorleben. On the edges of the salt domes, some slighter thicknesses occur, which, however, cannot be unambiguously interpreted as synsedimentary, as the reliability of the seismic reflection survey is lower in these areas and the data thus have to be classified as unreliable.

Upper Bunter and Muschelkalk (Middle Triassic)

The extent and geometry of the Upper Bunter and Muschelkalk complex corresponds approximately to that of the Lower and Middle Bunter. In the salt migration zones southeast of Gorleben, the base lies at approx. 2 300 m below sea level, in the northeast of the area of structural analysis, it plunges down to 3 900 m below sea level. On the edges of the salt domes, the base of the Upper Bunter has been dragged up to a maximum height of 1 190 m below sea level (Wittenberge salt dome). On the northwestern flank and in the central part of the southeastern flank of the Gorleben salt dome, the sediments of the Upper Bunter and Muschelkalk that had been raised upward in the pillow stage were eroded before the transgression of the Early Cretaceous.

The fault pattern corresponds to that of the Lower and Middle Bunter. The displacements at these faults are mostly below 50 m.

The thickness of the Upper Bunter and Muschelkalk complex outside the salt structures that were active at that time is between 300 m in the southwest and 600 m to 700 m in the northern, eastern, and southern margins of the area of structural analysis. The area around Gorleben presents a thickness minimum, which shows that the Altmark Ridge was also active at the time of the Upper Bunter and Muschelkalk sedimentation. At the flanks of the salt domes of Gorleben, Rambow, Groß Heide–Siemen, and Conow, this bedding complex thins out, which is due to the elevation of these salt structures during the pillow stage.

Of note are the slight thicknesses of the Upper Bunter and Muschelkalk northwest of the Gorleben salt dome, which cannot be solely attributed to the ridge location of this zone. This minimum thickness actually suggests the existence of a large salt pillow at that time (Zirngast 1991).

Keuper

The geometry of the Keuper base differs from that of the Upper Bunter base mainly in the area of the salt structures. In a large area around the salt domes of Gorleben, Rambow, Wustrow, Conow, and Lübtheen, the Keuper sediments are missing. At the time of the Keuper, these structures reached their maximum pillow stage, which led to the truncation of the sediments in the crest zones. The salt domes of Dömitz and Aulosen, which broke through during the Keuper, are covered by Middle and Upper Keuper of slight thickness. In these zones, the Keuper base reaches a very high position, at approx. 1 050 m and 800 m below sea level, respectively. At the edge of the Wittenberge salt dome above the large pillow base, the Keuper base is even higher. In this zone, the Keuper has been dragged up to a maximum height of 500 m below sea level. Outside the salt domes, the deepest zones of the base in the southeast of the area of structural analysis are at 2 300 m to 2 400 m below sea level. Towards the north, south, and east, the Keuper base plunges and reaches its maximum depth in the northeast at 2 800 m below sea level.

The fault pattern resembles that of the Upper Bunter base. The crestal trench faults in the area of Wittenberge and between Werle and Rambow were active at that time.

The position of the supraregional ridge in the area of Gorleben cannot be reliably proven in the area of structural analysis, due to the large thickness variation caused by salt movements in the underlying strata.

The thickness of the Keuper is between 0 m and 1 900 m. These extreme differences are mainly due to halokinesis. Whilst the Keuper thins out in the flank zone of the former common pillow of the salt domes of Wustrow, Gorleben, Rambow, and Groß Heide–Siemen and of the pillows of Conow and Lübtheen, it attains thicknesses of 1 100 m and 1 900 m due to synsedimentary salt migration in the area of the salt domes Dömitz and Aulosen, respectively, which were formed during the Keuper.

Lias (Black Jurassic)

The extent of the Lias is also influenced by halokinesis. In the area of the former pillows of the younger salt domes (Wustrow, Gorleben, Rambow, Wittenberge, Lübtheen, Conow, and Werle), the Lias has been eroded or was not deposited. In the area of the secondary rim synclines near the younger salt structures, the Lias reaches depths with maximum values of 2 700 m below sea level in the vicinity of the Werle salt dome. Above the structures of Dömitz and Aulosen, which were formed during the Keuper and which are situated in the centres of the primary rim synclines, the Lias reaches its highest position at 700 m and 950 m below sea level, respectively. At the edge of the Wittenberge salt dome, the youngest salt dome in the area of structural analysis, the base of the Lias is turned steeply upwards due to the marked pillow base.

Beside the crestal trench faults caused by halokinesis in the flank zone of the Wittenberge salt dome, there are only insignificant faults of little extent above the structures of Aulosen and Dömitz and between Dömitz and Groß Heide–Siemen, which were also caused by salt movements.

The Lias reaches the largest thicknesses in the primary rim synclines northwest and southeast of the Gorleben–Rambow salt structure, outside the salt domes of Aulosen and Dömitz, which broke through in these areas during the Keuper. The largest thicknesses of 600 m maximum occur in the southeastern rim syncline, while the thickness values in the northwestern primary rim syncline remain below 450 m.

Dogger (Brown Jurassic)

The areas, where the Dogger has been eroded are considerably larger than the erosion gaps of the Lias. In the area of the Gorleben–Rambow salt structure and of the salt domes of Groß Heide–Siemen and Wustrow, the outcrop line traces the edge of the former common salt pillow (ZIRNGAST 1991). The salt domes of Conow and Lübtheen also had a common salt pillow, on top of which the Lias was not deposited or was eroded. In the area of the uplands above the salt domes of Aulosen and Dömitz, which were immobilised in the Keuper, the Dogger sediments are also missing. The steep flanks of the youngest salt structure, Wittenberge, are also free of Dogger beds.

The crestal trench faults at Wittenberge and Werle still occur in the Dogger but display only a slight displacement.

The thickness generally increases from west to east. Northwest of the Gorleben–Rambow salt structure, the Dogger reaches a maximum thickness of only 300 m, while in the southeast, thicknesses of up to 650 m occur. The largest thicknesses occur in the northeast of the area of structural analysis. In that zone, the Dogger sediments reach their maximum thickness of 1 350 m in the secondary rim syncline of Werle.

Malm (White Jurassic)

The Malm is only present in the east of the area of structural analysis, in the area of the Jurassic rim syncline of Werle and in the southeastern primary rim syncline of Rambow. The Malm has also been preserved east and southeast of the flanks of the Wittenberge salt dome. The deepest zones are located between Werle and Rambow, where the maximum depth of 2 200 m below sea level occurs in the crestal trench southeast of Werle. The Malm base reaches its highest points in the northeast of the area of structural analysis and above the Werle salt dome, where it rises above 600 m and 700 m below sea level, respectively. The crestal trench between Werle and Rambow was also active in the Malm age, which is confirmed by the greater thicknesses in the graben.

The Malm reaches its maximum thickness of approx. 1 000 m in the crestal trench of the secondary rim syncline of Werle. Another thickness maximum of 950 m occurs east of the Rambow salt dome.

Lower Cretaceous

The Lower Cretaceous is the most important transgressive stratigraphic member. It covers the largest part of the area of structural analysis (Pl. 3: Fig. 32). Only in the crest zones of the elevations of Aulosen and Karstädt, where the salt migration was concluded at that time, the Lower Cretaceous is missing due to Tertiary truncation. In the area of the salt domes Gorleben, Rambow, Wustrow and Conow, the base of the Lower Cretaceous displays a remarkable morphological differentiation with the deep depressions in the rim synclines. While sediments of the lower Lower Cretaceous were deposited in these areas, only Albian sediments were deposited upon Dogger, Lias, and Keuper in the remaining area. The base of the Lower Cretaceous often lies deeper than 2 000 m below sea level in the secondary rim synclines (Wustrow approx. 2 500 m, Gorleben approx. 2 200 m, Conow approx. 2 400 m below sea level). The maximum elevation of the Lower Cretaceous of approx. 500 m below sea level occurs in the buried outcrop area.

The faults are of minor importance and occur only in the outskirts of the salt domes.

The increase in thickness correlates with the depth of the base of Lower Cretaceous. The largest thicknesses of the Lower Cretaceous occur in the rim synclines (Wustrow approx. 700 m, Gorleben approx. 700 m, Conow approx. 900 m). Of note are the great thicknesses north and east of Rambow where the Lower Cretaceous thickens to approx 900 m.

Upper Cretaceous

The structure of the base of the Upper Cretaceous corresponds mostly to that of the Lower Cretaceous, although the Upper Cretaceous crops out in the eastern part of the area of structural analysis. This is due to a regional elevation east of the area of structural analysis (Prignitz–Lausitzer Wall). The greatest depths of the Upper Cretaceous are again in the secondary rim syncline of Wustrow (approx. 2 100 m below sea level) and Conow (approx. 1 800 m below sea level). The outcrop zone is between approx. 500 m and 700 m below sea level. Boreholes encountered thin relicts of the Upper Cretaceous above the Gorleben salt dome, which indicates that the salt dome was overlain in that period. Transgressive upper Upper Cretaceous also lies on the peripheries of the salt dome tops of Wustrow and Groß Heide–Siemen.

The faults correspond to those of the Lower Cretaceous. The largest thicknesses occur at the edges of the salt domes of Wustrow (approx. 1 300 m) and Gorleben (approx. 1 100 m at the southeastern edge of the diapir).

7.3 Bedding of the Tertiary

The base of the Tertiary (Pl. 3: Fig. 33) generally dips from southeast to northwest, like the Upper Cretaceous. As the structure of the base surface is still strongly influenced by salt migration in the underlying strata, the regional dip of the base towards the northwest of the area of structural analysis is not recognisable. The base morphology of the Tertiary traces the salt structures, similar to the Upper Cretaceous but in reduced form. The afterthrusts of the salt domes caused shallow rim synclines in the younger salt structures. The deepest rim synclines resulting from afterthrusting are between Conow and Lübtheen, where the base is lower than 1 350 m below sea level. The northwestern rim syncline of Gorleben has also sunk very deeply (beneath 1 150 m below sea level), which is due to the reduction in the pillow base during the Tertiary. In the southeastern rim syncline of Gorleben and in the rim synclines of Rambow, Wustrow, Groß Heide–Siemen and Conow, the base of the Tertiary lies between 800 m and 1 000 m below sea level. In the area of the structures of Dömitz and Aulosen, which originated in the Keuper, and the Werle structure, which broke through during the Jurassic, the base of the Tertiary displays no structuring, which means that salt migration had concluded. This means in turn that in this area, the normal epeirogenic level of the Tertiary base prevails at 600 m below sea level. The youngest salt structure Wittenberge, which is at the end of the pillow stage and at the beginning of the diapir stage, displays only a movement of the Tertiary base that is due to salt migration in the area of the northerly adjoining residual pillow.

The Tertiary reaches its maximum elevation above the salt dome roofs of the younger salt structures of Conow (8 m below sea level), Rambow (91 m below sea level), and Gorleben (106 m below sea level). Outside the salt domes, the Tertiary base consists of Paleocene beds, whilst on the high-rising salt dome tops of the younger salt structures the cap rock is superposed by beds of the Paleocene and in parts of the Lower Eocene. Above the top of the Wittenberge salt dome, the youngest diapir in the area of structural analysis, the sediments of the Tertiary are missing. And in the area of the Quaternary channel above the Gorleben salt dome, the Quaternary lies directly upon the cap rock in a more or less continuous area of approx. 7.5 km².

Outside the salt domes, only few faults occur. Their displacement is usually below 50 m. Crestal faults have been detected only above the salt dome roofs of Conow, Groß Heide–Siemen, and Gorleben–Rambow. Crestal trenches, which show fault throws of up to 200 m as in the well-explored transition zone towards the Rambow salt dome between Lenzen and the Elbe, have formed especially in those salt dome zones that possess an updomed, layered overburden. These faults at the base of the Tertiary above the salt rock or cap rock do not displace the base of the Tertiary, which in this area corresponds to the top surface of the salt dome.

The Tertiary beds reach from the edge of the structure across its surface, the beds of the Paleocene and Lower Eocene having the largest extent. Due to Quaternary erosion, the more recent Tertiary beds are missing above the central area of the Gorleben salt dome and partially above the eastern part of the Rambow salt dome, though the information in the latter case is not very reliable, as no exploration has taken place.

Due to the relatively high borehole density and the results of the shallow seismic surveys, the knowledge of the bedding of the Tertiary and Quaternary above the Gorleben salt dome and the adjoining section of the Rambow salt dome as far as Lenzen can be assessed as good.

Paleocene and Lower Eocene

In those areas that were not influenced by halotectonics, the thickness of the layer complex of Paleocene and Lower Eocene is between approx. 120 m in the southeast and 200 m in the northwest. In the rim synclines of the Gorleben–Rambow salt structure, the thickness rises above 200 m in the southeast, while maximum thicknesses of over 300 m occur in the northwest. Around the salt dome of Groß Heide–Siemen, thicknesses of over 300 m were also reached. In the central area of the Gorleben salt dome roof, the thicknesses of the Paleocene and the Lower Eocene decrease to less than 50 m.

The thicknesses of the Paleocene (only Upper Paleocene, cf. Chapter 4.2.1) next to and above the Gorleben salt dome differ very little. In the centres of the two rim synclines, the thickness is approx. 30 m to 40 m and it diminishes towards the outside edges to approx. 20 m to 30 m (Fig. 34). Above the Gorleben salt dome, the thickness of the Upper Paleocene deposits is mainly 5 m to 20 m, though in some boreholes higher values were observed. The reduced thickness towards the outcrop is partly due to variations in the salt dome top, and partly to transgression of the Lower Eocene beds (Gartow Sand) over the Upper Paleocene.

Unlike the Upper Paleocene, the Lower Eocene displays a strong differentiation in thickness between the Gorleben salt dome and the rim synclines. Above the salt dome, the stratigraphic sequence of the Lower Eocene is 34 m thick on average, with considerable differences between the salt dome crest and the salt dome edge/ring wall (approx. 5 m and 60 m to 80 m, respectively). In the rim synclines of the salt dome, however, the thickness of the Lower Eocene increases enormously to more than 300 m in the northwestern rim syncline and more than 200 m in the southeastern rim syncline.

In the crestal trench in the transition zone towards the Rambow salt dome between Lenzen and the Elbe, this layer complex is missing in some places. Above the western section of the Groß Heide–Siemen salt dome top, the sediments of the Paleocene and Lower Eocene are also missing. The cover of the eastern salt dome summit decreases to a few metres. Above the Lübtheen salt dome, the beds of the Paleocene and Lower Eocene thin out. The Conow salt dome has a cover of mostly less than 100 m, which diminishes to a few metres in exposed areas.

Middle and Upper Eocene

In the areas that were not influenced by halokinesis, the base of this layer package lies at approx. 400 m below sea level around Aulosen and at approx. 500 m below sea level in the Dömitz area. Distinctive rim synclines have formed at the flanks of the salt domes Wustrow, Groß Heide–Siemen, Lübtheen, Conow, and Gorleben. The deepest depression of the Middle Eocene base is in the rim synclines around Lübtheen and Gorleben. South of Lübtheen, the base lies beneath 1 000 m below sea level. Northwest of the Gorleben salt dome, it sinks to 880 m below sea level. In the other rim synclines, the base lies between 600 m and 700 m below sea level. Above the salt domes, the base of the Middle Eocene reaches its highest elevation of 0 m above sea level in the central top area of the Conow salt structure. At Gorleben, the highest elevations are above the dragged up flanks (ring wall), where maximum heights of approx. 120 m below sea level are reached. Above the salt table, the base sinks to approx. 160 m below sea level. Above the central sections of Gorleben, Rambow, Groß Heide–Siemen, Conow, and Wittenberge, the layer complex is missing.

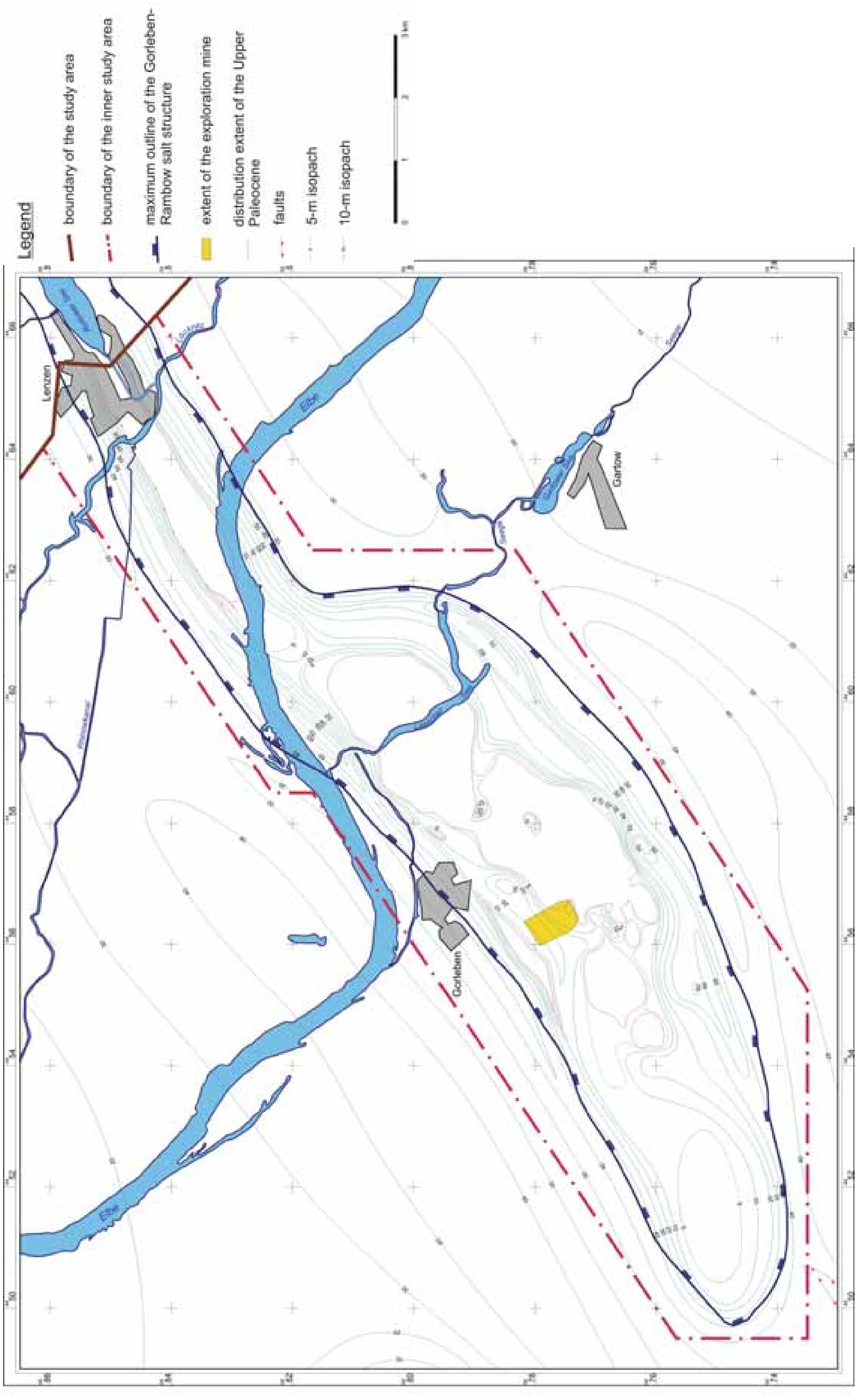


Figure 34: Thickness of the Upper Paleocene in the inner study area

In those areas where salt migration caused displacement of the beds of the overburden, faults have formed that mostly have fault throws of less than 50 m.

The thickness of the Middle and Upper Eocene is approx. 100 m in areas that were not influenced by halokinesis. The largest thicknesses of this layer complex in the rim synclines are northwest of Gorleben and north of Rambow where the beds grow to 300 m. This shows that the Gorleben–Rambow salt structure experienced the largest salt movements during this period compared to the other salt structures of the area of structural analysis. In the rim synclines of the other salt domes that were still active in this period (Wustrow, Groß Heide–Siemen, Lübtheen, and Conow) the Middle and Upper Eocene has a maximum thickness of 200 m.

Lower Oligocene

In the areas that were not influenced by halokinesis, the base of the Lower Oligocene lies at approx. 300 m below sea level around Aulosen and at approx. 400 m below sea level in the Dömitz area. Thus, it dips towards the northwest like the other beds of the Tertiary.

The deepest point of the Lower Oligocene base is in the rim syncline of Lübtheen (lower than 800 m below sea level). In the rim synclines of the salt domes of Wustrow, Conow and Rambow, the base of the Lower Oligocene lies between 500 m and 650 m below sea level. Above the salt dome tops, the base reaches its highest elevation at Conow, where it rises to 9 m above sea level. Above Gorleben, it also rises, above 100 m below sea level. Above the tops of the salt domes of Rambow and Groß Heide–Siemen, it is between 120 m and 200 m below sea level. In the central section of the salt dome top of Gorleben and above Conow and Wittenberge, this stratigraphic member is missing. Isolated summits of the salt domes of Rambow and Groß Heide–Siemen are also not covered by beds of the Lower Oligocene.

The fault pattern resembles that of the Middle Eocene base. The highest fault throws occur in the crestal trench area of Rambow where the southeastern crestal trench fault has a displacement of 100 m. The epeirogenic thickness varies between approx. 150 m in the southeast around Aulosen and approx. 170 m in the northwest around Dömitz.

The Lower Oligocene reaches it largest thickness of 260 m in the rim syncline southeast of Rambow. The rim synclines of the other active salt domes Gorleben, Wustrow, Groß Heide–Siemen, Lübtheen, Conow, and Wittenberge are filled with 200 m to 250 m of sediments of the Lower Oligocene. Above the salt structures, the Lower Oligocene thins out here and there. Northeast of Rambow, south of Gorleben, and around Wittenberge, the sediments thin out in the areas of the Quaternary channels, as the glacial erosion also affected this stratigraphic member.

Upper Oligocene

The depth of the base of the Upper Oligocene that was not influenced by halokinesis, lies at approx. 170 m below sea level around Aulosen and at approx. 220 m below sea level around Dömitz. The deepest point of the base is in the rim syncline of Lübtheen at approx. 600 to 700 m below sea level. In the northwestern rim syncline of the Gorleben–Rambow salt structure, the Upper Oligocene lies lower than 400 m below sea level. Of the other salt domes of the area of structural analysis, only Rambow, Conow, Wustrow, and Wittenberge possess significant rim synclines, where the Upper Oligocene, however, lies no deeper than 300 m below sea level. The base of the Upper Oligocene reaches its highest elevation above the Conow salt dome, where this stratigraphic member thins out at approx. 0 m above sea level. At Gorleben, the base lies above the ring wall at a maximum of 9 m below sea level. Above the central part of the salt dome roof of Gorleben, Conow, and Wittenberge, the Upper Oligocene is missing. The topmost parts of the salt domes of Rambow, Lübtheen, Wustrow and Groß Heide–Siemen are also free of sediments of the Upper Oligocene. Around of the Quaternary channels northeast of Rambow, south of Gorleben, and in the area of Wittenberge, the Upper Oligocene is completely eroded in some areas.

The fault frequency and the displacements are significantly lower compared to the underlying Tertiary beds.

The epeirogenic thickness is approx. 50 m around Aulosen and approx. 60 m southeast of Dömitz. The thickest sedimentary sequence of the Upper Oligocene occurs in the rim syncline of Lübtheen. There, the Upper Oligocene reaches the maximum thickness of 220 m in the area of structural analysis. The Upper Oligocene is also relatively thick in the northwestern rim syncline of Gorleben, where 140 m of sediments were deposited. Significant increases in thickness can also be found south of Rambow and north of Wittenberge, but these are less than 150 m.

Untere Braunkohlensande

The base of the Untere Braunkohlensande near Aulosen is at a depth of approx. 100 m below sea level and near Dömitz at approx. 120 m below sea level. This shows that the base also dipped towards the northwest during the sedimentation of the Untere Braunkohlensande. Significant rim synclines at the level of the Untere Braunkohlensande base were only formed at the salt domes of Lübtheen, Conow, Wustrow, and the Gorleben–Rambow salt structure. The deepest depression of the base is near Lübtheen where it lies at approx. 460 m below sea level. Northwest of the Gorleben–Rambow salt structure, the base is also below 300 m below sea level, which shows that the reduction of the pillow base continued. In the other rim synclines, the base lies between 160 m and 240 m below sea level. The Quaternary erosion zones, where the Untere Braunkohlensande are missing, have grown in size. The highest elevations of the base are at 20 m and 40 m below sea level above the salt dome edges of Gorleben and Conow, respectively.

The fault frequency is further reduced. Nonetheless, the faults in the crestal trench area between the Elbe and Lenzen continue to display fault throws of approx 150 m maximum.

The thickness of the Untere Braunkohlensande in the area of structural analysis is between 0 m and 140 m, as the surface of this stratigraphic member was indented by Quaternary erosion. The largest thicknesses occur in the rim synclines of the salt structures Gorleben–Rambow, Wustrow and Conow. The epeirogenic thickness can be estimated to be approx. 100 m.

Hamburg-Ton

The Hamburg-Ton is present only as a relict. Its largest extent is northwest of Gorleben. In this area it also reaches its deepest level, at 190 m below sea level. In the other areas it is between 0 m and 100 m below sea level. Above the top of the Gorleben–Rambow salt structure, relicts of the Hamburg-Ton have only been preserved in the crestal graben between Lenzen and the Elbe, which means that these faults were still active when the Hamburg-Ton was deposited.

The maximum thicknesses occur where there are residual salt deposits in the underlying strata; consequently the distribution of the Hamburg-Ton is linked to recent salt migrations. The largest thicknesses occur in the area of the pillow bases of Gorleben, Lübtheen and Conow (130 m maximum).

7.4 Bedding of the Quaternary

The bedding features of the Quaternary are smaller and more variable due to their glacial origin, compared to the large structural features of the beds from the Zechstein to the Tertiary. Thus, only the study area (Fig. 1) will be discussed in the following. The unconsolidated Quaternary rocks cover the older beds with a 10 m to 300 m thick sequence. The base of the Quaternary is polygenetic and heterochronic, i.e. it consists of elements of different genesis and age. The larger part of the base surface was formed by glacial forces of the Elster and Saalian Glaciations, the rest by fluvial processes during the preglacial and the Weichselian Glaciation.

The sedimentation of the Quaternary does not immediately succeed that of the Tertiary. The most recent Tertiary sediments are the Obere Braunkohlensande from the Early Miocene, the oldest Quaternary sediments are from the Menapian. The hiatus at the base of the Quaternary thus comprises a period of approx. 15 million years.

The Quaternary sequence of strata is represented by an almost complete sedimentary record from the end of the Menapian through to the Holocene. The bedding structure was primarily influenced by glacial processes such as erosion, exaration, and glacial dynamics, and to a lesser extent by subrosion.

Beds below the Quaternary

Beyond the limits of the Gorleben–Rambow salt structure, the beds of the Lower Miocene prevail (Braunkohlensande and Hamburg-Ton, Pl. 1: Fig. 35). Above the salt dome Groß Heide–Siemen in the core section southwest of Siemen, the clayey-silty rocks of the Lower Eocene and Rupelton lie at the base of the Quaternary sequence. In the Gorleben channel, the beds below the Quaternary consist of Eochattian and Neochattian to the north of the Gorleben–Rambow salt structure and additionally Rupelton to the south.

Above the Gorleben–Rambow salt structure, rocks of the Eocene and the Rupelton mainly occur at the base of the Quaternary sediments. Only in the area of the crestal trench faults southwest of Lenzen, deposits of the Untere Braunkohlensande and the Hamburg-Ton occur at the surface of the Tertiary. Above the northern half of the Gorleben salt dome, however, the Tertiary is missing. In a zone of approx. 7.5 km^2 size in the area of the Gorleben channel, the Quaternary lies directly on the cap rock.

The distributional mosaic of the beds is primarily dominated by the salt uplift from the Tertiary to the Early Pleistocene and by the deep Quaternary erosion. The beds of the Early Tertiary that had sunk in the northwestern rim syncline to a depth of approx. 1 150 m below sea level are domed up above the salt dome roof by halokinetic movements to a maximum elevation of 106 m below sea level (borehole GoHy 850). The clays and silts of the Lower Oligocene even reach heights of 30 m to 20 m below the surface in the northwestern part of the ring wall (approx. from Gorleben to the southwestern end of the salt dome). The Tertiary deposits that were hoisted by the halokinetic salt uplift display a centroclinal strike. From the rim synclines towards the salt dome, the beds underlying the Quaternary get successively older. The core of the updoming is occupied by rocks of the Early Eocene. The Tertiary beds dragged up into the halokinetic ring wall dip at values up to approx. 40°. This steep dip and the reduced thickness of the Tertiary beds on the salt dome flanks is expressed by very slim outcrops especially of the Middle to Upper Eocene and of the Upper Oligocene beds.

Quaternary Basement

The Quaternary basement displays a variable relief, where zones of slightly undulating morphology between approx. 20 m and 80 m below sea level alternate with elevated areas, where the Quaternary base lies above 20 m below sea level, and channel-like depressions, where the Quaternary base is at depths from approx. 100 m to below 280 m below sea level. In the area of structural analysis, the base depths sink below 400 m below sea level in those depressions. Due to the importance of the Quaternary channels, especially of the Gorleben Channel, with regard to the groundwater dynamics, these will be discussed in a chapter of their own (Chapter 7.4.1).

The elevations outside the channels form larger continuous areas on which the Hamburg-Ton and the Obere Braunkohlensande have been preserved at the Base of the Quaternary. These are therefore an image of the flat Early Tertiary ground surface that was cut up by erosion later on in the Quaternary. A series of minor crest-like elevations flank the northwestern and less markedly the southeastern edge of the Gorleben salt dome. This is the ring wall of the salt dome, where also older Tertiary beds outcrop at the Quaternary base, in contrast to the structures mentioned above.

Beds cropping out at the Quaternary base

The complicated bedding of the Quaternary can already be recognised by the fact that all major stratigraphic units of the Pleistocene – preglacial age, Elsterian Glaciation, Holsteinian Interglacial, Saalian and Weichselian Glaciations – are represented at the base (Pl. 1: Fig. 36).

The oldest deposits of the Quaternary – preglacial sands of the Menapian and to a lesser extent sands and silts of the Bavelian to Cromerian Complex –, have been preserved only above the southwestern part of the Gorleben salt dome. In the Gorleben Channel and the channel of Siemen–Wootz, the base of the Quaternary sequence is dominated by outwash sands of the Elsterian Glaciation. The Elsterian till represents the lowermost stratigraphic member of the Quaternary in large parts of the Gartow Channel, in scattered isolated spots in the centre of the Gorleben Channel, and locally on the channel flanks. Sediments of the Late Elsterian Lauenburger-Ton-Komplex, which are wide-spread in the Quaternary channels, form the Quaternary base only at the flanks of the channels and in the continuation of the Gartow Channel.

Outside of the extent of the Elsterian sediments, mainly deposits of the Drenthe substage of the Saalian Glaciation lie at the Quaternary base. In terms of areal extent, the outwash sands outweigh the tills and occasional lacustrine deposits. Amongst the tills, the till of the early Drenthe substage has the largest extent. The till of the late Drenthe substage and the beds of the Warthe substage occur only in small areas of the Quaternary base. The most recent sediments of the Quaternary base are the sands of the Lower Terrace above areas of elevated Tertiary, especially above the Tertiary elevation of Gusborn–Groß Schmölen.

Preglacial age

In the southwestern crestal area of the Gorleben salt dome, progressive subrosion created a shallow sedimentation basin during the Menapian (Chapter 8.2), which grew deeper in the centre and wider towards the flanks. According to palynological analyses by Müller (1986, 1992), the ground surface in this sedimentation basin at the beginning of the Bavelian consisted of a slightly depressed peneplain of approx. 3.5 km^2 size with shallow perennial lakes and bogs where subsidence and accumulation were approximately in step.

The developments took a completely different turn in a very limited area on the northeastern edge of the preglacial depression. At this spot, in the area of borehole GoHy 940/944, the slight thicknesses of the Menapian sediments (10 m), their resemblance to slippage and collapse masses, and the largest thicknesses of the Bavelian deposits (64 m) indicate that this is a sinkhole filling (Chapter 4.3.1).

It is probable, that the preglacial sediments originally extended even further to the northeast above the central part of the Gorleben salt dome. The reliable identification of preglacial gravels and sediments of the Bavelian in the cap rock of borehole GoHy 1171, approximately 5 km northeast of the secluded occurrence of preglacial sediments, permits this conclusion. The sediments were eroded during the Elsterian Glaciation when the Gorleben Channel was formed.

Elsterian Glaciation

The Elsterian sediments – advance sands, till, channel sands, deposits of the Lauenburger Ton, and retreat sands – form the thickest complex of strata within the Quaternary sequence, reaching a thickness of sometimes more that 200 m. Their distribution is closely related to the creation and filling of the Quaternary channels. Thus, their bedding will be discussed in more detail in the description of the Quaternary channels (Chapter 7.4.1). The sediments extend only rarely over and never far beyond the channel rims and in those cases they reach a base level of approx. 60 m below sea level.

The exception is a larger occurrence of Elsterian sediments above the southwestern central part of the Gorleben salt dome, where outwash sands of approx. 10 m thickness, superposed by till of approx. 30 m to 50 m thickness, form a plateau above preglacial sediments.

Holsteinian Interglacial

In the channel hollows that were not completely filled in the Elsterian age, limnic to limnic/fluvial silts, mud and sands were deposited during the following Holsteinian Interglacial. In these deposits, a marine transgression, which reached across the Lower Elbe into the study area, introduced beds with clayey and sandy sediments. The occurrences of these beds are closely bound to the Elsterian channels, in some areas the deposits extended beyond these channels. In large areas outside of the channels, the sediments of the Holsteinian Interglacial were probably not deposited. This is particularly true for areas of elevated Tertiary. The previously continuous distribution in the channels was divided into individual areas by Saalian erosion and exaration.

During the following Saalian Glaciation, the surface of the Holsteinian beds was locally greatly changed. The sediments of the Holsteinian and the upper parts of the Lauenburger-Ton-Komplex were intensely pushed and partially imbricated by the continental ice sheet of the Drenthe substage. In borehole GoHy 1301, four repetitions of the same pollen zone sequence of the Holsteinian beds were found. When the beds were imbricated, the clays of the Lauenburger-Ton-Komplex and the Holsteinian Interglacial acted as sliding planes. A particularly conspicuous example was encountered in the push moraine area of the Höhbeck (Duphorn 1980) where, according to mapping results, pushed Holsteinian lies at an elevation of up to 40 m above sea level. Boreholes identified pushed Holsteinian sediments down to 6.9 m below sea level (borehole GoHy 2325). The bedding complexes of the Holsteinian sediments that were disturbed by glacial processes are concentrated in an area southwest of the Höhbeck and east to southeast of Gorleben (Fig. 15). The complicated bedding is illustrated in Figure 9. Frequently, barely decimetre-thick sections of the Holsteinian were relocated by meltwaters of the Drenthe substage as compact blocks, which were more or less undisturbed, or were incorporated in the Drenthe till: in the Drenthe 1 till, e.g. in borehole GoHy 1170, and in the Drenthe 2 till in borehole GoHy 1560.

Saalian Glaciation

The sediments of the Saalian Glaciation are found almost everywhere in the subsurface of the study area. They crop out at the ground surface near the Elbe in the area of the push moraine of the Höhbeck and on elevations on the southern periphery of the study area (Chapter 4.3.4). In contrast to the sediments of the Elsterian and Holsteinian ages, the sedimentary distribution exhibits no dependency on the Quaternary base or the Quaternary channels. During the Saalian Glaciation, the Scandinavian glaciers transgressed the study area three times. As the processes of meltwater erosion, glacial exaration and sedimentary accumulation were repeated and superimposed during the different glaciations, the deposited sediments (outwash sands, till and glaciolacustrine deposits) vary strongly in their extent, thickness and depth. Comparing the exposure density and the frequent rapid pinch-out of single stratigraphic members, the bedding conditions can be described only in general terms. The base of the Saalian beds most often lies between 20 m and 80 m below sea level. It is mainly formed by the deposits of the Drenthe substage.

The base of the till of the older Drenthe substage is sometimes lower than 100 m below sea level, the maximum depth is at 152.6 m below sea level, in an exaration form northeast of Woltersdorf (borehole GoHy 370). The base surface is mostly at a level between 35 m and 85 m below sea level. The Drenthe 2 till usually lies higher, between 5 m and 50 m below sea level, but also reaches depths of 90 m below sea level (borehole GoHy 230). The tills partially overlap; in 42 boreholes both tills were encountered. On the other hand, there are differences in the distribution. The Drenthe 2 till, for instance, is dissected into smaller sections and is missing in large areas south and northwest of the Gorleben–Rambow salt structure.

Increased thicknesses of Drenthe outwash sands were found in sections of the Gorleben Channel. Advance sands contributed to a considerable degree. According to observations from neighbouring areas (Ehlers 1990, Rühberg et al. 1995), this could represent a last relief levelling of the Quaternary channels. Above the Gorleben salt dome, especially in the area of the Weißes Moor and its vicinity, this process was accompanied by local post-Holsteinian subrosion (Chapter 8.3).

The average depth of the sedimentary base of the Warthe substage is at approx. 11 m below sea level and thus significantly higher than that of the Drenthe sediments. The sediments mainly consist of outwash sand and till. The till of the Warthe moraine crops out in large areas of the western Höhbeck as a so-called cover moraine. In the subsurface, it occurs in large areas, primarily between Gartow and Prezelle as well as northwest of the Gorleben salt dome. The deepest depression of the Warthe till is situated above the salt dome of Groß Heide–Siemen and has a depth of 52.5 m below sea level. Duphorn (1983) refers to this hollow as a subrosion depression of the Saalian age. As similar depressions and thicknesses of the Warthe till occur, irrespective of the presence of salt structures underneath, it is more probable that this depression above the salt dome of Groß Heide–Siemen is an exaration form of the Warthe substage.

A major part of the Warthe outwash sands were deposited after the retreat of the Warthe continental ice sheet. These sands signify the start of the burial and flattening of the glacial relief of the Saalian Glaciation. It is probable that the Weichselian Elbe ice-marginal valley was created during this period (Chapter 4.3.4).

Eemian Interglacial

Autochthonous Eemian sediments were detected only in one borehole (GoHy 620) far away from the Gorleben–Rambow salt structure, at a depth of 6 m to 10 m below sea level. The deposits are embedded between fluvial sands of the older Lower Terrace and glaciofluvial deposits of the Warthe substage of the Saalian Glaciation. Allochthonous Eemian debris was encountered in the Lower Terrace sands of borehole GoHy 312, which indicates that thin deposits of Eemian sediments may have been eroded and relocated during the Weichselian Glaciation.

Weichselian Glaciation

The sediments of the Weichselian Lower Terrace are distributed throughout the whole study area except for the Geest uplands. They form a coherent deposit and reach from the ground surface to a maximum depth of 32 m below ground level (borehole GoHy 620). The base depth of the Lower Terrace varies between 3 m below sea level and 9 m above sea level on average. The deepest value is 14.9 m below sea level (borehole GoQ 14). The average thickness of the deposits is 16 m. The beds below the Lower Terrace are mainly formed by Saalian sediments. On the Tertiary elevation of Gusborn–Groß Schmölen and occasionally south of the Gorleben salt dome, deposits of the Tertiary (Hamburg-Ton and Obere Braunkohlensande) lie below the base of the Lower Terrace. Above the ring wall, Rupelton (borehole GoHy 140) or Untere Braunkohlensande (GoHy 1720) lie locally directly beneath the Lower Terrace.

The base of the **older Lower Terrace** displays a marked relief with several channels, depressions, and minor higher areas. The depressions are mostly restricted to areas where outwash sands lie underneath. Till and glaciolacustrine silts frequently form the higher areas or jut out through the older Lower Terrace. This relief, which mainly originated from the Warthe substage, was buried and filled by the older Lower Terrace. On the whole, there is a slight dip towards the northwest.

The initial relief of the Warthe substage was mostly buried by the accumulation of the older Lower Terrace deposits with the exception of the Geest uplands. Due to this burial, the deposits of the **younger Lower Terrace** occupy the whole lowland surface of the Elbe floodplain (Duphorn 1980: 26). The base surface has become more level and lies higher, at a depth between 5 m and 12 m above sea level.

When the peak of the Weichselian Glacial ebbed, the sedimentation of the Lower Terrace stopped. In the higher areas of the Elbe floodplain, cover of aeolian sands that is approx. 2 m thick and in some spots dunes more than ten metres high were deposited by the wind during the Late Weichselian Glaciation stage (Chapter 4.3.7).

Holocene

At the surface of the Elbe floodplain, floodplain loam crops out in large areas, or floodplain sand as the youngest sediment overlies the Lower Terrace without a distinct boundary. Muds and peat, which formed preferentially in the river valleys of the Löcknitz, Elde, and Seege, are less common. The deposits are mostly between 1 m and 3 m thick, the maximum thickness is 6.5 m. The structure, thickness, extent, and development of the Holocene sequence of strata were investigated and described in detail in the Quaternary geological survey (Duphorn 1980).

7.4.1 Quaternary channels

The most significant feature of the Quaternary base are deep, more or less parallel channels. The prevailing opinion is that the channels were formed polygenetically by exaration and subglacial glacio-hydromechanic processes at the height of and at the beginning of the decline of the first Elsterian advance (main Elster) (Chapter 4.3.2). They are a phenomenon that can be observed on the whole North German Plain from the town of Bremen to Lower Lusatia, and they exhibit mostly a NNE to SSW or NE to SW direction. Their overdeepening reaches far below the level of the Elsterian ground surface. In areas with high borehole density, they can be recognised as structures with diverse gradients, which often begin and end abruptly. In their course, overdeepenings occur in series, like strings of pearls. No close relationships with salt structures or the pre-Quaternary geology have been shown (Kuster & Meyer 1979; Hönemann et al. 1995; Schwab & Ludwig 1996; Lippstreu 2002).

The Quaternary channels in the study area correspond in their configuration, direction, and sedimentary filling to the structures in the general region. However, they do not attain the dimensions of the Hagenow Channel (deeper than 500 m below sea level) or the Prignitz Channel (deeper than 400 m below sea level), which are situated to the northwest and southeast, respectively.

The dominating element and largest coherent depression is the **Gorleben Channel**. It extends across the whole study area from NNE to SSW (Fig. 14) and ends relatively abruptly beyond the area, towards the north-northeast roughly east of Gorlosen, and towards the SSW at the Bockleben salt dome (Brückner-Röhling et al. 2002). The overall length is approx. 40 km. It crosses the Gorleben–Rambow salt structure on a stretch of approx. 10 km at an acute angle. The channel width at the 100 m isobath is approx. 2 km to 4 km. Genetically, the Gorleben Channel is to be considered as a unit that was predominantly formed by glacio-hydromechanic erosion and filled with outwash sands (Fig. 36). Upon entering the study area in the northeast, the channel mostly reaches depths deeper than 200 m below sea level (Fig. 14). Its gradient is variable. Above the Gorleben salt dome and in the southwestern continuation of the channel, depths of more than 250 m below sea level are lined up like a string of pearls. Outside the Gorleben–Rambow salt structure, sediments of the Upper Oligocene form the channel base. Above the Gorleben salt dome, erosion cut through sediments of the Lower Oligocene to Lower Eocene. Above the central part of the salt dome, for a length of approx. 6 km and a surface of approx. 7.5 km^2, the Tertiary beds were completely eroded, so sediments of the Elsterian Glaciation lie directly on the cap rock and in some spots even on the salt table. In this area, the channel base relief is highly variable, with depths between 240 m below sea level and almost 300 m below sea level (borehole GoHy 484 = 292.0 m below sea level). According to Bornemann (1991), this marked relief is due to reef-like protrusions of the main anhydrite where the surrounding rock salt was partially eroded during the Elsterian Glaciation.

The formation of the **cap rock breccia** is causally associated with the formation of the Gorleben Channel. It mainly consists of jagged lumps of brecciated cap rock as well as clastic and carbonaceous material of the former overburden. When the channel was formed, the beds of the overburden and parts of the cap rock were destroyed and blended with Nordic material (e.g. Nordic debris of millimetre to cobble size) to form breccia (Bornemann 1991). During this process, meltwaters were able to penetrate to a certain depth into the zone between cap rock and salt formation, which is considered to be a zone of weakness due to its lacking resistance to erosion (Jaritz 1994). They extended laterally from where the channel was being formed and deposited the breccia at the base of the otherwise intact cap rock. Depending on the distance to the Gorleben Channel, a decrease in breccia formation and in the amount of injected Nordic material can be observed.

Other overdeepenings that were formed in the Elsterian Glaciation are the channels of Gartow and Siemen–Wootz. Between Mödlich and Wootz, in the area of boreholes GoHy 1510 and GoHy 1520 (Quaternary base at 135.3 m and 110.3 m below sea level, respectively), the **channel of Siemen–Wootz** (Fig. 14) branches from the Gorleben Channel, extends north of Dünsche approximately in the area of the northwestern rim syncline, subsequently turns towards the northwest, and ends near Gusborn. In the area described, it embraces the Tertiary elevation of Gusborn–Groß Schmölen and has its greatest depth of more than 200 m below sea level east of the salt dome of Groß Heide–Siemen. The basal filling of this channel consists of outwash sands of the Elsterian Glaciation and indicates, like the Gorleben Channel, a mainly glacio-hydromechanic genesis of this structure. Relicts of Elsterian till at the flanks of the channel indicate a priming of the hollow by exaration. The assertion that formation of the rim synclines continued in the Quaternary, and the conclusion from the course and the sedimentary structure of the channel that there is even a “Quaternary rim syncline” (Duphorn 1983: 106) are no longer accepted. Firstly, the depression of the Quaternary only partially coincides with great depths of the Miocene rim syncline; and secondly, and more compellingly, the erosive incision of the Elsterian outwash sands in the beds of the Lower Miocene contradicts a continued trend of halokinetic subsidence in the Elsterian Glaciation (Pl. 1: Fig. 10). North of the Elbe, the Quaternary base even has a relative elevation above the Miocene depression centre (boreholes GoHy 1580 = 75.6 m below sea level and GoHy 1690 = 37.0 m below sea level).

The **Gartow Channel** (Fig. 14) reaches depths of 160 m to 180 m below sea level and joins the Gorleben Channel north of Prezelle. The wide-spread distribution of Elsterian till on the channel bottom indicates that it was mainly formed by glacial plucking (exaration) by the Elsterian continental ice, unlike the other two channels of the study area mentioned above. The channel extends with a variable gradient towards the northeast into the area of Klüß–Marnitz. It sinks locally to depths of more than 400 m below sea level, which in large sections is attributed to glacio-hydromechanic erosion.

As previously mentioned, the lower part of the channels is dominated by sandy sediments with thicknesses of more than 100 m (Chapter 4.3.2). In many places, they contain large proportions of Miocene sediments that had been flushed from the channel rims. In some parts, the channel sands consist exclusively of relocated Tertiary material or whole blocks are embedded, e.g. a block of 18 m size consisting of Hamburg-Ton sediments in borehole GoHy 1710. Layers and larger packages of till, less often silt, occur relatively frequently at varying levels. Their emplacement is mainly due to slippage, flow, and collapse from higher levels. The overall bedding of the lower channel sections can be described as largely chaotic.

Towards the top, the filling of the channels consists of the thick sequence of strata of the Lauenburger-Ton-Komplex. In the seemingly compact layer package, which reaches a thickness of almost 150 m, the bedding is complicated by repeated changes of facies between clayey/silty and more sandy material. Due to deep-thaw processes, ice floe transport, and slumps, till was locally embedded.

In the upper clayey-silty parts of the Lauenburger-Ton-Komplex, bedding disturbances frequently occur, due to destructive processes. These were caused by slope failure and subsidence caused by buried dead ice during the melting phase of the Elsterian ice sheet. Further post-sedimentary bedding disturbances were caused by subsidence and glacigenic isostatic movements during the Saalian Glaciation. The upthrust of clayey/silty sediments as reported from shaft Gorleben 2 (Ludwig 1993) may be mainly attributed to gravitative, auto-plastic processes (Mollisol). Due to glacigenic deformation, extensive block- and scale-forming processes took place in the upper zones of the Lauenburger-Ton-Komplex, mainly in the area of the Höhbeck, its environs, and locally in other areas (Pl. 1: Fig. 9).

7.4.2 Glacigenic deformation

In numerous borehole profiles and during the Quaternary geological survey of the Höhbeck push moraine, many characteristics of glacigenic deformations were found. They are confirmed by blocks of older rocks in the Quaternary beds, repetition of beds, and large bed displacements. Locally, the deformations reach below the Quaternary base. They were caused by the continental glaciers of the Drenthe substage.

North of the Elbe, in the area of boreholes GoHy 1560, GoHy 1580, and GoHy 1690, deeply penetrating glaciotectonic bedding faults are common (Pl. 1: Fig. 9; Fig. 10, cross section B–B'). Sequence inclinations of the silts and clays of the Hamburg-Ton of up to 90° were detected in driven cores as well as in core sequences of the boreholes. Within the disturbed core sequences, there are also horizontally bedded, undisturbed zones of several metres thickness. The glaciotectonic stress left steep inclinations, folds, and imbrications of the sediments without large-scale displacement or compression of parts of the Hamburg-Ton.

The vertical extent and depth of these deformations vary. According to point measurements in driven cores of boreholes GoHy 1630 and GoHy 1650, the penetration depth reaches between 60 m and 90 m below ground level to a depth of 141 m below ground surface in longer core sections of borehole GoHy 1584 and thus up to approx. 50 m into the Hamburg-Ton. The deeper-lying zones of the Hamburg-Ton in these boreholes are undisturbed and level-bedded. In the area south of the Elbe, the glaciotectonic deformations gradually disappear at a depth between 120 and 150 m below ground level according to the mapping results of the Höhbeck and the borehole profiles (Duphorn 1983: 153). The Gorleben salt dome is not affected by these disturbances.

The largest coherent block of Tertiary beds (silts of the Reinbek and Hamburg-Ton) that the glacier plucked from the surface has a thickness of 51 m in borehole GoHy 110 and is inserted between Drenthe 1 and Drenthe 2 till.

Beside deformations due to channel formation (slope failures, kettle holes caused by buried ice melt) and gravitative auto-plastic processes (Mollisol), there are also local glaciotectonic bedding disturbances in the upper part of the Lauenburger-Ton-Komplex. These are particularly conspicuous in the shallow seismic profiles of the southwestern environs of the Höhbeck, in an area from the Laascher See (Laasche Lake) to northeast of the exploration mine. In that area, several clayey/silty top sections have been pushed out of the Lauenburger-Ton-Komplex and have been obliquely stacked or imbricated with Holstein-Ton (see above and Pl. 1: Fig. 9). The vertical extent of these disturbances reaches to approx. 100 m below ground level.

A glaciotectonic imbricate structure with Lauenburger Ton and Holstein-Ton, and rarely Tertiary clay acting as sliding planes, has been reported by Duphorn (1980, 1983) based on the mapping results from the push moraine complex of the Höhbeck. The eastern half of the Höhbeck is morphologically dominated by a WNW to ESE-striking relief of crests and hollows consisting of pushed-up sediments of the Drenthe substage. Scales from the Tertiary, Lauenburger Ton and the Holsteinian Interglacial are embedded with the same strike. The western part of the Höhbeck exhibits a simpler structure. In this area, the Warthe till lies widely spread as a “cover moraine” on top of older, more or less compressed beds. The textural features in the exposures and the reconstruction of the directions of the three Saalian ice advances indicate that the significant push-up processes at the Höhbeck took place during the two Drenthe substages, and the glacier of the Warthe substage only modified the results.

7.5 Structures below the salt structure

The bed immediately beneath the salt structure consists of the upper boundary of the pre-existing Zechstein sequence (basal anhydrite), as the strata older than the rock salt of the Stassfurt sequence did not participate in the halokinetic processes due to their rigidity.

Below the Gorleben–Rambow salt structure, the Zechstein base was penetrated by four boreholes, though only two of these were sunk in the central zone of the salt structure (E RmwL 12/Ah3 and E RmwL 11A/69). Borehole Gorleben Z1 reached the base at the northwestern edge of the Gorleben salt dome, whilst boreholes RmwL 17/10 and RmwL 101/64 explored the depth of the Zechstein base at the northeastern edge of the Rambow salt dome.

Reflection seismics show the geometry of the Zechstein base directly below the salt structure in three salt dome and salt flank undershootings performed in 1984 (Fig. 37). No fault displacements of the Zechstein base are discernible in these seismograms. Beneath the Gorleben–Rambow salt structure, the Zechstein base overlies concordantly, but with a stratigraphic gap the Upper red beds of the Permian. The Gorleben salt dome lies above an elevation of the Zechstein base, the highest section of which (3 100 m below sea level) lies under the southwestern part of the Gorleben salt dome. This elevation is caused by the Altmark ridge (Chapter 5). The axis of the elevation runs beneath the Gorleben–Rambow salt structure and dips towards the northeastern end of the Rambow salt dome to a depth of 3 800 m below sea level.

In the area of the Wustrow salt dome southwest of Gorleben, numerous boreholes and extensive seismic reflection surveys mapped a tightly spaced fault pattern above the top of the Altmark ridge, which shows strikes of mainly SSW to NNE, E-W, and less often NW to SE (BRÜCKNER-RÖHLING et al. 2002). BENOX et al. (1997) note, however, that the multiple changes of orientation in the area of the Zechstein base often prevent the detection of significant displacements and thus hinder or even prevent their mapping. Hence, faults with small displacement (< 50 m) may also be present under the Gorleben–Rambow salt structure but cannot be detected in the seismic reflection survey.

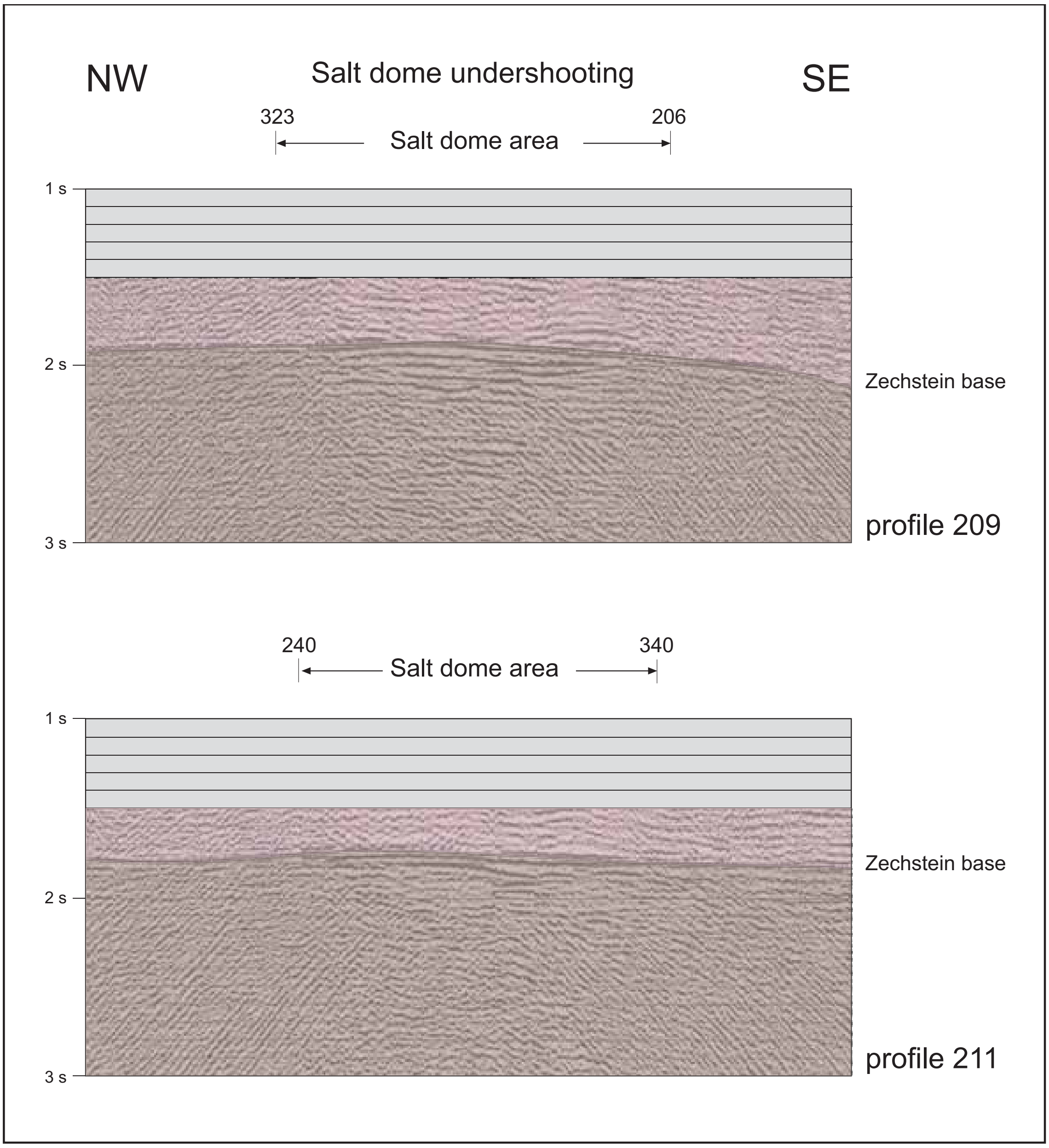


Figure 37: Seismograms of the salt dome undershootings of the seismic reflection survey Gorleben 1984

Boreholes E RmwL 12 Ah3 and E RmwL 11A/69, which penetrated the Zechstein base under the Rambow salt dome, revealed no indications of faults under the structure. The presumed Lower Elbe fault, which is believed to cross underneath the Gorleben–Rambow salt structure (Beutler 2001), could not yet be detected in the area (Chapter 5.4).

A detailed description of the internal structure of the Gorleben salt dome can be found in Bornemann et al. (2007).

7.5.1 Basement faults

Investigations of salt domes in Northwest Germany have shown that especially elongated diapirs often occur along basement fault zones (Fig. 26; BALDSCHUHN et al. 1996). Thus, basement faults are thought to trigger diapirism. Experiments have shown that movements in the base of salt beds lead to the formation of trenches in the buffered beds of the overburden above the salt (thin-skinned extension). These trenches present a zone of weakness in the overburden, which is invaded by the underlying salt (reactive diapirism), where the trench formation and thus the ingress of the diapir often occur in the vicinity of the triggering basement fault. Hence, the salt accumulation does not necessarily have to take place directly above the basement faults (see GUGLIEMO et al. 1995).

KAPUSTIN (1971) and RÜHBERG (1976) postulated that a supraregional fault line existed under the Gorleben–Rambow salt structure, which was believed to extend north-eastwards to the Marnitz salt pillow. Subsequent investigations and interpretations, however, produced no evidence of a significant basement fault, neither in the area of the Gorleben–Rambow salt structure nor in the north-easterly extension towards the Marnitz salt pillow. While prospecting for hydrocarbons, seismic reflection surveys were conducted in the area of the Rambow salt dome and three deep boreholes were sunk to explore the strata underlying the salt dome in the area between Lenzen and the Elbe. These investigations revealed that there is no displacement in the Zechstein base under the salt structure. As normal seismic reflection methods produce no or only inconclusive reflections of the Zechstein base under the salt dome, the seismic reflection survey of the Gorleben salt dome in 1984 comprised three salt dome and salt flank undershootings, which also produced no evidence of a basement fault.

7.6 Structures on top of the salt structure

7.6.1 Salt table

The salt table (the interface between the cap rock and the underlying salt formation) above the Gorleben salt dome lies between approx. 340 m and 160 m below sea level (BORNEMANN 1991). In the adjoining transition zone towards the Rambow salt dome between the Elbe and Lenzen, the salt table was also encountered in boreholes at depths between 341 m and 230 m below sea level. On the Rambow salt dome, there are only two boreholes, which encountered the salt table at 207 m and 91 m below sea level. There is no borehole in the area of the Elbe, where the surface of the structure between the salt domes of Gorleben and Rambow sinks to approx. 400 m below sea level, thus no evidence of the salt table at this depth is available.

On top of the Gorleben salt dome, the highest zones of the salt table are situated in the southeastern part of the structure surface. In the area of the Gorleben Channel, the Elsterian erosion caused a lowering of the salt table to below 300 m below sea level. Except for this zone, the salt table forms a slight updoming across the central areas of the salt dome. Towards the salt dome edges, it dips to a minimum depth of 300 m below sea level.

7.6.2 Cap rock

Above the salt table, cap rock is usually found (a cap on top of the salt formation that mainly consists of gypsum). The cap rock has different zones of characteristic textures from top (old) to bottom (young) (BORNEMANN 1991):

- **Flaser and nodular gypsum** ("Flaser- und Knollengips", maximum thickness 10 m)
- **Pinstriped gypsum** ("Liniengips", average thickness 10 m)
- **Spotted gypsum** ("Sprenkelgips", a few metres to approx. 15 m)

Underneath follows the **cap rock breccia** that was formed during the Elsterian Glaciation, a mixture of lumps of the overlying cap rock types with a matrix of sandstone, in parts with Nordic tills. The formation of the cap rock breccia is causally associated with the formation of the Gorleben Channel during the Elsterian Glaciation. When the channel was cut, the beds in the overburden and the cap rock were destroyed, blended to breccia, and pressed from the channel into the weak zone at the salt table by the load of the overlying ice.

Under the cap rock breccia follows the youngest bed, the **gypsum anhydrite laminate** ("Geschichtetes Gips/Anhydritgestein"), which consists of residues of post-Elsterian subrosion.

The cap rock surface exhibits a strong relief with differences in elevation of approx. 200 m (elevations: approx. 100 m below sea level; troughs: approx. 300 m below sea level), which can be attributed to the varying thickness of the cap rock on the one hand and the influence of the Quaternary channel on the other hand, where the cap rock was partially or completely eroded. The thickness of the cap rock as encountered in boreholes varies between 111 m maximum and 0 m. The average thickness of the cap rock is between 20 m and 40 m. Larger thicknesses only occur where blocks of main anhydrite ("Hauptanhydrit") or subrosion residues of the upper Zechstein 3 are enclosed in the cap rock.

On top of the cap rock of the Gorleben salt dome, the oldest sediments found in boreholes were isolated relicts of the former Cretaceous cover. Their thickness is usually under 10 m. The largest part of the cap rock is overlain by Tertiary sediments. Only in the centre of the Quaternary channel and in areas of isolated cap rock protrusions, are the Quaternary beds directly on the cap rock surface.

Outside the salt dome, immediately southeast of the southeastern edge of the salt structure, borehole GoHy 1005 encountered salt of the Upper Bunter accompanied by a **pre- or Early Cretaceous cap rock** at a depth of 1 894 m (Bornemann et al. 1989).

This is an early form of cap rock, which was formed in the uplift interval from the Malm to the Early Cretaceous, when the salt cropped out at the ground surface. Figure 38 illustrates the possible genesis and preservation of this cap rock relict. Phase I shows the outcrop of the salt at the time of the Malm/Early Cretaceous, when the salt dome lay bare at the surface. The salt flowed over the adjoining rock at the level of the Upper Bunter salts and was dissolved there. The residues were covered during the Albian transgression, while the salt uplift of the salt dome continued (phase II). An indication of the salt spill at the beginning of the Cretaceous is provided by the current internal structure of the salt dome. The boundary of the Stassfurt salt to the salt of the Leine and Aller sequences ends at the adjoining rock of the southeastern flanks at the level of the Lower Cretaceous.

During the continued diapirism, new cap rock formed at the top of the salt dome (phases III and IV). The salt supply consisted mainly of the mobile Stassfurt salt. To a lesser extent, younger rock salt also migrated into the salt dome and caused the formation of the inverted syncline in the southeastern part of the salt dome.

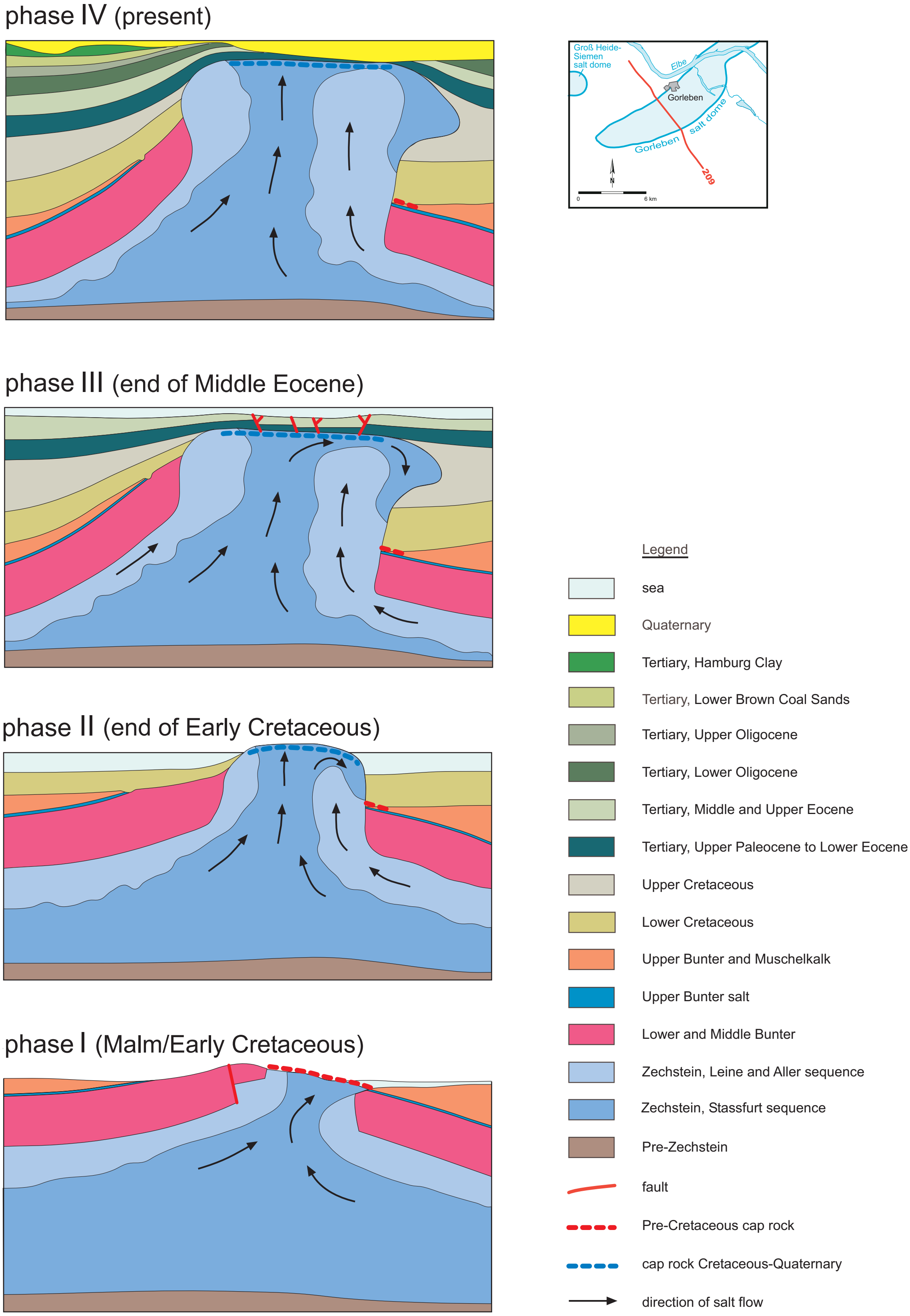


Figure 38: Development history of the Early or pre-Cretaceous cap rock encountered at the southeastern flank

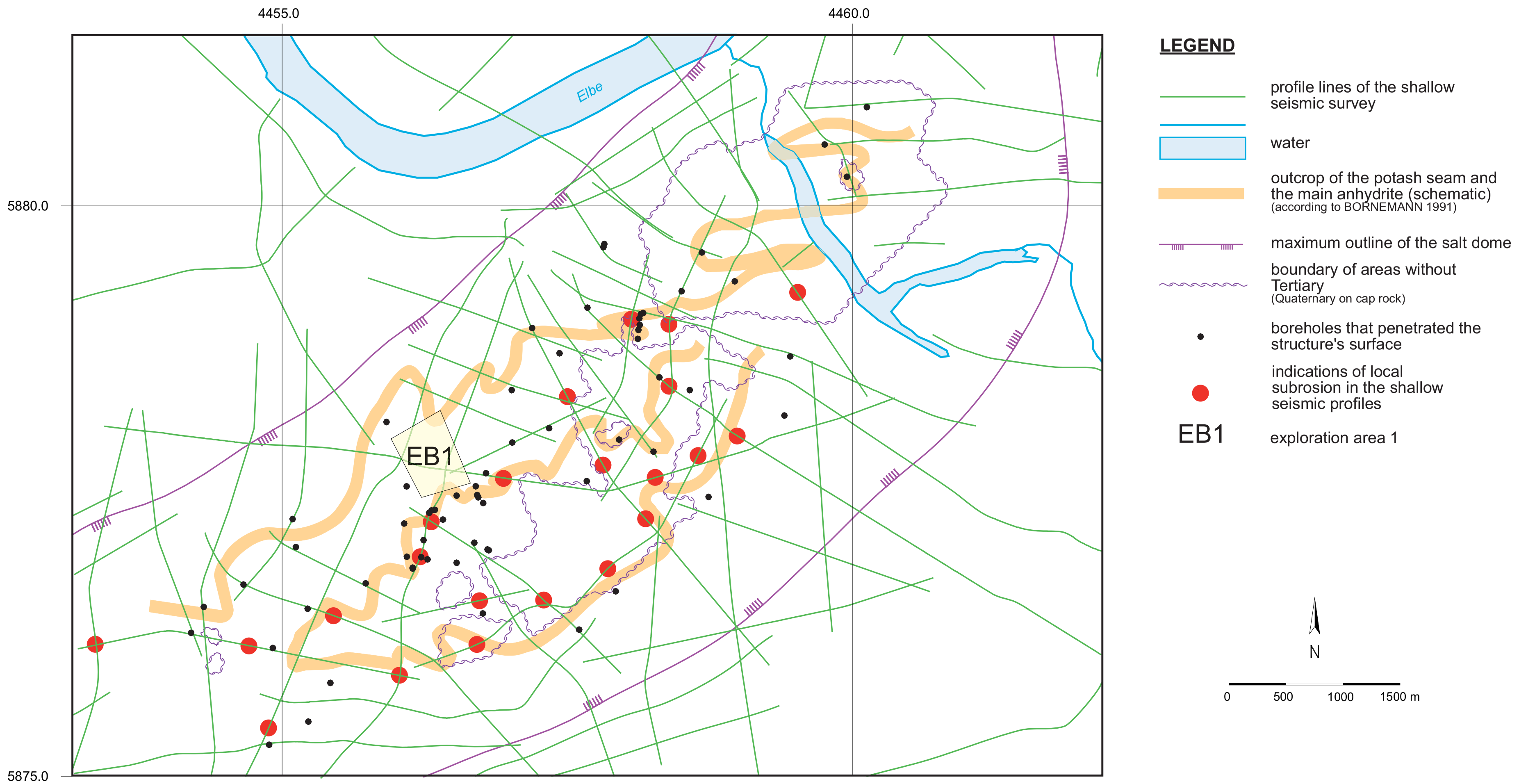


Figure 39: Small-scale thickness and bedding variations in the cap rock indicating local subrosion in the outcrop area of the potash seam and the main anhydrite

For the structural geological subdivision of the present-day cap rock above the salt structure, the lithological sequences of the salt structure that are recognisable even after the transformation are relevant. Compact anhydrocks, e.g. main anhydrite or pegmatitic anhydrite, are embedded in the cap rock. Thus, the main anhydrite that crops out at the salt table and the adjoining potash seam cause conspicuous thickness variations over short distances in the cap rock. Figure 39 shows anomalies of the cap rock that were detected in the shallow seismic survey in the area of the potash seam and main anhydrite outcrop at the salt table. In this zone, ribs and blocks of main anhydrite locally protrude up to 75 m from the surrounding cap rock surface. The shapes of these protrusions are round to oval or elongated.

Clay-rich sections of the Upper Zechstein 3 and Zechstein 4 affect the cap rock formation. The residual clays decrease the subrosion rate in these areas.

The Elsterian channel has a significant influence on the cap rock thickness. During the formation of the channel, sections of the cap rock were destroyed and removed.

Faults that displaced the cap rock could not be detected either in boreholes or in the shallow seismic surveys.

7.6.3 Crestal trenches

When consolidated beds of the overburden are domed up, dip-slip faults occur due to dilatation, which often border a lowered block in the crest of the updoming (crestal trench). Such an updoming above a salt dome is usually caused by halokinetic uplift movements of the salt, which apply a vertical upward pressure on the overburden (active diapirism). The differing geomechanical conditions in the overburden and the salt (compression in the ductile salt, dilatation in the rigid overburden) lead to a dissociation of the two bedding packages. This is why the dilatation faults form only in the overburden and in the rigid cap rock, i.e. the crestal faults do not continue in the salt.

Investigations of the salt domes of Northwest Germany (Baldschuhn et al. 1996) have shown that the salt uplift can be different on the two sides of a crestal fault, thus creating a displacement in the top of the salt dome. Gugliemo et al. (1995) calculated and modelled the formation of overburden faults caused by a halokinetically rising salt diapir (active diapirism) that is free of tectonic influences using a finite element model. They confirmed the formation described above.

An updoming of the overburden can only occur if the salt uplift rate is greater than the subrosion rate. Thus, crestal faults form preferentially where the salt dome roof is well-insulated by clayey layers or lies so deep that subrosion is slight (BALDSCHUHN et al. 1996). The investigation of the overburden above the Gorleben–Rambow salt structure detected significant crestal faults only in the area between Lenzen and the Elbe, where they have formed crestal trenches above the up-domed salt dome roof. In the centre of the updoming, the Paleocene and Eocene are missing, which can be attributed to the dilatation caused by the updoming and to erosive processes during the sedimentation of the Oligocene. The flattening of the salt dome roof in the centre of the updoming (Fig. 30, profile 9502) indicates the formation of a salt table. The large displacement of approx. 100 m at the southeastern crestal fault also indicates subrosion processes, as this value cannot be explained by dilatation alone.

8 Subrosion

The strongest subrosion at the Gorleben salt dome occurred at the time of the diapir phase (end of Malm to Upper Cretaceous) with the salt migration to the ground surface. As the sedimentary cover of the salt dome grew in the Tertiary, the subrosion rate decreased considerably.

8.1 Subrosion in the Tertiary

After a large stratigraphic hiatus of approx. 71 million to 62 million years, the covering of the salt dome roof restarts in the Paleocene with mainly clayey deposits. The oldest beds (topmost Lower Paleocene) have been preserved only in one borehole on the salt dome roof – not in the rim synclines! This is attributed to local subrosion in this part of the salt dome.

From the Late Paleocene to the Early Oligocene, the salt dome roof was covered by clays and silts of highly varying thickness. Due to the salt uplift, the deposits are considerably reduced compared to the rim synclines. The detailed biostratigraphic analysis of the Lower Tertiary by means of dinocyst classification detected high local thickness variation of the individual stratigraphic members. In the Upper Paleocene and the Lower Eocene, the thicknesses above the southeastern edge of the salt dome are larger than above the northwestern edge. In the Middle Eocene, the sides are reversed and the thicknesses of the Middle Eocene are larger above the northwestern edge than above the southeastern edge. According to JARITZ (1994: 201), these variations in thickness are due to the intricate relations of partial insulation of the salt dome and subrosion and to variations in salt uplift speed in the different parts of the salt dome.

In the transition zone towards the Rambow salt dome between the Elbe and Lenzen, sections of the Paleocene and Eocene are missing in the central graben area. The shallow seismic profile 9502 (Fig. 30), which crosses this area, displays a flattening of the salt dome roof due to subrosion. The salt dome was probably exposed at the seafloor in this period and was thus subjected to erosion and subrosion. Local roof zones of the Gorleben salt dome may have been exposed at the same time. The detailed petrographic analysis of the cored borehole GoHy 994 in the southwestern rim syncline revealed fine-grained anhydrite crystals with a quartz crust in the beds of the basal Upper Paleocene, the upper Lower Eocene, and the Middle Eocene. Such findings are indications of erosion and possible subrosion on the salt dome roof (DILL et al. 1996).

There is no evidence of subrosion in the Oligocene and Miocene, as these beds have been extensively eroded. In the crestal trench area northeast of the Elbe, however, the sediments of the Lower Oligocene through to the Hamburg-Ton have been preserved. The beds have been displaced at the southeastern crestal trench fault by approx. 100 m. The increased thickness and the displacement of the bed in the central part of the crestal trench are mainly attributed to subrosion. This means that at least 100 m of salt have been subroded since the covering in the Lower Oligocene.

The examples given result in annual subrosion rates of approx. 0.005 mm to 0.015 mm for the Tertiary period.

8.2 Subrosion during the preglacial age

Towards the end of the Tertiary and during the preglacial, the cover of the salt dome roof consisting of clayey sediments of the Paleogene had decreased by erosion to such a degree that subrosion could commence locally. In the southwestern crestal area of the Gorleben salt dome, progressive subrosion created a shallow sedimentation basin during the Menapian, which grew deeper in the centre, approximately between boreholes GoHy 2222 and GoHy 65, and wider towards the flanks.

According to palynological analyses by MÜLLER (1986, 1992), the ground surface of this area at the beginning of the Bavelian formed a slightly depressed peneplain of approx. 3.5 km^2 size with shallow perennial lakes and bogs, where subsidence and accumulation were approximately in step. These facies conditions prevailed until the end of the Cromerian Complex, so sedimentary accumulation and subrosion-induced subsidence were kept in balance.

The average thickness of the overall preglacial sediments of 57 m divided by the time interval of 700 000 years (Menapian to the end of the Cromerian, cf. Fig. 12) results in a subsidence rate of 0.1 mm per year. When using the largest thickness of 88.3 m found in borehole GoHy 2222, the subsidence rate increases to 0.13 mm per year. The calculation of respective values for individual periods of the preglacial produces average values between 0.06 mm per year for the period of the Bavelian and 0.2 mm per year for the Menapian. Higher subsidence rates of 0.4 mm to 0.5 mm per year for the preglacial age as stated by Duphorn (1983, 1986) are unrealistic, as these are based on a "slumping" of the preglacial sediments by 240 m to 280 m. However, this finding is not reliable, as the Menapian sands and silts that lie on the cap rock at 239.1 m below sea level in borehole GoHy 940 must not be correlated with the gravels of the Loosen beds, which usually lie at 35 m to 45 m above sea level beyond the Elbe. According to Bülow (most recently 2000a), the gravels of Loosen belong to the period from the earliest Quaternary to the latest Pliocene and thus they are 2 million to 4 million years old (gravels of Gorleben approx. 1 million to 1.1 million years). From the position of sediments so different in age and petrography (Chapter 4.3.1) no reliable subrosion rate can be calculated. Moreover, the peak value of 239.1 m below sea level is from the area of a sink hole (Müller 1986).

In addition, the proximity of the currently deepest spot of the preglacial gravels to the Gorleben Channel has to be taken into account; thus, this depth is also due to Elsterian subrosion. The sediments of the Holsteinian Interglacial lie in normal position in the zone of the preglacial deposits (Pl. 1: Fig. 9, cross section B–B'). From the difference between the baselines of the preglacial sediments and the Holsteinian Interglacial beds, the value of subsidence can be derived for the interval from the Menapian cold stage to the Elsterian Glaciation. This difference is approx. 140 m to 160 m. For a period of approx. 700 000 years, the calculation produces values of approx. 0.2 mm per year, corresponding to the rate calculated by Müller (1986) instead of the 0.4 mm to 0.5 mm per year calculated by Duphorn (1986, 1987).

8.3 Subrosion from the Elsterian Glaciation to the Saalian Glaciation

The **Elsterian** deep erosion laid bare the cap rock and in small areas even the salt in an area of 7.5 km^2 in the Gorleben Channel (Chapter 7.4.1). Thus, subrosion was increased. The subrosion intensity probably reached its Quaternary maximum in the short period when the Elsterian subglacial outwash sands (channel sands) were deposited. However, this is not measurable because the considerable subrosion was superimposed by the much stronger glacial erosion. Due to the lateral penetration that formed the cap rock breccia (Chapter 7.4.1), the subrosion could take effect where the Tertiary cover had been preserved. The extent of the subrosion that took place after the formation of the channel and the cap rock breccia (so-called post-Elsterian subrosion, see below) is documented by the thickness of the gypsum anhydrite laminate. A part can still be attributed to the ending Elsterian Glaciation.

From the large depth difference in the Holsteinian base between the numerous though relatively tightly spaced boreholes on the central part of the Gorleben salt dome and the few boreholes outside it, Duphorn (1983, 1987) and Appel & Habler (1993, 1998) derived a considerable **post-Holsteinian** subrosion. The authors have in common that they derive their conclusions from a relatively elevated Holsteinian base in the boreholes southeast of the Gorleben salt dome and from the increased thicknesses of Saalian deposits above deep-lying Holsteinian on the salt dome roof. According to Duphorn (1983: 205), the Elsterian channel sediments and the Holstein-Ton below the Weißes Moor subsided by 109 m during the Saalian Glaciation. This value is the result of the depth difference between the Holsteinian base in the southern Gorleben Channel, which was not affected by subrosion (borehole GoHy 190 = 28 m below sea level), and below the Weißes Moor (borehole GoHy 840 = 137 m below sea level). As the Warthe till was not involved in the subsidence, Duphorn (1983: 207) estimated a value of 1.9 mm per year for the subrosive subsidence above the Gorleben salt dome during the Drenthe substage.

Appel & Habler (1993, 1998) included the data of 79 boreholes in their statistical analysis: 40 boreholes above the Gorleben salt dome with deep base positions of the Elsterian, Holsteinian and Saalian deposits were subsumed in the class “subrosion”. The other 39 boreholes displayed normal values for the corresponding beds. These were subsumed in the class “channel”. The seven boreholes beside the salt dome were also included in the latter class. Using statistical parameters and taking into account a minor subsidence of the older Elsterian clay beds of up to 5 m, they arrive at a difference of 46 m between the mean base positions of the Holsteinian deposits in the boreholes classes “subrosion” and “channel” and at a maximum value of 91 m. Assuming a duration of the Saalian Glaciation of 100 000 years, the authors arrived at an average Saalian subrosion rate of 0.46 mm per year.

Both investigations assume a starting level of the “normally” bedded Holsteinian that is too high and presume a mainly uniform level of the Gorleben Channel at the beginning of the Holsteinian Interglacial. According to borehole results from the partial study area Dömitz-Lenzen outside the Gorleben–Rambow salt structure, the base surface of the Holsteinian sediments varies by more than 30 m and reaches deeper base positions (boreholes GoHy 1620 = -59.6 m and GoHy 1520 = -91.8 m). In neighbouring areas of southwestern Mecklenburg, actual depths of more than 100 m below sea level are reached (Müller 1993), where areas are ignored that have been affected by halokinesis. In addition, it has to be noted that at the deep level of the Holsteinian in borehole GoHy 840, a part of the overlying strata is glacigenically imbricated. A minimum of 26 m of Holsteinian sediments and Lauenburger Ton have been inserted in the Drenthe deposits (Pl. 1: Fig. 9, cross section B–B'). Also, no significant parallel subsidence of the Lauenburger-Ton-Komplex and the Holsteinian sediments can be found. The base of the Lauenburger Ton sinks by only 29 m from borehole GoHy 970, which was classified by Appel & Habler (1993: Tab. 5) as not affected by subrosion, to borehole GoHy 840, whilst the Holsteinian base sinks by 75 m.

The drilling results prove the existence of a stronger relief in the deposition area at the beginning of the Holsteinian Interglacial than was previously presumed. This decreases the amount of post-Holsteinian subrosion mentioned above. Due to the bandwidth of the base positions, only boreholes with base values deeper than 90 m below sea level are considered for the calculation of the subrosion since the Holsteinian Interglacial. These 17 boreholes are all situated in the central part of the Gorleben salt dome, mostly below the area of the Weißes Moor southeast of Gorleben (Pl. 2: Fig. 15). The average difference to 90 m below sea level is 24.8 m, the maximum is 47 m. Assuming a subrosion duration of 110 000 years for the period of the Upper Saalian (Saalian Glaciation in the narrower sense) (Fig. 12) results in an average subrosion rate of 0.22 mm per year (maximum value 0.43 mm per year).

Another method to localise and quantify the post-Elsterian subrosion is based on the formation of the cap rock (Bornemann 1991). Due to the relatively reliable dating of the cap rock breccia as being formed during the Elsterian Glacial, the cap rock layers of the gypsum anhydrite laminate that were formed subsequently become very important for estimating the latest subrosion processes. In correlation with the composition of the underlying salt formation, the thicknesses of the gypsum anhydrite laminate reflect the extent of the post-Elsterian subrosion. According to Bornemann et al. (2007), calculations based on the anhydrite content of the salt rock at the salt table and the thickness of the gypsum anhydrite laminate in 31 boreholes produce subrosion rates of hundredths to tenths of millimetres per year with average rates of the order of 0.1 mm to 0.2 mm per year for the period from the Elsterian Glaciation until present.

8.4 *Subrosion from the Eemian Interglacial until present*

For the analysis of recent subrosion processes, the considered period has to be extended in order to obtain reliable results. In this case, the beginning of the Eemian Interglacial age was chosen, so a period of approx. 128 000 years can be studied.

No borehole on the Gorleben–Rambow salt structure encountered Eemian lacustrine deposits or peats that would indicate the presence of an Eemian hollow above the salt structure that might have been created by subrosion.

In the frame of the Quaternary geological survey (Duphorn 1980, 1983; Schröder 1988) and the analysis of the stratigraphic borehole records, the Lower Terrace (117 000 to 14 400 years) was subjected to a detailed investigation, as it represents the youngest geological marker bed in the study area. Its fluvial base surface, which is mostly level compared to the older glacial deposits, was assumed to permit conclusions on the more recent underground salt movements: either an “updoming” above the salt dome, or a “sagging” above subrosion areas or possibly above the halokinetically formed rim synclines (Duphorn 1983: 125). The investigations revealed that the Lower Terrace is a bipartite sedimentary unit (older and younger Lower Terrace) and that the base surfaces were significantly affected by the initial glaciomorphological conditions, i.e. the Warthe ground moraine landscape.

A major result of the investigation of the Lower Terrace is the fact that the base and thickness maps of the Weichselian Lower Terrace show no features that indicate a post-Eemian subrosion as far as mapping accuracy permitted (vertically decimetres to metres, horizontally tens to hundreds of metres). The structural shapes can only be interpreted as a result of fluvial erosion and deposition. Indicators of subrosion processes or uplift such as cauldron shapes or elevations could not be detected above the salt structure. The area of the Weißes Moor was the object of particularly intense investigations, as Grimmel (most recently 1995) had repeatedly interpreted this area as a fault-tectonic Holocene subrosion feature. The base of the Lower Terrace exhibits no “sag” of the Lower Terrace and, according to Duphorn (1983: 52 ff.), the present-day hollow of the Weißes Moor is clearly due to wind erosion.

The structure, thickness, extent and development of the Holocene sequence of strata were investigated and described in detail in the Quaternary geological survey (Duphorn 1980). Special attention was given to indicators that suggest that subrosion or uplift processes could have taken place above the Gorleben–Rambow salt structure during the last 11 600 years. Morphological features or increased thicknesses of Holocene sediments, which might indicate subrosive processes in the near-surface above the salt structure, were not detectable.

In summary it can be stated that subrosion or subsidence movements above the Gorleben–Rambow salt dome in the area between Lenzen and the southwestern end of the Gorleben salt dome during the last 128 000 years could not be detected by geological methods (Chapter 4.3.5 ff.). As the subrosion of this period and that of the preglacial, Elsterian, and post-Holsteinian ages cannot be regarded separately, it may be assumed that only very slight subrosion has taken place during the last 128 000 years. Table 17 gives an overview of the subrosion phases and rates that were derived from different geological results in the chapters 8.2 through 8.4.

Table 17: Overview of periods and extent of subrosion in the Quaternary

<table>
<tr><th>Stratigraphy</th><th>Facies</th><th colspan="2">Subrosion phases/rates</th></tr>
<tr><td>Holocene
Weichselian
Eemian Interglacial</td><td>fluvial, aeolian
fluvial
– –</td><td>• subrosion rate between ~ 0.01 and 0.05 mm/year</td><td rowspan="3">• formation of Post-Elsterian cap rock, subrosion rate between 0.1 and 0.2 mm/year</td></tr>
<tr><td>Saalian</td><td>glacial</td><td>• subrosive subsidence of the Holsteinian sediments in the central salt dome area by Ø 25 m
• subrosion rate 0.2 mm/year, maximum 0.4 mm/year</td></tr>
<tr><td>Holsteinian Interglacial</td><td>limnic–fluvial
partially brackish–marine</td><td>not detected</td></tr>
<tr><td>Elsterian</td><td>glacial</td><td>• deep erosion to 290 m below sea level
• denudation of the cap rock surface of approx. 7,5 km²
• formation of cap rock breccia</td><td rowspan="2"></td></tr>
<tr><td>Cromerian Complex
Bavelian
Menapian</td><td>fluvial,
limnic–fluvial</td><td>• subrosive subsidence of the cap rock surface by Ø 57 m
• subrosion rate 0.1–0.2 mm/year</td></tr>
</table>

The assumption of a currently very slight subrosion is confirmed by the isotopic composition of the salt waters in the Gorleben Channel. According to Klinge et al. (2007), these are mainly waters stemming from the (Weichselian) cold age or combinations of Pleistocene and Holocene salt waters. Relatively young waters of clearly Holocene age were encountered only occasionally. This indicates only a small water throughput in the channel aquifer in the Holocene.

At present, the salt table lies considerably deeper than in the period from the preglacial to the Elsterian Glaciation so subrosion is possible in present and future times but will be smaller under the current hydrological conditions. According to Bornemann et al. (2007), the average subrosion rate should be about 0.01 mm to 0.05 mm per year, which corresponds to 10 m to 50 m of subroded salt rock in one million years.

9 Balance of salt movements

9.1 Salt flow velocities and salt dome uplift

Table 18 lists the volumes of salt that migrated into the salt dome as calculated in the analysis of the rim synclines. The Table also contains all data that are necessary for calculating salt flow velocity and salt dome uplift. The data are geological periods, absolute ages, and epeirogenic subsidence.

The surfaces of the horizontal cross sections of the salt dome used for calculation are:

- Largest horizontal salt dome cross section at the level of the overhang: 44.4 km²
- Smallest horizontal salt dome cross section at the level of the Bunter base: 26.9 km²
- Surface area of the mobile Hauptsalz (main salt) at the exploration level: 11.1 km². The estimate of this surface area was made after a survey at a depth of approx. 840 m (Bornemann 1991). At this depth, the surface area of the mobile Hauptsalz (z2HS) is 25 % of the area of the largest horizontal cross section.

The left column of the table contains the seven analysed time sections from the beginning of diapirism (at the transition Malm/Early Cretaceous) until today. The bottom row shows the averages of the calculations over the whole period. The second column contains the values of epeirogenic subsidence per time section.

Table 18: Results of the rim syncline analysis of the Gorleben salt dome (time scale according to Deutsche Stratigraphische Kommission 2002)

	Epeirogenic subsidence [m]		Salt volume migrated into the salt dome [km³]		Height of the subroded salt column with regard to the main salt at 840 m below sea level [km]		Height … smallest horizontal cross-section [km]		Height … largest horizontal cross-section [km]		Salt-flow velocity in the area of the main salt at 840 m below sea level [mm/year]		Salt-flow velocity … smallest horizontal cross-section [mm/year]		Uplift of the salt dome top [mm/year]		Time-scale duration [Ma]	Time-scale *boundary* time [Ma]
Quaternary to Miocene	100		18.80		1.594		0.599		0.323		0.071		0.029		0.018		23.8	*23.8*
Upper Oligocene	55		11.01		0.937		0.354		0.193		0.211		0.087		0.052		4.7	*28.5*
Lower Oligocene	150		8.65		0.629		0.173		0.046		0.150		0.062		0.038		5.2	*33.7*
Upper Eocene to Middle Eocene	100		22.87		1.960		0.750		0.415		0.135		0.056		0.034		15.3	*49*
Lower Eocene to Upper Paleocene	150		21.39		1.777		0.645		0.332		0.210		0.088		0.054		11.9	*60.9*
Upper Cretaceous (Lower Paleocene to Cenomanian)	100	min. 0	114.57	152.08	10.221	13.898	4.159	5.653	2.480	3.425	0.252	0.337	0.104	0.138	0.058	0.084	38.1	
		max. 150		97.49		8.633		3.475		2.05		0.214		0.088		0.054		*99*
Lower Cretaceous	50	min. 0	82.16	101.29	7.402	9.125	3.054	3.765	1.850	2.281	0.173	0.212	0.072	0.088	0.044	0.053	43	
		Max. 75		73.68		6.638		2.739		1.659		0.156		0.065		0.040		*142*
Quaternary to Lower Cretaceous	705	min. 555	279.45	336.09	24.47	29.723	9.684	11.93	5.59	7.01	0.172	0.209	0.068	0.084	0.039	0.049	142	
		max. 780		253.89		22.092		8.76		4.92		0.156		0.062		0.034		

For the Early and Late Cretaceous, whose values vary widely due to the uplifting of the Prignitz–Lausitzer Wall, the extreme values as well as the averages are listed. The next column contains the calculated halokinetically affected volume of the rim synclines, which corresponds to the volume of salt that has migrated into the salt dome. In total, approximately 280 km³ of salt migrated into the salt dome since the beginning of diapirism (bottom row). If this salt volume is converted into a column with a cross section equal to that of the largest horizontal cross section of the salt dome and the amount of epeirogenic subsidence is subtracted from the height of this column, then the result is the part of the salt column that theoretically protruded from the ground surface and was subroded or eroded (column 6 in Table 18).

The maximum salt loss since the beginning of diapirism corresponds to a column of approx. 7 km height (with respect to the largest horizontal cross section). During this salt migration, the highest flow velocities occurred in the area of the exploration level. These maximum flow velocities, based on the stratigraphic time scale of the Deutsche Stratigraphische Kommission (German Stratigraphic Commission, 2002), are listed in the seventh main column. The maximum salt flow velocity of 0.337 mm per year occurred in the Late Cretaceous, the lowest value is calculated for the most recent period of the Miocene and Quaternary. If the largest horizontal cross section at the level of the salt dome overhangs is used for the salt flow velocity calculation, then the result is the theoretical uplift velocity of the top of the salt dome. These results are listed in the last but one column. The salt dome attained the maximum uplift velocity of 0.084 mm per year during the diapir phase of the Late Cretaceous, the lowest velocity (0.018 mm per year) occurred during the Miocene and the Quaternary. The calculated salt flow velocities in the Hauptsalz at the planned repository level of 840 m below sea level reached a maximum of 0.337 mm per year, again, in the Late Cretaceous, and 0.071 mm per year as the lowest value in the period from the Miocene to the Quaternary.

The calculated velocities in the respective geological time sections are illustrated in Figure 40. The salt uplift velocity exhibits an increase from the Early Cretaceous to the maximum in the Late Cretaceous. Subsequently, the velocity declined and reached its minimum in the most recent period, from the Miocene to the Quaternary. In the Early and Late Oligocene, however, increased salt uplift occurred. However, these two are relatively short periods of 5 million years each, which are difficult to identify, as conflicting values in different time scales illustrate (Zirngast 1991). However, these relatively high salt flow velocities in the Oligocene correspond to the increased epeirogenic subsidence in this period. The relatively rapid sedimentation could be the cause for the greater uplift rates during this period.

9.2 *Primary thickness of the Zechstein*

The primary thickness of the Zechstein beds was calculated by reconstructing the former salt pillow (Rühberg 1976). This is done by adding the thicknesses of the rim synclines that are due to salt migration to the Zechstein salt that is still present outside the salt dome, to calculate the geometry of the salt pillow shortly before salt breakthrough. In this calculation, the area of the diapir is interpolated. If no salt was subroded before and during the pillow phase, then the pillow volume represents the initially available salt volume in the catchment area of the salt dome. If this calculation is done in three dimensions for the Gorleben salt dome, a primary Zechstein thickness of 1 150 m results for the salt catchment area around Gorleben.

The palaeographical structural cross sections show that the initial Zechstein salt thickness must have been higher, at least in the areas of the salt domes Dömitz and Aulosen, which were formed in the Keuper. The Zechstein geometry before the formation of the diapir in the Wealden was reconstructed by adding, for example, the thicknesses of the Bunter and the Muschelkalk, which were affected by epeirogenic subsidence, to the primary Zechstein thickness of approx. 1 150 m. Subsequently, the actual thicknesses of these two stratigraphic members were subtracted from the total thickness. The result represents the status of the Zechstein at the beginning of the Keuper.

These calculations can be performed for all beds if their normal thickness due to epeirogenic subsidence and their current actual thickness is known. If the Zechstein status at the end of the Keuper is thus reconstructed, i.e. if the normal thicknesses of the Bunter, Muschelkalk, and Keuper are added to the primary thickness of the Zechstein, and the actual thicknesses of these beds are then subtracted, the Bunter base sinks below the level of the Zechstein base in the area of the thick Keuper rim synclines. Thus, the presumed Zechstein thickness was not sufficiently large if small-scale displacements of the Zechstein base can be ruled out and that the incomplete knowledge of the geology in these areas did not lead to mapping errors. The precondition for the formation of the thick rim synclines in the Keuper is a primary Zechstein thickness of approx. 1 400 m.

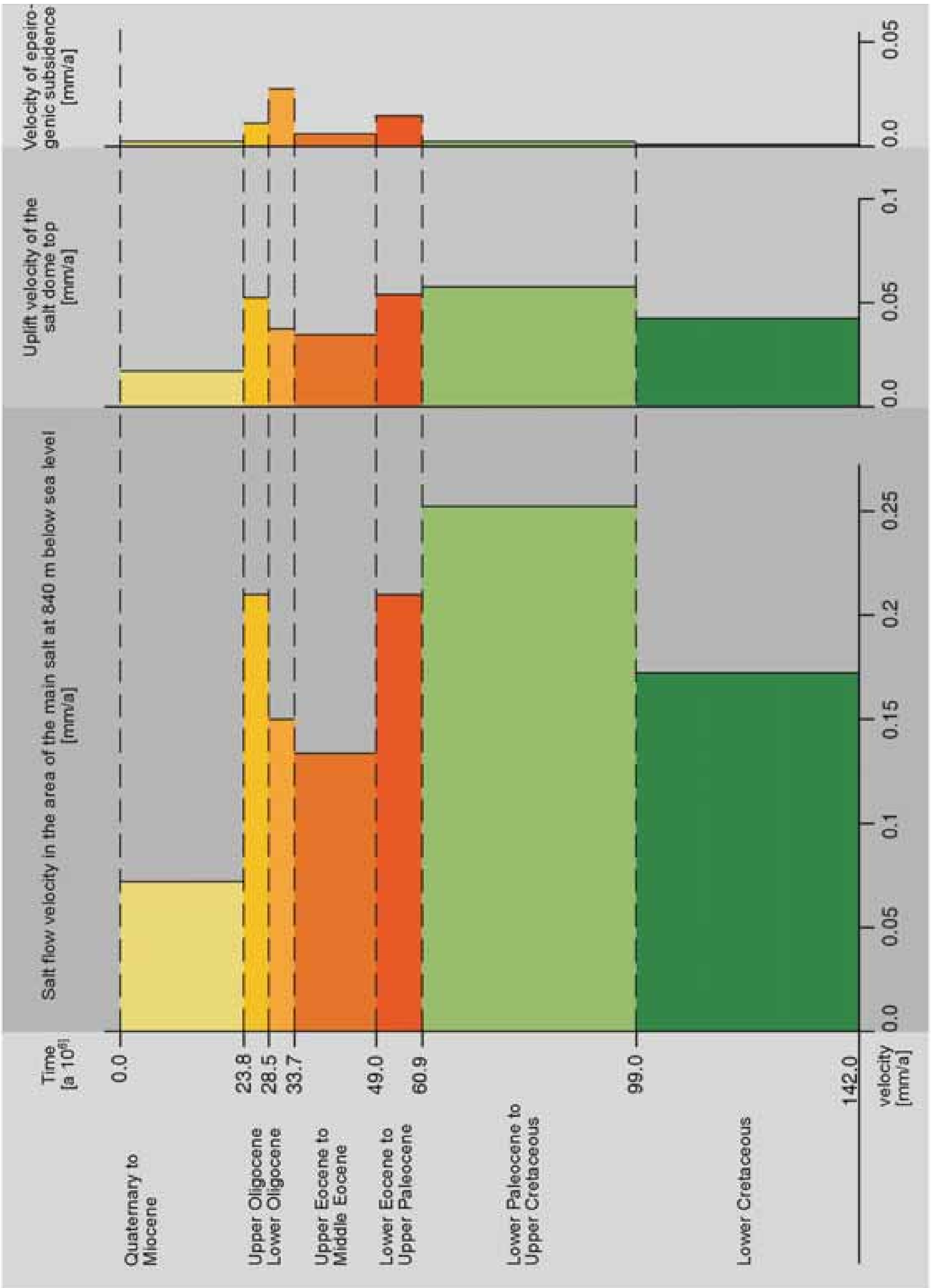


Figure 40: Salt flow velocities in the Gorleben salt dome (absolute ages according to Deutsche Stratigraphische Kommission 2002)

9.3 Balance of the salt volumes

In Table 19 the calculated subroded salt volumes and those initially present in the catchment area of the Gorleben salt dome are compared. Since the beginning of the diapir phase at the Malm to Early Cretaceous transition, approx. 248 km³ of the Zechstein salt have risen above ground level. The actual volume of the subroded salt is approx. 9 km³ larger, as today‘s salt table lies at approx. 200 m below sea level. Depending on whether 1 400 m primary thickness, as has to be assumed for the whole study area, or only 1150 m are used, as has been determined in the catchment area of the salt dome, the calculated subrosion is 47 % or 57 %, respectively. This means that only 53 % or 43 % of the Zechstein salt initially present has been preserved.

If a primary Zechstein thickness of 1 400 m in the catchment area of the Gorleben salt dome is assumed, which cannot be reliably proven, then approx. 18 % (approx. 93 km³) of the initial salt must have been subroded, although there is no discernible equivalent for this salt volume in the rim synclines. Jaritz (1980) notes in the case of the Zwischenahn salt dome,whose breakthrough occurred similarly to that of the Gorleben salt dome in the period from the Malm to the Hauterivian age, that an epeirogenic uplift took place in that period, the amount of which has to be taken into account in the rim syncline analysis by adding a corrective factor. In the area of Gorleben, the uplift in the Late Jurassic and Wealden was approx. 200 m to 300 m. During this period, salt losses by erosion or subrosion occurred at the top of the salt dome, while the corresponding development in the rim synclines was compensated by the uplift, or contemporaneous rim syncline deposits fell prey to erosion. Thus, the primary Zechstein thickness that was calculated using the rim syncline thicknesses in the catchment area of the salt dome represents only a reliably proven minimum thickness.

Table 19: Balance of the salt volumes in the salt catchment area of the Gorleben salt dome

Zechstein balance sheet			
	Salt migrated into the salt dome	Height of the subroded salt column with regard to the largest horizontal cross-section	Volume of subroded salt
Quaternary to Miocene	18.8 km³	323 m	14.3 km³
Upper Oligocene	11.1 km³	193 m	8.6 km³
Lower Oligocene	8.6 km³	46 m	2.0 km³
Upper Eocene to Middle Eocene	22.9 km³	415 m	18.4 km³
Lower Eocene to Upper Paleocene	21.4 km³	332 m	14.7 km³
Upper Cretaceous	114.6 km³	2480 m	110.1 km³
Lower Cretaceous	82.2 km³	1850 m	79.9 km³
	279.6 km³	**5589 m**	**248.0 km³**

Salt in diapir including cap rock and pre-salinar Zechstein:		**94,67**	**km³**
Salt still available in the catchment area (w/o salt dome overhangs):		**185,6**	**km³**
Subroded + available salt			
248.0 km³ + 185.6 km³ =		**433,6**	**km³**
	= primary thickness: approx	**1150**	**m**
Volume of the primary Zechstein thickness in catchment area (376.4 km²) of the Gorleben salt diapir			
based on 1400 m primary Zechstein thickness:	**approx.**	**527**	**km³**
based on 1150 m primary Zechstein thickness:	**approx.**	**434**	**km³**
Subrosion: 248 km³ of **527 km³** (= prim. thickness 1499 m)	=	**47 %**	
248 km³ of **434 km³** (= prim. thickness 1150 m)	=	**57 %**	
Salt migrated into the salt dome:			
279.6 km³ von 527 km³	=	**53 %**	
279.6 km³ von 434 km³	=	**64 %**	

10 Recent tectonics and recent crust movements

The term "recent tectonics" refers to the most recent neotectonic movements that occurred up to the present, which comprise the period from the beginning of the Early Tertiary or the beginning of the Rupelian (Lower Oligocene) until the present. As tectonic references cannot be made to a point in time but rather to a certain time span, recent tectonics in the broader sense can be narrowed down to the period of reliably dated historic records, and in the narrower sense to the period of instrumental records.

The latest map of recent crust movements of the Baltic Sea depression at a scale of 1 : 5 000 000 (Frischbutter 2001), which was generated with a calculated isoline adjustment from numerous international individual contributions, provides only a rough overview of the current trends in recent crust movements due to its wide-spaced datum points.

Between the Fennoscandian Block, which is characterised by glacially induced isostatic uplift rates of more than 8 mm per year in the northern part of the Gulf of Bothnia, and the Carpathian Arc, which is characterised by uplift rates of more than 6 mm per year, lies a wide depression area comprising the more subdivided "young" Western European plate, which was consolidated from the Caledonian through Variscan, and the less differentiated, "old" Eastern European plate, which was consolidated in the Precambrian. The latter has the largest subsidence values of 6 mm per year in the Orsha–Valdai depression (headwater region of the Volga and Western Dvina) and 2.5 to 3.5 mm per year in the Polish–Lithuanian depression. In the North German basin, the largest subsidence values of 2.0 mm per year occur in the area of the Elbe estuary. The area of the Gorleben–Rambow salt structure is in a zone of subsidence of less than 1.0 mm per year. This circum-Fennoscandian subsidence zone has been related to a collapse structure of a marginal bulge of the upper mantle that had formed as a reaction to the glacial isostatic uplift of the Fennoscandian crust block. The last Scandinavian glaciation of 15 000 years ago created a marginal bulge of 60 m according to models by Fjeldskaar (1994). This value shows the order of magnitude for the compensation movements that occur if a complete reduction of the marginal bulge is assumed.

Small-scale geodetic surveys of the sheet section are not available. The importance and reliability of such survey values (repeated levellings and triangulations) for a site-related assessment of recent vertical and horizontal crust movements is the subject of controversy. It is undisputed that recent endogenic vertical and horizontal crust movements also occur in relatively stable areas and can be measured with the methods mentioned (Ellenberg 1988; Bankwitz et al.1993). Whilst the velocities of vertical movements of tectonic cause are at or below 1 mm per year in extra-Alpine Central Europe, larger values can be observed at faults. No absolute values, only movement trends at best, can be stated for horizontal movements in Central Europe. Usually, the observation period is too short for reliable assessment.

11 Diapirism

The different stages of salt accumulation can be deduced from the changes in thickness of the beds overlying the Zechstein. The formation of the pillow causes a thinning of the overlying strata above the salt structure and an increased thickness above the salt migration areas, the primary rim synclines. At the transition from the pillow to the diapir stage, the salt formation breaks through the overburden and large volumes of salt are subroded at the surface. The salt flows from the flanks of the former pillow, thus causing the ground surface above to sink. The secondary rim synclines thus formed approach the salt dome during the diapir stage.

Development until the beginning of the Keuper

The thickness of the Lower and Middle Bunter exhibits no anomalies that can clearly be attributed to salt movements. Small changes in thickness are due to basement movements in the area of the Altmark ridge. In the Upper Bunter and the Muschelkalk, significant thickness variations due to salt migration are recognisable. These are caused by sudden salt losses in the area of today‘s salt domes of Dömitz and Aulosen. This salt migration begins atypically without a discernible pillow stage and primary rim synclines. Faults in the basement and the overburden are assumed to be the cause, but there is no evidence for their existence. They may be a trigger for the subsequent development in these areas. There is positive proof of the basement faults of Gülden–Braudel west of the area of structural analysis (Fig. 25, Fig. 28). Here, there were also early salt breakthroughs, albeit, in a well-documented rift system, which led to increased thicknesses in the Upper Bunter and Muschelkalk.

Development in the Keuper

The salt migrations that started in the Bunter in the area of Gülden–Braudel, Dömitz, and Aulosen formed a large salt pillow in the area of the present salt structures of Gorleben–Rambow, Groß Heide–Siemen, Wustrow and Dannenberg (Zirngast 1991). At this stage, a bigger salt culmination with probable crestal graben trench was formed in the area of the later Rambow salt dome compared to the present Gorleben salt dome, where the pillow exhibits only a slightly domed surface. At the end of the Keuper, the diapir stage of the salt domes Dömitz and Aulosen had come to an end. The poor degree of exploration of these salt domes does not allow a better resolution of their diapiric development.

Development in the Jurassic

By the beginning of the Albian transgression, the Gorleben salt dome had broken through in the central area. The Rambow salt dome also had reached the ground surface in the northeastern part. Its point of breakthrough was at the southeastern edge of the large salt pillow, and thus the southeastern flanks of the salt dome were considerably steeper than the northwestern flanks, where there were still parts of the salt pillow. As only parts of the Jurassic have been preserved, the movement of the salt dome can only be reconstructed in general terms. The occurrences of Lias and Dogger in the rim synclines of Gorleben show that the centres of the rim synclines moved towards the salt dome. This movement of the primary synclines is also shown by the Malm, which has been preserved only in the northeastern part of the Rambow salt dome. This proves that the Rambow salt dome was on the edge of breakthrough in the northeastern part at that time. The arrival at the diapir stage at the end of this period is not only due to salt uplift but also to regional uplift , during which approx. 400 m to 500 m of the overburden were eroded in the Upper Jurassic (Jaritz 1969, 1980), laying bare the tops of the salt pillows. The salt domes of Conow and Wittenberge also had reached the surface at the beginning of the Early Cretaceous.

Development in the Early Cretaceous

At the end of the Early Cretaceous, the Gorleben–Rambow salt structure had broken through the overburden in all areas. Throughout whole Early Cretaceous, large salt migration from the environs of the salt structure occurred, which caused the flanks to subside and the large secondary rim synclines to form. An indication of large salt discharge was found in borehole GoHy 1005, which penetrated cap rock of the Cretaceous in the area of the base of the Lower Cretaceous. This indicates that a discharge of Zechstein salt at the level of the Upper Bunter occurred at the end of the Early Cretaceous. Another indication of this is the geometry of the internal structure of the salt dome at this spot.

As illustrated in Figure 41, the Zechstein 3 salt of the southern flank of the inverted syncline ends at the level of the Lower Cretaceous sediments at the salt dome edge. Thus the Zechstein 3 lay upon the adjoining rock at that time, where it karstified (Fig. 38). The inverted syncline was formed at a later stage by another salt uplift of Zechstein 3 and Zechstein 4. The salt supply was provided mainly from the southeast, which can be deduced from the lower-lying southeastern flank. A mirror-image formation is the salt dome of Groß Heide–Siemen, which exhibits a development similar to the southwestern part of the Gorleben salt dome. The Groß Heide–Siemen salt dome, however, broke through at the northern edge of the common pillow and thus displays a greater subsidence in the northern flank. Between the two salt domes, a large residual pillow has formed.

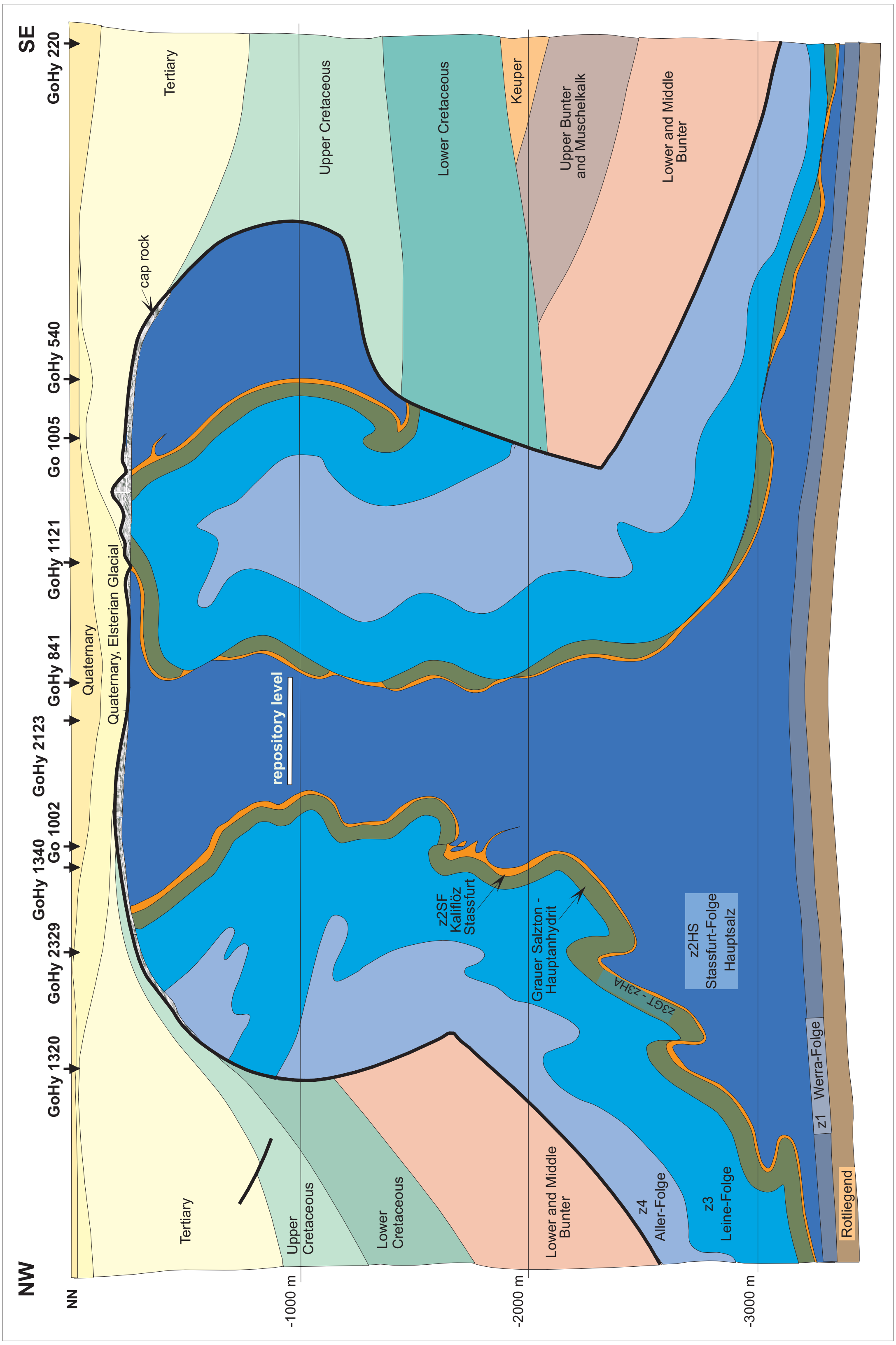


Figure 41: Simplified cross section of the Gorleben salt dome (modified according to Bornemann 1991)

The salt domes of Wittenberge and Conow, however, display a symmetric pillow bottom in their cross sections.

Development in the Late Cretaceous

During the Late Cretaceous, too, the development of the Gorleben–Rambow salt structure was characterised by large salt migrations from the flanks into the salt dome. Especially the southeastern flank of the Gorleben salt dome sank markedly. The strong salt uplift on this flank led to a discharge of the salt at the surface and thus to the formation of the salt dome overhang in this area. At the end of the Cretaceous, the salt uplift slowed down in relation to the regional subsidence and the salt dome was locally covered by upper Upper Cretaceous. During the continued uplift, the salt migrated into the overhang, which led to an updoming of the structure‘s surface. The dip in the base of the Cretaceous and in the underlying beds directly below the overhang shows that the salt migration into the overhang continued after the end of the Cretaceous. This dip is a result of the construction of the paleo-cross sections generated by the programme 2DMove. The base of the Tertiary was assumed to be a plane and the thicknesses of the older deposits downwards were added. As the intrusion of the salt into the overhang and thus the uplift of the Tertiary base occurred later, the precondition for reconstruction, i.e. specifying the Tertiary base as a level plane at the beginning of the Tertiary, was not met in this zone. The degree of subsidence below this overhang is approximately equal to the later uplift of the Tertiary base, which is a result of the salt migration into the overhang after the end of the Cretaceous.

The uplift velocity of the Gorleben–Rambow salt structure decreased from southwest to northeast during the Late Cretaceous, which can be deduced from the thicknesses of the Upper Cretaceous in the rim synclines. The particularly small thicknesses of the Upper Cretaceous in the rim synclines in the northeastern cross section are not solely due to the reduced salt uplift. In this area, the uplift of the Prignitz–Lausitzer Wall led to a truncation of the initially deposited Upper Cretaceous by the Tertiary. Hence, no sediments of the Upper Cretaceous have been preserved in the environs of the still rising Wittenberge salt dome, while thick deposits of the Upper Cretaceous in the rim synclines of Conow are testimony to continued salt uplift.

Development in the Paleocene and Eocene

At the end of the Cretaceous, the active diapir phase of the Gorleben–Rambow salt structure was concluded. It is probable that the whole surface of the structure at Gorleben was covered by Paleocene and Eocene beds. However, the renewed salt migrations were significant, especially in the area of the Gorleben salt dome. The sedimentary cover, which was probably thin, was strongly domed upwards, leading to the formation of crestal faults. The relatively large rim syncline thicknesses due to renewed uplift northwest of the Gorleben–Rambow salt structure prove that large amounts of salt continued to migrate into the salt structure and that large amounts of salt were subroded.

The salt domes at Groß Heide–Siemen and at Conow display a similar development, whilst the Wittenberge salt dome is still in the diapir stage.

Development in the period from the Oligocene to the Quaternary

The development of the salt structure in the Paleocene and Eocene continued in the Late Tertiary, though in diminished form. The salt migrations originated mainly from the northwestern pillow base of Gorleben, whilst the salt southeast of the salt dome had almost completely gone. The Rambow salt dome still had distinctive pillow bases, which is why salt migration from both flanks into the salt dome was still possible here. Thickness peaks in the rim syncline during the Late Tertiary in the area of Rambow indicate a stronger salt influx into this area of the structure. These salt migrations caused only a slight uplift of the salt dome surface. The Tertiary beds continued to cover the salt dome surface, mostly with reduced thickness, though in some parts of the crestal trenches with excessive thicknesses. Not until the Elsterian Glaciation in the Quaternary were the faulted and loosened beds of the Tertiary overburden removed and the salt dome surface partly exposed. The salt domes of Groß Heide–Siemen and Conow are in a similar stage of development.

On the whole, the salt structures in the area of structural analysis display a mainly halokinetic development. There are no large basement structures where tectonic movements could have controlled the salt movements by compression and dilatation in the overburden, as was identified in rift zones. The basement anomalies of the Altmark ridge, maybe linked with faults, can be assumed to have triggered the salt movement. The salt uplift was controlled by early departure of the salt (Aulosen and Dömitz) in the environs of the Gorleben–Rambow salt structure and by regional epeirogenic movements of the basement.

According to Ge et al. (1997), progressive sedimentary deposits (progradation) cause the formation of salt walls. They cite the Gorleben salt structure as an example, by interpreting the sequences of the primary and secondary rim synclines as delta-like progressive deposits. As this is contrary to the geological conditions of this region, this type of development is out of the question for the Gorleben salt dome.

Development of the overburden in the transition area of the salt domes of Gorleben and Rambow

The paleo-cross sections of Figure 42 show the development of the overburden in the area of profile 9502 from the beginning of the Middle Eocene to the deposition of the Hamburg-Ton. The construction of the cross sections did not take into account the erosion processes within the Tertiary.

At the beginning of the Middle Eocene, the structure‘s surface has a symmetric updoming. The maximum culmination of the salt dome lay at the ground surface. During the Middle Eocene, crestal faults formed mainly at the northwestern flank – due to the progressing salt uplift and the correlated updoming of the salt dome roof. These crestal faults facilitated increased subrosion in this area, which lowered the base of the Middle Eocene above the northwestern flank to an almost horizontal bedding. Not until the sedimentation of the Lower Oligocene was the salt dome covered. The high, dragged-up southeastern flank proves that the salt uplift continued. The large thicknesses of the Lower Oligocene in the central crestal trench are mainly due to the subrosion of the top of the salt dome, caused by the higher degree of faulting in this area, and only to a small extent to dilatation and formation of crestal trenches in the area of updoming (Prexl 1997). This development continued at least until the deposition of the Hamburg-Ton and caused a displacement of approx. 100 m at the southeastern crestal trench fault. This means, that at least 100 m of salt have been subroded since the covering in the Lower Oligocene. The cap rock thicknesses of less than 10 m that were encountered in this zone conform this finding.

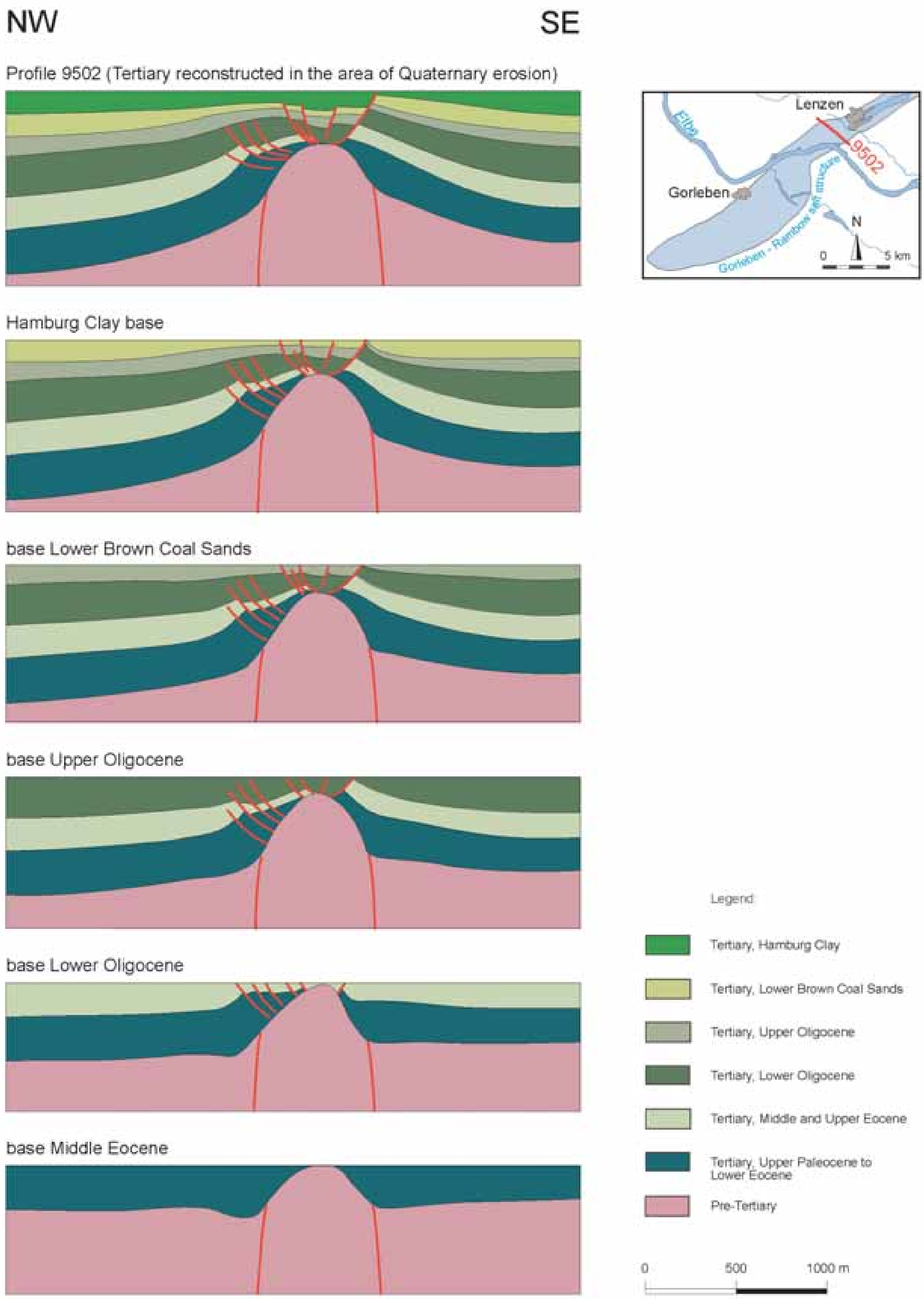


Figure 42: Paleo-cross sections in the area of profile 9502 of the shallow seismic survey at Gorleben

12 Future development of the Gorleben salt structure

According to the analysis of the rim synclines, the halokinetic development of the Gorleben salt dome displays a strong increase in uplift velocity from the beginning of its breakthrough until the culmination in the Cretaceous, and subsequently a slow decline until the present, if the slightly increased uplift velocities during the short periods of the Early and Late Oligocene are ignored. A change in the current uplift velocity is not to be expected under the present regional geological conditions.

A regional geological subsidence with increased sedimentation might have a slight influence on the uplift rate, as the increased uplift rates in the Oligocene indicate. Changes in the regional stress field could equally lead to compression and cause an increased uplift of the remaining salt.

In the Oberes Allertal salt structure (upper valley of the Aller river), compression led to salt squeeze-off. However, that structure is a salt-filled fault zone at a block boundary, whilst the Gorleben–Rambow salt structure is an individual structure that does not overlie a fault system.

Thus, only events of longer geological duration could lead to a change in the present uplift behaviour. According to JARITZ (1994), it can be assumed, due to the dynamic conditions on which the salt re-supply depends, that the future salt dome uplift will display no significant change for at least one million years. This means that an average uplift rate of approx. 0.01 mm to 0.02 mm per year or a flow velocity at the repository level of approx. 0.07 mm per year can be expected. This will cause an uplift of approx. 10 cm to 20 cm and a salt migration at the repository level of 70 cm during the next 10 000 years. Extrapolated to one million years, this means a salt uplift of 10 m to 20 m and a salt migration at the repository level of 70 m.

13 Summary

The Gorleben–Rambow salt structure with its adjoining rim synclines on both sides strikes from the southwest to the northeast and extends for approx. 30 km diagonally across the analysed area. The average depth of the salt table is between 200 m and 300 m below sea level. Southwest of the Elbe in the area of Gorleben, the salt structure has a width of approx. 3.5 km to 4 km. Directly south of the Elbe, it narrows to approx. 1.5 km to 2 km and widens back to 3.5 km at Rambow. The salt structure consists of the Gorleben salt dome situated southwest of the Elbe, and the Rambow salt dome. The narrow part between the Elbe and Lenzen is referred to as a transition area between the two salt domes. The Gorleben salt dome including the transition area, but not the Rambow salt dome, was the object of the investigations.

The sediments above the Gorleben salt dome are of Tertiary and Quaternary origin – except for relicts of the Cretaceous.

The **Tertiary** sediments of the Paleocene to Lower Miocene used to be present throughout almost the whole study area. Gaps in the stratigraphic sequence occur locally but also supraregionally. Nowadays, there are gaps in the Tertiary beds due to Quaternary erosion, especially in the channels, and less so due to erosion in the Tertiary. The sediments, which are mostly clastic (sands, silts, clays), were deposited at the southern edge of the Northwest European basin of the Tertiary on a mainly marine shelf that was affected by the varying extent of the North Sea of that time. In the study area, the Tertiary sequence of strata was significantly affected by the halokinetic development of the Gorleben–Rambow salt structure. Above the salt structure, it is highly condensed (to approx. 50 m to 200 m) and its thickness increases in the rim synclines beyond normal thicknesses (approx. 600 m) to approx. 1 100 m in the northwestern rim syncline.

The oldest Tertiary (upper **Lower Paleocene**) was biostratigraphically detected in one borehole. It consists of highly calcareous clay with a thickness of 1 m. The stratigraphic sequence of the **Upper Paleocene** starts with fine sands that gradually turn into clays and, in the upper layers, into silts. The base area of the Upper Paleocene is largely identical with the base of the Tertiary. Between the Upper Paleocene and the Lower Eocene, a stratigraphic gap has been biostratigraphically identified.

The base of the **Lower Eocene** consists of the Gartow Sand, an alternating sequence of highly fine sandy silts and clays. Towards the top, silts of the Lower Eocene beds follow. The beds of the Lower Eocene are the stratigraphic member with the widest distribution in the Tertiary sedimentary sequence. Above the Gorleben salt dome, they are only missing in parts of the Gorleben channel, and above the Gorleben–Rambow salt structure in a small area southwest of Lenzen. The **Middle Eocene** is subdivided into the Brussel Sands (fine sands) at the bottom, which are still present throughout almost the whole study area, and the overlying Middle Eocene beds (silts and clays). The Middle Eocene beds cannot be distinguished – neither by lithological nor by seismological means – from the monotonous silt series of the **Upper Eocene** beds and could only be subdivided biostratigraphically. In the structural geological investigations the two beds were analysed conjointly.

The **Lower Oligocene** starts with a fine sand silt horizon, the Neuengammer Gassand. Towards the top, the sandy facies of the Neuengammer Gassand is quickly replaced by the monotonous lithographical facies of the basin area farther from the shore. In this basin, the Rupelton, which documents the highest sea level of the whole Tertiary, was deposited as a relatively monotonous sequence. In the **Upper Oligocene**, increasingly shallow marine conditions prevail, where clayey silts gradually change to silty fine sands towards the top. The Upper Oligocene is biostratigraphically subdivided into the Eochattian and Neochattian beds. Today, these sediments are largely missing above the Gorleben–Rambow salt structure and have been preserved in the area of the Gorleben salt dome mainly at the edge of the structure, in the ring wall. The sequence is partially condensed, partially truncated at the top by subsequent erosion.

The continental sedimentation conditions that had already set in during the late Late Oligocene grew stronger in the **Lower Miocene**, which is lithostratigraphically subdivided into the Untere Braunkohlensande, the Hamburg-Ton, and the Obere Braunkohlensande. The Untere Braunkohlensande mainly consist of fine to medium sands, with an increasing grain size in the upper part. Approximately ten metres below the top, a brown-coal seam is often intercalated (third Lusatian seam horizon). Except for the salt domes of Groß Heide–Siemen and Gorleben as well as parts of the Gorleben channel, the Untere Braunkohlensande occur as a coherent sedimentary unit in the study area. Above the Untere Braunkohlensande, the clay/silt sedimentation of the Hamburg-Ton sets in abruptly, which is increasingly interstratified towards the roof by sandy formations. The thickness and facies of the deposits are subject to highly varying conditions and reflect the repeated alternation between limnic-brackish and fluvial-terrestrial environments with increasingly continental influences towards the top. The beds of the Hamburg-Ton occur especially in the northwestern rim syncline and southwest of the Gorleben salt dome. Southeast of the Gorleben–Rambow salt structure, they occur very sporadically. The Obere Braunkohlensande, which are fine sands, are the youngest autochthonous sediment of the Tertiary in the study area. Due to denudation after the Early Miocene as well as to Quaternary erosion, they are preserved only in relicts and reduced in their overall thickness.

The sediments of the **Middle Miocene** (Reinbek beds) were only found in one borehole, as an allochthonous block in deposits of the Drenthe substage of the Saalian Glaciation. After the retreat of the sea from the North German Plain during the Late Miocene to Pliocene, the Tertiary soil was subjected to profound weathering and erosion.

The **Quaternary** sediments, which cover the whole study area, follow with a temporal hiatus of approx. 15 million years. Based on a wide range of investigation methods (pebble and boulder counts, sedimentological and palynologicalal analyses), the lithologically diverse sequence of strata was subdivided and subsequently its bedding structure was determined.

The **base of the Quaternary** consists of elements of different age and genesis. The most significant feature of the Quaternary base are deep, more or less parallel channels (>200 m). They were formed mainly by glacio-hydromechanic removal when the ice of the first Elsterian Glacial advance began to disintegrate. The most dominating element and largest coherent depression is the Gorleben Channel. It extends across the whole study area with a NNE to WSW strike and ends relatively abruptly outside the study area. The overall length is approx. 40 km. It crosses the Gorleben–Rambow salt structure on a stretch of 10 km at an acute angle. Above the central part of the salt dome, for a length of approx. 6 km and a surface of approx. 7.5 km^2, the Tertiary beds were completely eroded, so sediments of the Elsterian Glaciation lie on the cap rock and in some areas directly on the salt formation. In this area, the channel base relief is highly variable, with depths between 240 m below sea level and almost 300 m below sea level.

The **bedding structure of the Quaternary** was primarily influenced by glacial processes such as erosion, exaration, and glacial dynamics, and to a lesser extent by subrosion. The sequence of strata is represented by an almost complete sedimentary record from the Menapian cold stage to the Holocene.

In the southwestern crestal area of the Gorleben salt dome, progressive subrosion created a shallow sedimentation basin during the **Menapian**. The sequence can be subdivided into a lower sandy area of the Menapian age, and an upper section with an alternating sequence of clayey-silty and humous fine sandy beds, which represent the Bavelian to Cromerian Complex. The facies conditions were fluvial or limnic to fluvial. The sediments of the Bavelian were subdivided into two interglacial deposits, the sediments of the Cromerian Complex into five interglacial deposits, each with intercalated glacial formations, reflecting intense climatic variation. Initially, preglacial sediments were probably present above the northeast of the Gorleben salt dome. Older sediments of the Lower Pleistocene were not found in the study area.

During the **Elsterian Glaciation**, the Scandinavian ice sheet transgressed the study area for the first time. The sediments of the Elsterian Glaciation occur mainly in the deep Quaternary channels and above the southwestern area of the Gorleben–Rambow salt structure. Their lower section consists mainly of outwash sands. Locally, till is interstratified. The channel filling is concluded by fine-grained sediments of the Lauenburger-Ton-Komplex, which are partially superposed by retreat sands.

In the channel hollows that were not completely filled in the Elsterian age, limnic to limnic/fluvial silts, mud and sands were deposited during the following **Holsteinian Interglacial**. A marine transgression interstratified clayey and sandy sediments.

Towards the end of the Holsteinian Interglacial, not all sedimentation areas had silted up. In the remaining, only partially filled sedimentation areas, the limnic and limnic-fluvial sedimentation continued with fine and medium sands, without apparent major recession under the glacial conditions of the Early Saalian Glacial, in this case the Fuhne Glacial.

The glacial deposits of the **Saalian Glaciation** are the most widespread of the Quaternary beds. Compared to the older Quaternary sediments, which are mostly bound to the Quaternary channels, they are present in the subsurface throughout almost the whole study area. During the Saalian Glaciation, the Scandinavian glaciers transgressed the study area three times. Accordingly, three ground moraine horizons of till formed, which were intercalated with outwash sands and glaciolacustrine deposits, with the outwash sands being the dominating feature of the two. The structure of this sequence on the whole is characterised by narrow, complicated variation.

The sediments of the Holsteinian and the upper parts of the Lauenburger-Ton-Komplex were intensely contorted and partially imbricated by the continental ice sheet of the Drenthe substage. Above the Gorleben salt dome, the vertical extent of the glacigenic deformation reaches down to a depth of approx. 100 m below ground level. Beyond the salt structure, the glacigenic stress locally reaches into the beds of the Hamburg-Ton Complex, sometimes down to 140 m below ground level.

The only sediments of the **Eemian Interglacial** found were in two boreholes beyond the limits of the inner study area.

During the **Weichselian Glaciation**, the study area was not covered by ice. In the periglacial environment, the mainly vegetationless area experienced erosion and relocation processes on the geest plateaus and the accretion of the Lower Terrace in the Elbe valley. The sediments of the Lower Terrace are distributed throughout the whole study area except for the geest uplands and thus frequently form the present-day ground surface. The medium to coarse sands can be petrographically differentiated into an older (lower) and a younger (upper) Lower Terrace. The bottom surface of the Lower Terrace exhibits no potholes or plateaus that might indicate post-Eemian subrosion or a more recent uplift of the Gorleben salt dome. The structural shapes can only be interpreted as an image of fluvial erosion and deposition. During the Late Weichselian Glaciation, aeolian sands and organogenic sediments were deposited.

During the **Holocene**, predominantly fluvial sediments, floodplain loam, and floodplain sand were deposited, as well as local muds and peat. The accumulation of aeolian sands, which started in the Late Weichselian Glaciation, continued into the Holocene and formed individual dunes and dune fields. Morphological features or increased thicknesses of

Holocene sediments, which might indicate subrosive processes in the near-surface above the Gorleben salt dome, do not exist.

Using the structure of the beds from the Zechstein to the Quaternary, the **developmental history** of the Gorleben–Rambow salt structure can be reconstructed, from the Zechstein to the present day. The **Zechstein** beds, which initially had a thickness of more than 1 000 m, have only residual thicknesses of 100 m to 500 m outside the salt domes. The largest part of the mobile salt has migrated into the salt domes. Nowadays, the base lies at depths of 3 100 m to 4 450 m below sea level. Below the Gorleben salt dome, the Zechstein base is elevated, which contributed to the formation of the salt dome. There are no significant fault zones that could have triggered the salt uplift.

Above the Zechstein follows the **Bunter**, whose structure was affected by salt movements. In areas from which the salt migrated, the base of the Bunter lies at depths between 3 000 m and 4 300 m below sea level. At the salt dome flanks, it is sometimes steeply dragged up. The thickness of the Lower and Middle Bunter varies between 500 m and 800 m. Variations in thickness that are clearly due to salt movements cannot be detected. Only the structure of the bedding complex of the **Upper Bunter and Muschelkalk**, with thicknesses of 300 m and 700 m respectively, shows the effects of salt migrations. Northwest of the Gorleben salt dome, small thicknesses indicate a beginning salt accumulation, which led to the formation of an extensive salt pillow. During the **Keuper**, the salt accumulation increased, which can be deduced from local thickness variations of this formation. During this period, the diapirs of Dömitz and Aulosen were formed northwest and southeast of the Gorleben–Rambow salt structure, which caused a salt migration away from these areas. These areas of salt migration delimit a large salt pillow in the area of the later Gorleben–Rambow salt structure. During the **Jurassic**, the salt continued to migrate from the margins to the centre of the pillow, causing primary rim synclines to form, which were filled with Jurassic sediments. Due to regional uplift during the Upper Jurassic, approx. 400 m to 500 m of sediment were eroded, which is why the beds of the Jurassic were preserved almost exclusively in the rim synclines. During this phase of uplift, the diapir stage of the Gorleben–Rambow salt structure began, which lasted until the end of the Late Cretaceous.

The large thicknesses of the **Lower Cretaceous** in the secondary rim synclines reflect the salt flow into the salt structure. Outside the rim synclines, the widely distributed sediments of the Albian transgression indicate the end of the uplift phase. The **Upper Cretaceous** crops out east of the Gorleben–Rambow salt structure, as the formation of the Prignitz–Lausitzer Wall led to Tertiary truncation in that area. The relicts of the Upper Cretaceous on top of the cap rock of the Gorleben salt dome confirm that it was covered in the Late

Cretaceous, which indicates the end of the diapir stage. Large thicknesses of the Upper Cretaceous occur in the northwestern rim syncline of Gorleben, which prove the continued strong salt outflow during this period.

In the **Tertiary** the salt migration diminished considerably. The Gorleben–Rambow salt structure was almost completely covered by Tertiary beds in spite of the continued salt uplift. The thicknesses in the rim synclines were caused by salt migration. The largest thicknesses occur in the northwestern rim syncline, as the residual salt thicknesses in that area facilitated further salt migration. Above the salt dome top, the continued salt uplift caused the formation of crestal trenches in the up-domed covering beds of the Tertiary. The last Tertiary stratigraphic member of ubiquitous extent, except for the channel areas, is the Untere Braunkohlensande. Only relicts of the overlying Hamburg-Ton have been preserved. It has its largest coherent extent northwest of Gorleben, as larger residual salt thicknesses underground in that area increase the probability of halokinetically induced subsidence.

It was possible to reconstruct the epeirogenic-tectonic and halokinetic movements in the vicinity of the Gorleben–Rambow salt structure. The salt movements from the beginning of the diapir stage until today were calculated by means of a quantitative **rim syncline analysis**.

The analysis revealed that approx. 53 % of the initially 1 400 m thick Zechstein salts in the salt catchment area of the Gorleben salt dome have migrated into the salt dome. The salt flow velocities that occurred in the main salt at the planned repository level at 840 m below sea level were 0.337 mm maximum per year in the Late Cretaceous and up to 0.071 mm per year in the period from the Miocene through the Quaternary. The amounts of salt that migrated in to the salt dome caused an uplift rate of the salt dome surface of 0.08 mm per year during the Upper Cretaceous and 0.02 mm per year from the Miocene through the Quaternary. The calculations show that the salt migration has declined since the Cretaceous, when the maximum occurred, to the lowest value in the most recent period analysed. Salt migration depends on the overlying beds, tectonics, and the underground salt supply. As the geological conditions will not significantly change in the foreseeable future and the remaining amount of salt below the adjoining rock is relatively small and diminishing further, it can be expected that salt migration into the salt dome will further decline.

Up to now, approx. 47 % of the initially present Zechstein salt have risen to the ground surface and were subroded or eroded. In the salt catchment area, 185 km³ of salt have remained, about half of this has been accumulated in the salt dome.

In the North German Plain and thus in the study area, relatively stable **tectonic conditions** have sett in. Particularly the period since the Holsteinian Interglacial until the present is considered to be calm. Analyses of recent crust movements have revealed subsidence rates of less than 1 mm per year for the area of the Gorleben–Rambow salt structure. The stated value, however, is only a size range. If a subsidence of approx. 20 m (≥ 0.1 mm/year) since the Holsteinian Interglacial is assumed, then the absolute values are smaller.

Towards the end of the Tertiary and during the preglacial age, the cover of the salt dome top had eroded to such a degree that **subrosion** commenced locally. In the southwestern crestal area of the Gorleben salt dome, progressive subrosion created a shallow sedimentation basin during the Menapian that grew deeper in the centre, where sedimentary accumulation and subrosive subsidence were in balance during the Bavelian and Cromerian Complex. The subsidence rate was between 0.06 mm per year and 0.2 mm per year.

In the period from the formation of the Quaternary channels to the post-Holsteinian age, subrosion of the salt rock occurred at the top of the Gorleben salt dome. This local subrosion is proven by the formation of the cap rock breccia, the deposits of the gypsum anhydrite laminate, and the large difference in the Holsteinian base above the salt dome. The average subrosion rate was 0.2 mm per year.

Above the Gorleben–Rambow salt structure, subrosion or subsidence movements within the last 128 000 years, i.e. since the Eemian Interglacial, could not be detected by geological methods in the area between Lenzen and the southwestern end of the Gorleben salt dome. This leads to the conclusion that very little subrosion took place during this period. As the geological conditions in the overburden of the Gorleben salt dome and at the salt table have not fundamentally changed during the last 128 000 years, it can be concluded that future subrosion is possible, but will probably be very low.

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Abbreviations

API	American Petroleum Institute (unit of measure for radiometric borehole logging)
BfS	Bundesamt für Strahlenschutz, Salzgitter
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover
C_{org}	organic carbon
DBE	German Company for the Construction and Operation of Waste Repositories
EEG	VEB Erdöl Erdgas, Gommern
GGD	Gesellschaft für Geowissenschaftliche Dienste mbH, Leipzig
GK	geological map
IMS	Ingenieurgesellschaft mbH, Hannover
SK	salt pillow
s. l.	sensu lato, Latin: in the broad sense
SST	salt dome
s. str.	sensu stricto, Latin: "in the strict sense"
TGL	terms of technical quality and delivery
TGZ	Theoretisches Geschiebezentrum, "theoretical pebble stone centre"
TK	topographic map
TOC	Total organic carbon
VEB	Volkseigener Betrieb, "people's enterprise", state-owned enterprise of the former German Democratic Republic
ZGI	Zentrales Geologisches Institut, Berlin
ZIPE	Zentralinstitut Physik der Erde, Potsdam

Borehole acronyms

BKN	brown-coal exploration hole
Bzg	Boizenburg
E	oil/gas exploration hole
Ela	Eldena
Go	Gorleben
GoHy	Gorleben, hydrological investigation programme
GoQ	Gorleben, Quaternary geological shallow drilling programme
Grs	Gorlosen
HWW	Hamburg waterworks, borehole for water resources planning
HY	hydrogeological borehole
Pa	Parchim
Pes	Peckensen
Pröt	Pröttlin
RmwL	Rambow near Lenzen
SEEW	Seewiesen
SELI	Sellien
WSTR	Wustrow

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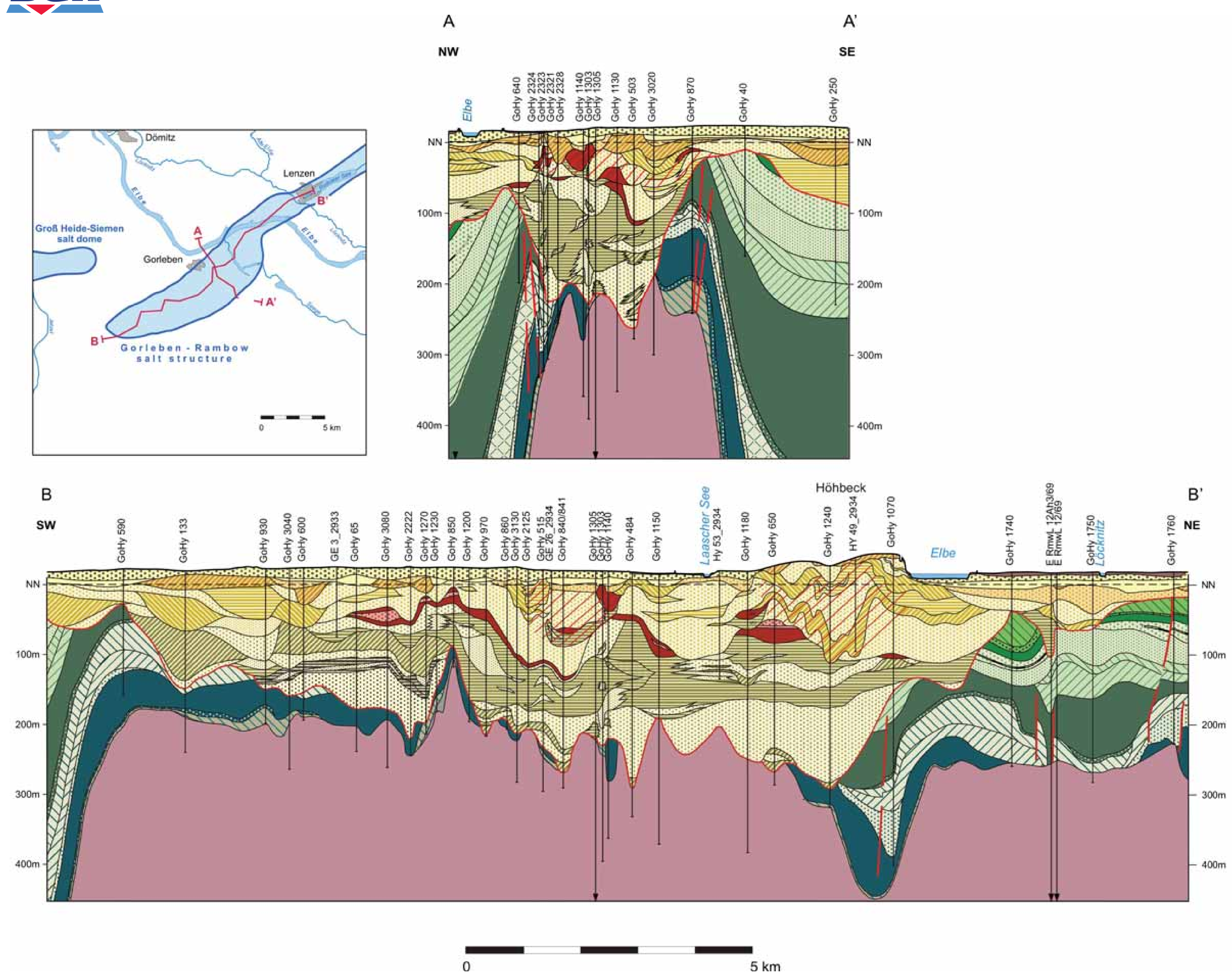

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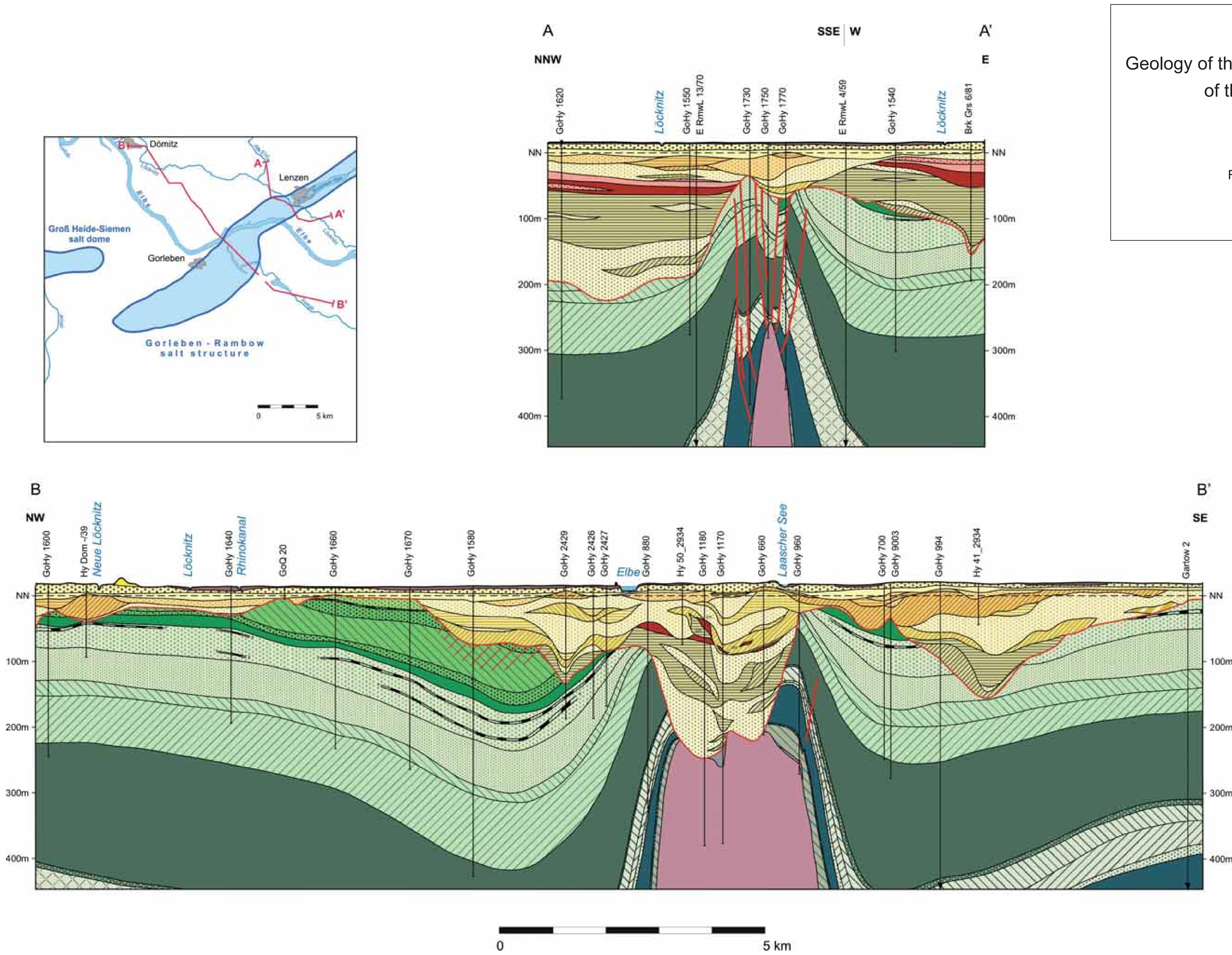

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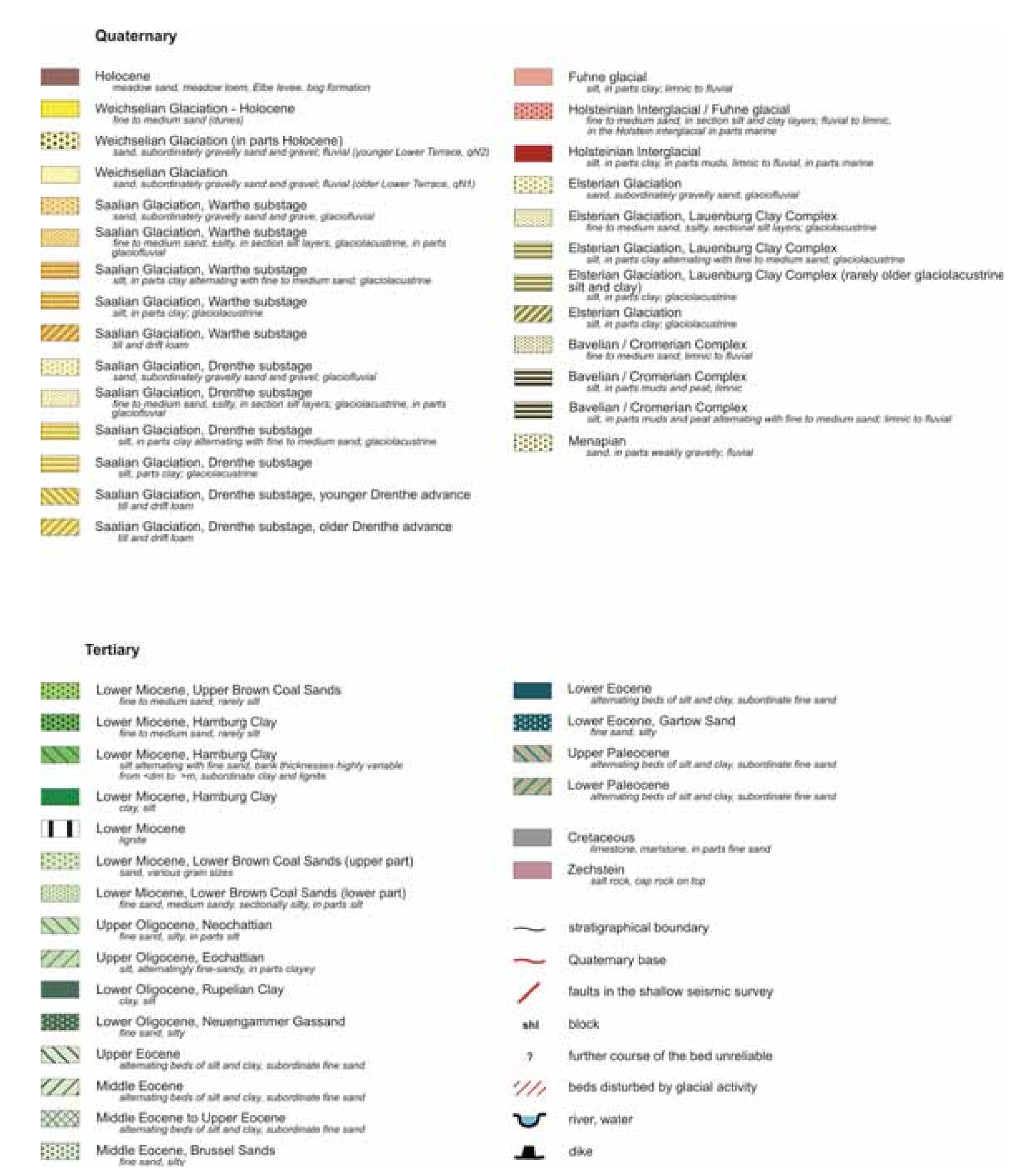

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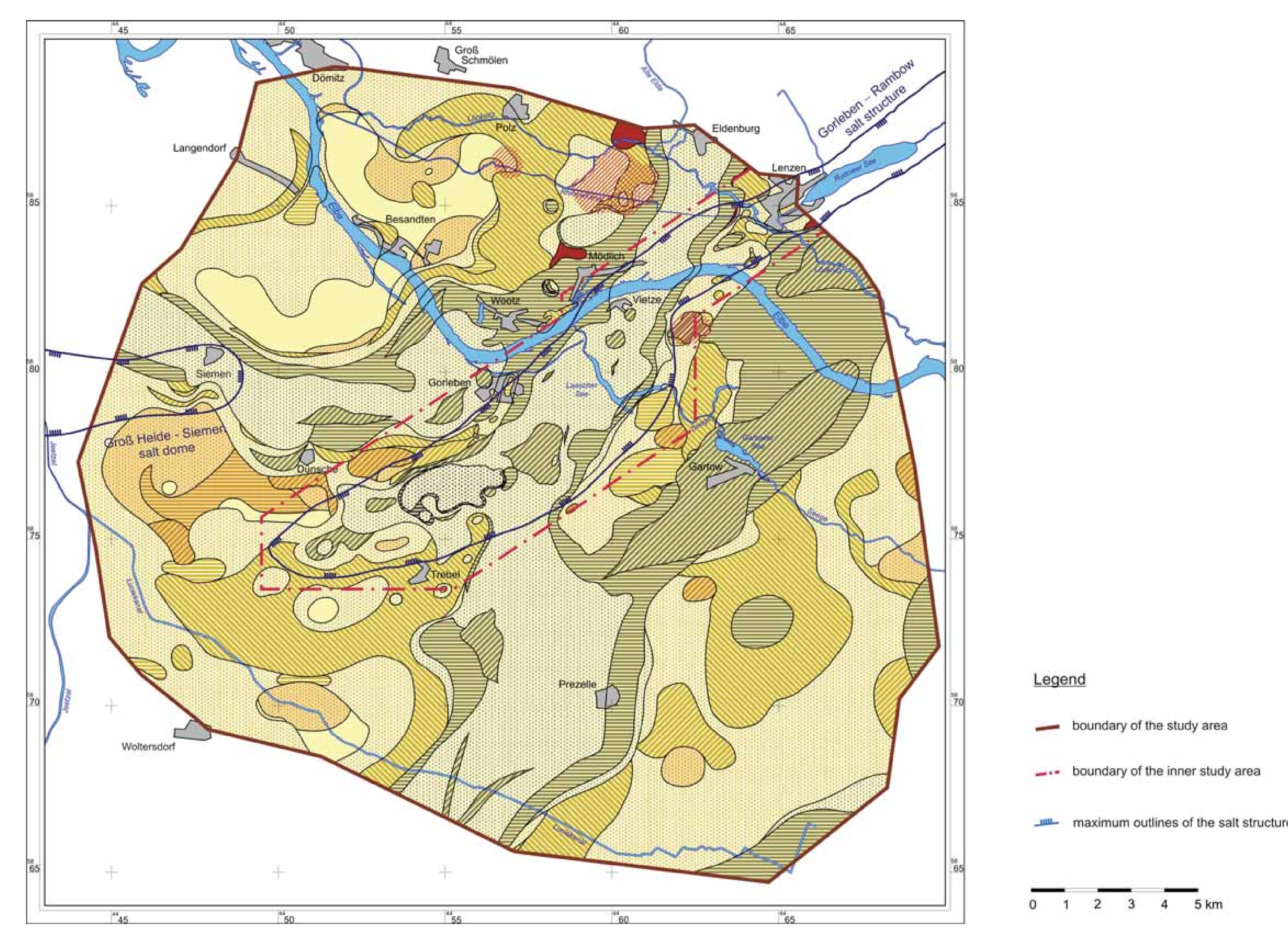

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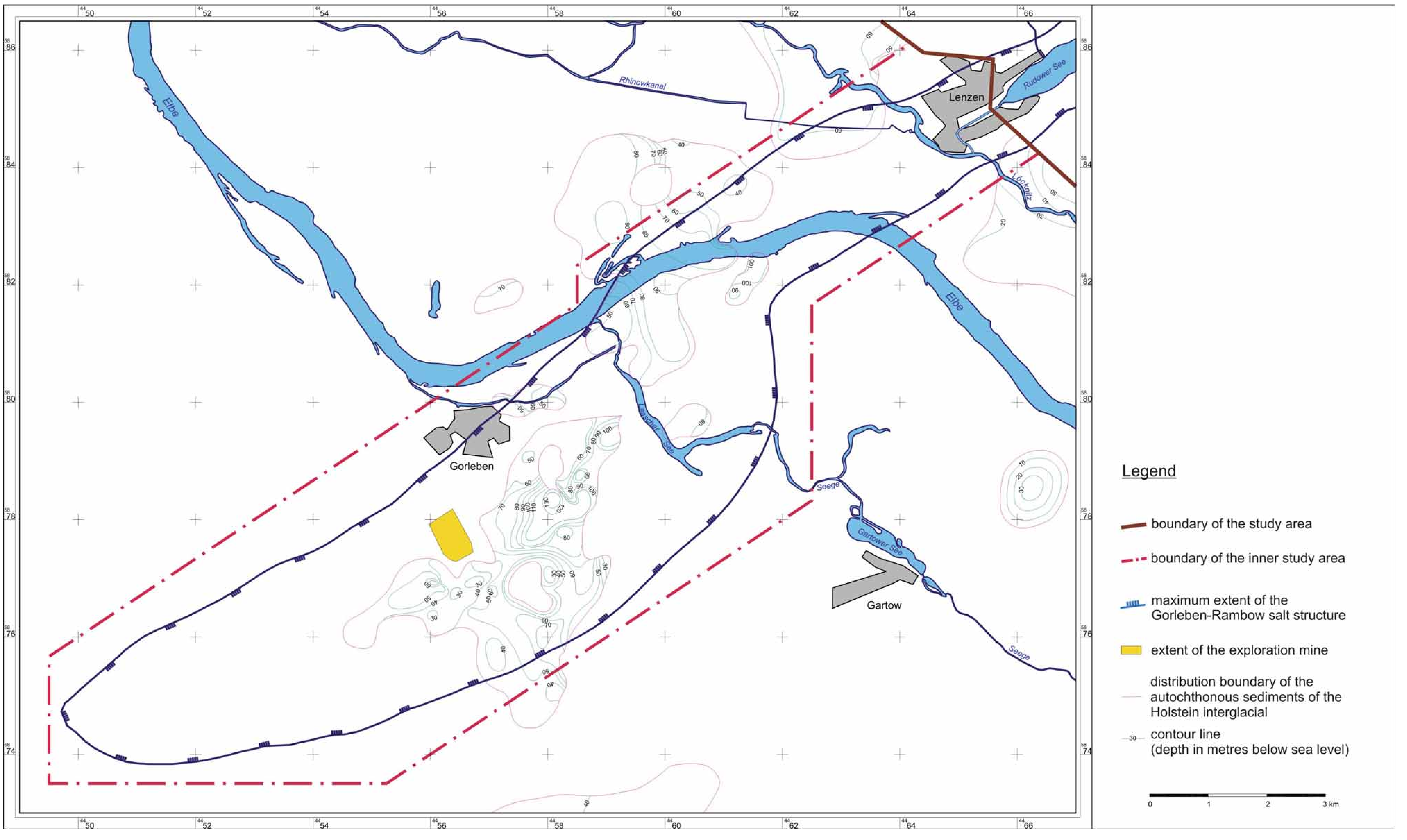

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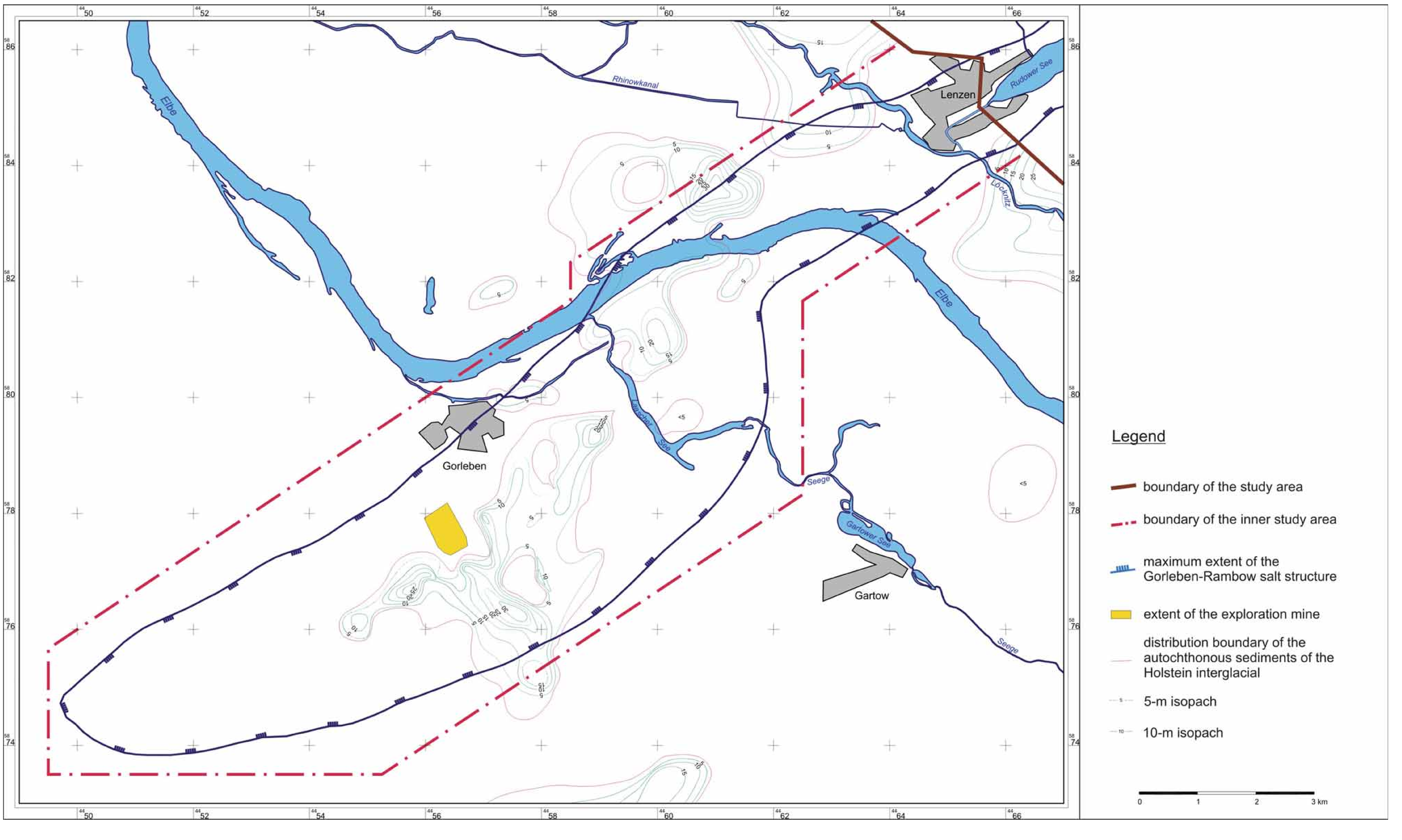

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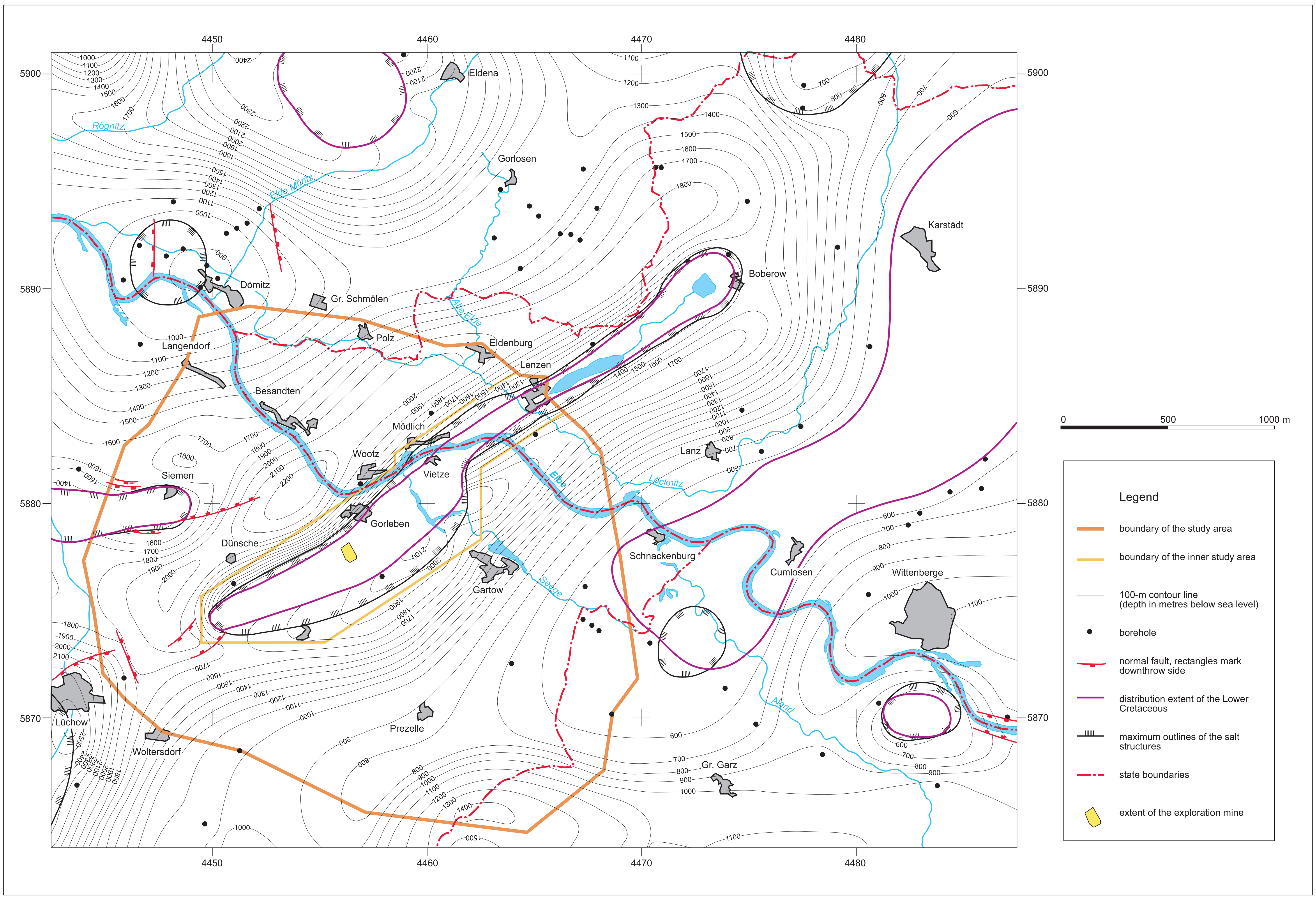

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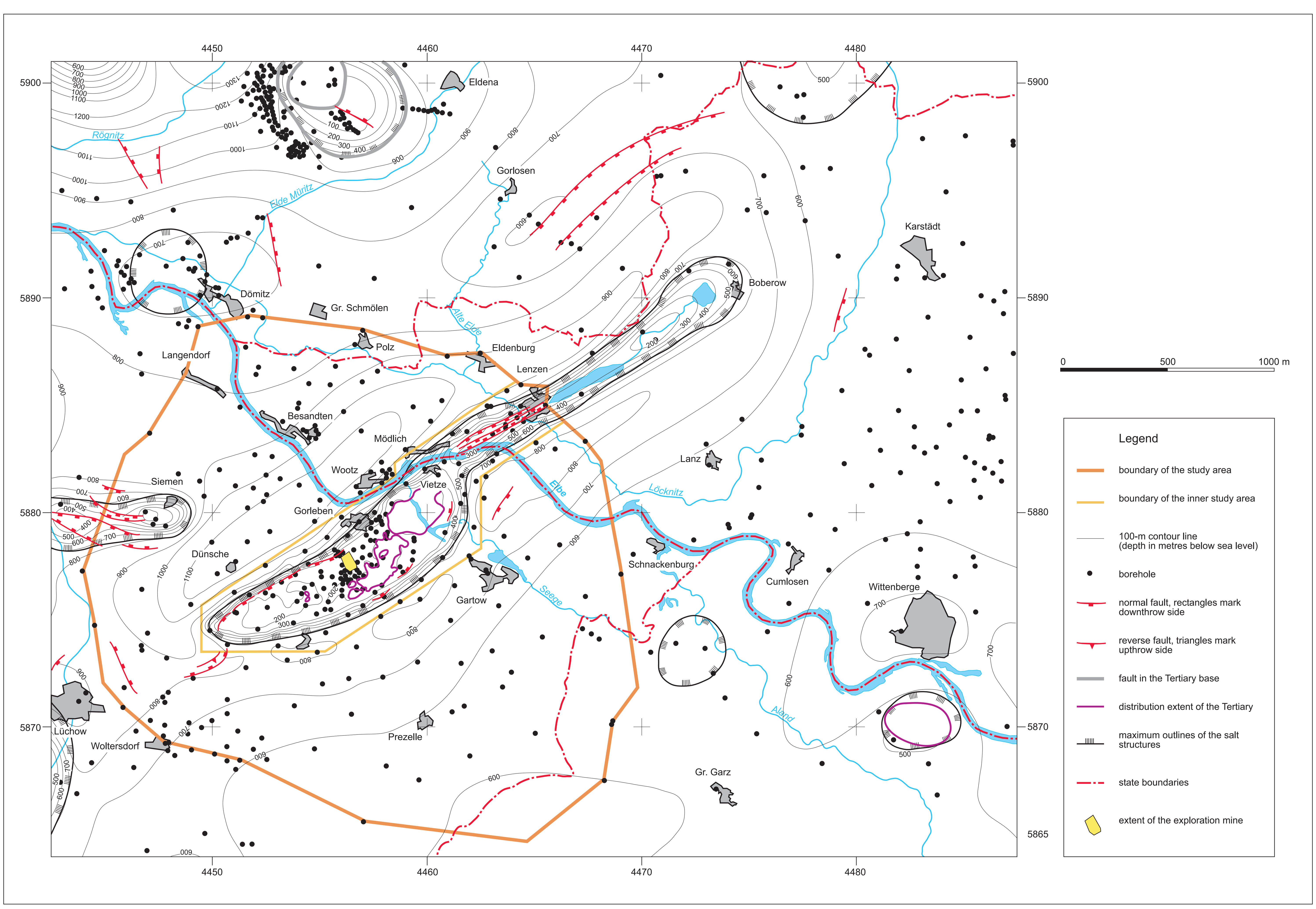

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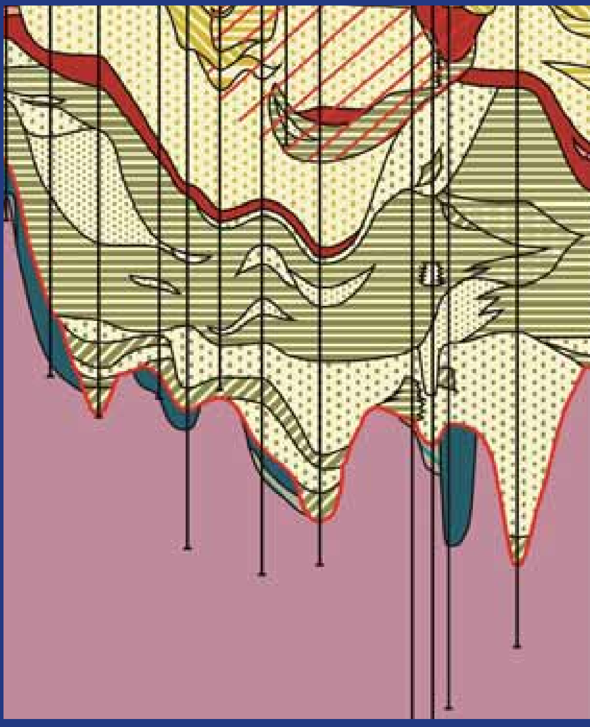

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