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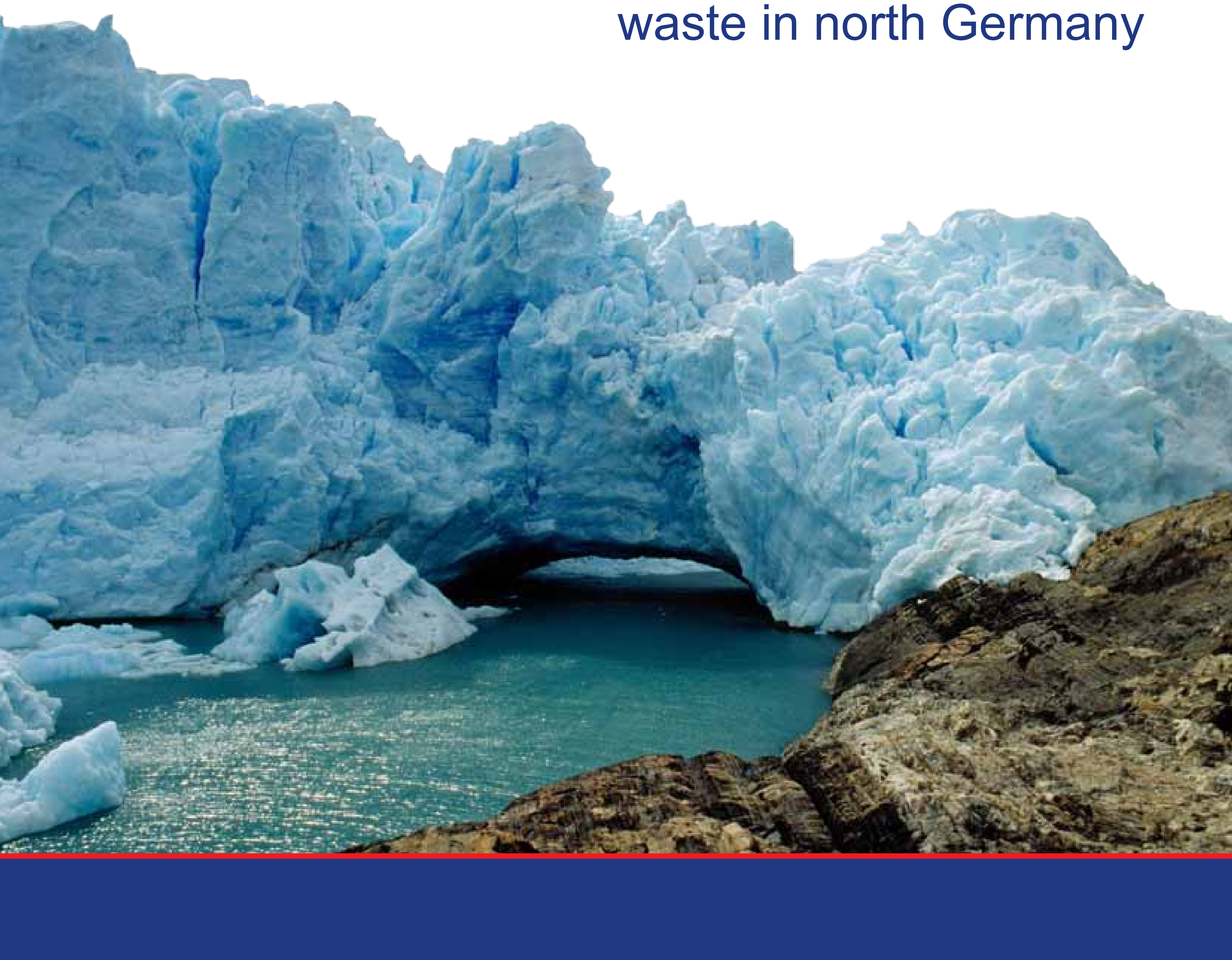
Glacial channel systems and their significance for the long-term safety of potential geologic repository sites for high-level radioactive waste in north Germany



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Glacial channel systems and their significance for the long-term safety of potential geologic repository sites for high-level radioactive waste in north Germany

Hannover, August 2009

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1 Introduction

In Germany, the primary host rocks for the disposal of high-level radioactive, heat-generating waste (HAW) in geologic repositories are rock salt and argillaceous rocks. Because of the accumulation of thick salt formations with favourable properties, the salt domes in north Germany which have not been affected by extractive mining activities or other uses, are considered to be potential geologic repository sites for HAW. In addition, the argillaceous formations of the Mesozoic in north Germany are also considered worthy of investigation (Hoth, P., Wirth, H. et al. 2007: cf. Fig. 4.30).

In the German geologic repository concept, the main component safeguarding the isolation of high-level radioactive waste is a geological barrier. A key aspect in this regard is the so-called isolating rock zone (cf. AKEND 2002). This is intended to guarantee the safe sealing of the waste (HAW) and its isolation from the biosphere by virtue of the special properties of the host rock, combined with the technical barriers. The cover rock overlying the host rock is usually not an integral part of the isolating rock zone, which means that the cover rock is not assigned any significant relevance as a barrier. Nevertheless, it is accorded some long-term significance within the framework of the proposed isolation period of one million years, for reasons including its role in protecting the host rock and the isolating rock zone from exogenic influences.

The Gorleben salt dome has been investigated since 1979 to assess its suitability for the construction of a possible geologic repository for high-level radioactive, heat-generating waste. Surface exploration revealed that the cover rock incorporates a channel of glacial origin which has completely eroded the previously existing, low-permeable argillaceous beds of Cretaceous and Tertiary age. Under the hydrogeological conditions existing at the time, this led to increased subrosion of top salt. This means that a minor thinning of the approx. 600 m thick rock salt barrier at the Gorleben salt dome is possible when assuming the expected long-term average subrosion rates of 0.01 to 0.05 mm/year (10 - 50 m/million years) (Bornemann, O., Behlau, J. et al. 2008). In the case of the Gorleben salt dome, as well as other potential locations where rock salt is the host rock, the emplacement concept therefore stipulates the drifting of repository levels at significant depths of between 800 and 1000 m.

By comparison, the depth of argillaceous formations worthy of investigation is at around 300 to 1000 m, whereby depths of 300 to 400 m are favoured for the emplacement of HAW for geophysical, technological and economic reasons (cf. AMELUNG, P., JOBMANN, M. et al. 2007; BGR 2007; HOTH, P., WIRTH, H. et al. 2007; JOBMANN, M., AMELUNG, P. et al. 2006; UHLIG, L., AMELUNG, P. et al. 2007).

A description of the development of the cover rock is generally required when preparing a safety assessment report for a potential geologic repository site in rock salt or argillaceous rocks as the host rock. This safety assessment report includes an evaluation of the geological and climatically-driven processes which might cause significant changes to the properties of the cover rock over the specified isolation period, and which could therefore have potential consequences on the isolation capacity of the host rocks.

The following discusses the outlook for the climate over the next million years, and looks at the genesis of the subglacial channels. The current and future distribution of the channels is described, and their significance is discussed for potential geologic repository sites within rock salt or argillaceous host rocks.

2 Outlook for future climatic development derived from the changes in the climate over the last million years

2.1 The past

The amount of energy derived from solar radiation which enters the climate system of the earth depends amongst other things on the position and orientation of the earth with respect to the sun. Astronomical parameters such as the eccentricity of the earth‘s orbit, the angle of the ecliptic, and the precession of the earth‘s axis of rotation, are subject to characteristic cyclic variations because of the gravitational influence of the sun, moon and planets (Milanković cycles). These can give rise to climatic changes lasting for periods corresponding to the specific cycle: almost 100,000 years (eccentricity), approx. 41,000 years (obliquity) and around 22,000 years (precession). The latitude-dependent and season-dependent fluctuations in insolation associated with the Milanković cycles have an impact on long-term variations in climate in particular, and are currently considered as the pacemakers for the Pleistocene climate cycles with fluctuations between glacial periods (ice ages) and interglacial periods (the periods between ice ages = warm periods).

After the very warm global climatic conditions which existed during the Cretaceous and early Tertiary periods, temperatures began to drop around 35 to 40 million years ago, giving rise to the first glaciation within the Antarctic continent. Glaciation of the northern hemisphere began at a very much later date only approx. 3 million years ago. It can therefore be assumed for the northern hemisphere that to reach these low temperatures, it was first necessary to create the conditions for reinforcement mechanisms (plate tectonic processes, changes in oceanic circulation patterns, ice-albedo-temperature-feedback, natural fluctuations in atmospheric CO_2 concentrations, etc.), which, when modulated by the Milanković cycles, finally initiated the typical fluctuations between glacial and interglacial periods experienced over the last million years. Figure 1A shows the climatic changes on the earth derived from the average oxygen isotope data over the last 70 million years (70 Ma) (BARTLEIN, P. J. 2007). The data indicate a continuous cooling of the earth‘s climate, interrupted at specific intervals by warmer climatic periods.

The visualisation of the change in climate compiled from various oxygen isotope plots and shown in Figure 1B, highlights in the grey shaded areas, the change in the astronomical cycles which began around 2.7 million years ago (2.7 Ma), where the length of the cycles changed from 19 - 23 thousand years (19 - 23 ka) to cycle lengths of 41,000 years (41 ka). This change is associated with the glaciation of the Arctic zone which can be indirectly verified in the North Atlantic by material transported by the ice. The reasons for the delay in the glaciation of the northern hemisphere compared to the Antarctic glaciation, and for the subsequent change from 41 ka cycles to 100 ka cycles during a transition period around 800,000 years before present (Middle Pleistocene transition zone: MPT) are still not adequately understood. Some climate scientists hypothesise that the change is associated with the long-term decrease in the CO_2 concentrations in the atmosphere or continental weathering processes.
HUYBERS, P. (2009) is of a different opinion and considers that the Pleistocene glacial variability is chaotic and that the transition from the 41 ka to the 100 ka cycles is spontaneous. A notable feature of the climate in the last hundreds of thousands of years after the Middle Pleistocene transition zone, is the large

amplitude of the temperature changes, i.e. the temperature differences between glacials and interglacials are more extreme than in the period before the Middle Pleistocene transition zone. As a consequence, rewarming after significant glacial events in particular occurs much faster than the build-up of the continental ice during the preceding glacial period. There is a correlation between the start of rewarming and the build-up of a volume of continental ice critical for the development of the climate. After the Middle Pleistocene transition zone, there are also differences in the heights of the amplitudes between each glacial period.

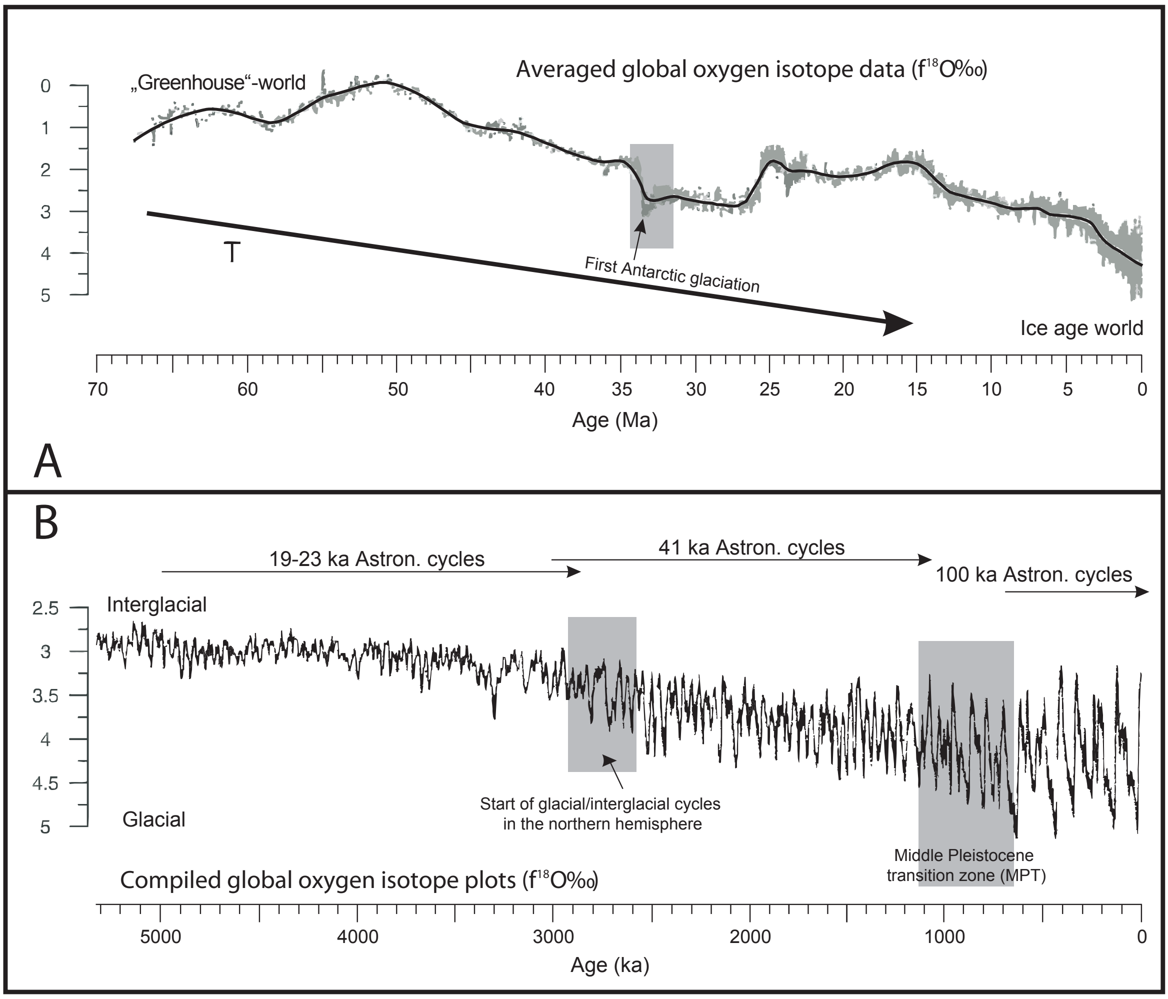

Fig. 1: Changes in climate derived from oxygen isotope data. 1A: Average global oxygen isotope data; 1B: compiled global oxygen isotope plots (modified after Bartlein 2007; Köhler & Bintania 2008; Poore 2007).

2.2 Future

If the climatic outlook for the future is to be derived from our understanding of the climatic changes in the past, a problem arises because the changes in climate over the last one million years have not been uniform, and the rules which govern this non-uniformity are not understood. Moreover, it is only possible to speculate at the present day on how the human influence on the future long-term changes in climate will act out. MÜLLER, U. C. & PROSS, J. (2007) postulate that the expected change from the current interglacial period to glacial climatic conditions has already been delayed by the greenhouse gas emissions generated by human activity, with the consequence that glacial conditions will not develop until approx. 50,000 years from today at the earliest. MYSAK, L. A. (2006) estimates that interglacial conditions could even dominate in future for another 500,000 years because of the anthropogenic influences on the climate (cf. CHOCHELIN, A.-S. B., MYSAK, L. A. et al. 2006).

When undertaking a long-term safety analysis, it becomes necessary to define a hypothetical climate construct for the period covering the next one million years because the changing course of the climate in the past cannot be directly extrapolated to predict what will occur in the next one million years. For conservative reasons, the behaviour of the climate after the Middle Pleistocene transi-tion zone is used as the basis for considering what the future could hold for the geological development of the cover rock above the host rocks of geologic repositories for high-level radioactive waste. This takes into consideration the large temperature differences between interglacials and glacials, and the wide-spread distribution of the continental ice in Central Europe which did not exist at such a scale prior to the Middle Pleistocene transition zone.

The following assumptions are therefore made for the hypothetical climate model:

- that the changes which occurred in the past after the Middle Pleistocene transition zone provide a basis for predicting the future climate over the assessment period of 1 million years,
- that the changes in insolation arising from the cyclic variation of astronomical parameters such as eccentricity, obliquity and precession (→Milanković cycles) will continue to drive climate change - which means renewed gla-

ciation of the northern hemisphere around 100,000 years from now and the wide-spread distribution of continental ice,

- that analogous changes in climatic behaviour (cyclic changes), such as that marked by the Middle Pleistocene transition zone around 800,000 years ago, will not take place,
- that there will be no large-scale global changes arising from events such as the alteration of global ocean currents or the uplift of mountain chains, or changes which, despite the continuation of the Milanković cycles with insolation minima, could give rise to a fundamental change in climatic conditions which prevent glaciation in the northern hemisphere,
- ignoring the impact of today‘s greenhouse gas emissions.

The consequences of the anthropogenic effects on future climate will tend to reduce the possible number of ice ages in the future and can thus ameliorate the impact of glaciogenic effects on the cover rocks during the period in question.

Furthermore, consideration will be given to the work of LISIECKI, L. E. & RAYMO, M. E. (2005) which identify nine glacial/interglacial cycles up to the present day since the Middle Pleistocene transition zone around 800,000 years ago.

Extrapolating these ideas gives a hypothetical climate model for the next one million years which features ten additional ice ages, some of which could match the extent of the Elsterian or Saalian glacial periods (see ice sheet edge conditions in Fig. 2 and 3).

According to this forecast, the ice in north Germany during an ice age comparable to the Elsterian and Saalian glacials in the past would reach the German Mittelgebirge. During future glacial periods analogous to the most recent ice age (Weichselian) the southern edge of glacial ice sheets would be located to the north of the river Elbe. The growth of continental ice sheets would be interrupted by interim warming periods (interstadials) lasting for several tens of thousands of years. This would be followed by the maximum southern extensions of the glaciers for periods of approx. 20 - 40 thousand years, which would cover large parts of northern Germany with ice sheets.

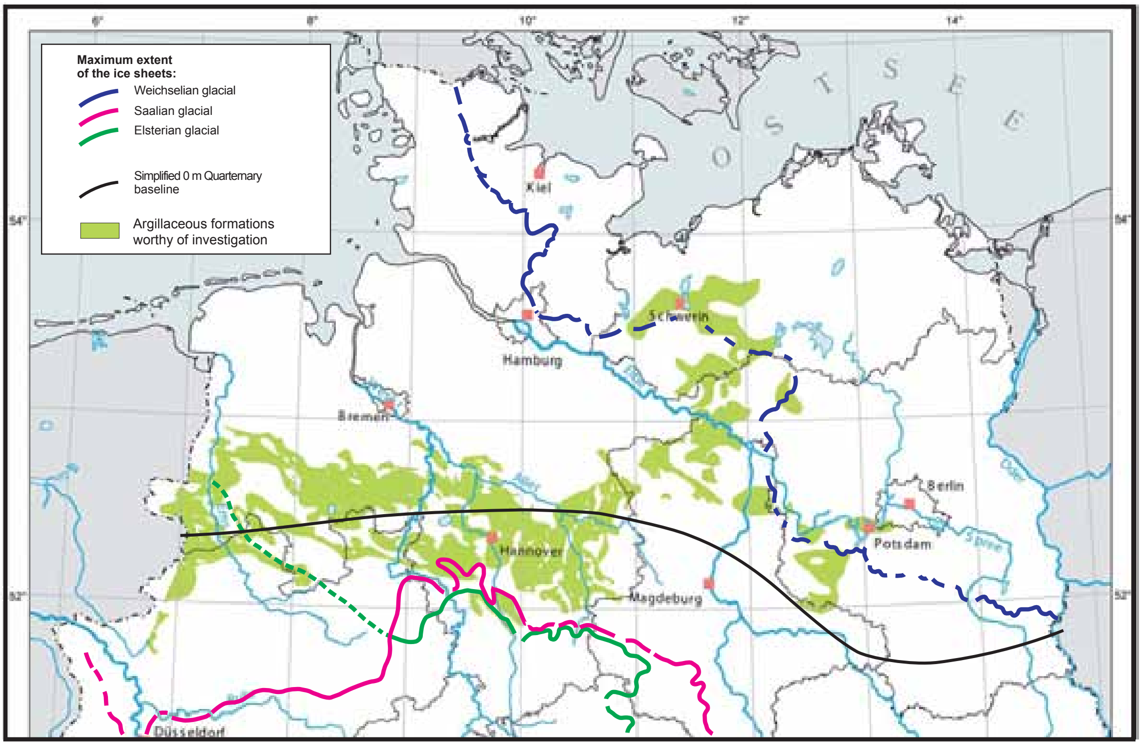

Fig. 2: Distribution of argillaceous formations worthy of investigation; maximum extent of the ice sheets; and simplified 0 m Quaternary baseline (supplemented after: HOTH, P., WIRTH, H. et al. 2007).

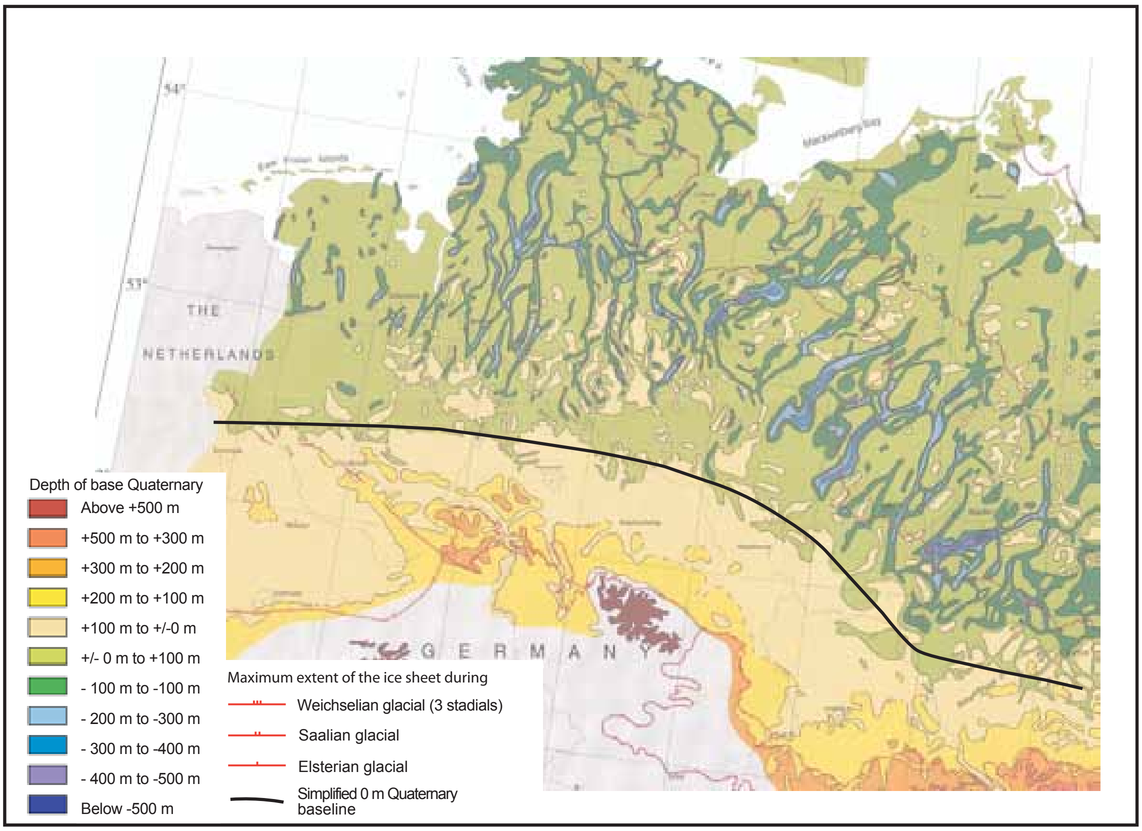

Fig. 3: Distribution of the Elsterian glacial channel system visualised by depicting the depth of base Quaternary (from: STAKEBRANDT, W., LUDWIG, A. O. & OSTAFICZUK, S. 2001).

3 Glacial channel formation

The formation of channel systems is possible during a glacial period giving rise to continental glaciation in Central Europe. Channel systems are caused by the outflow of large volumes of melt water. Channels can form either beneath the continental ice under subglacial conditions or in front of the edge of the ice sheet.

Channels formed in front of the continental ice sheet are frequently associated genetically with ice lakes: when the ice barrier forming the dam breaks, the catastrophic release of the water masses causes severe erosion of the sediments in rocks lying in the path of the flood water. Ice lakes formed at various locations in north Germany at the margins of the Mittelgebirge where the surface water flowing from the south combined with the melt water from the margin of the ice sheet which had moved south, to the northern edge of the Mittelgebirge, and so trapped the water because it could no longer flow along its natural course in the direction of the North Sea (cf. Feldmann, L. 2002; Thiermann, A., Koch, M. et al. 1970; Thome, K. N. 1980). The channels which formed as a result have comparable dimensions to river valleys. Depending on the volumes of water draining away, analogous channels with depths of a few tens of metres may develop under future glacial scenarios in north Germany. Compared with related glacial channels in North America, their dimensions will therefore be relatively modest (cf. Kehew, A. E., Lord, M. L. et al. 2007).

Unlike the channel systems which developed in front of the ice sheet, the subglacial channel systems which formed beneath the continental ice reached depths of up to 500 m during the Elsterian glaciation, with lengths of tens to hundreds of kilometres and widths of several kilometres (see Fig. 3; Kuster, H. & Meyer, K.-D., 1979; Stakebrandt, W., Ludwig, A. O. et al. 2001). The channels are relatively uniformly aligned in a NNE to SSW direction in western north Germany, and NE to SW in eastern north Germany. No preferential location for the formation of these kinds of channels has been identified so far. However, no comparably deep channel systems were formed in north Germany during the subsequent Saalian glacial period even through the continental ice sheet extended just as far south as during the Elsterian glacial period – and in some cases even further. Deep channels which formed during the Saalian glacial period and during the most recent glacial period (Weichselian) have only been identified in localities lying further to the north in the vicinity of the North Sea and Denmark, or further to the east in the area covered by Poland and the Baltic region. Glacigenic basins linked to the Saalian glacial period and associated with deep channels have been described in the northern Netherlands (Van Dijke, I. J. & Veldkamp, A. 1996).

The conditions under which the various subglacial channels are interpreted to have been formed are still the subject of heated debate (Kehew, A. E., Lord, M. L. et al. 2007: 826). Overall though, most of the channels, and particularly those formed in north Germany during the Elsterian glacial period are considered to be the product of the action of melt water which flowed under very high hydraulic pressure, and cut down erosively into the underlying rock during one single event or during a continuous process. Associated conditions such as average air temperature, the presence of permafrost at the edge of the ice sheet, the absence of permafrost below the continental ice sheet in adjacent areas far from the edge of the ice sheet, ice thickness, presence of a continental ice sheet covering a large flat-lying area, etc., are considered to be the causes or the prerequisites for the formation and dimensions of the subglacial channels. The depth of the individual channels was apparently not only attributable to the presence of adequate volumes of water, but especially also to the permeability and the nature and hardness of the underlying sediments and rocks: the more permeable and softer the beds beneath the continental ice sheet, the greater the extent of the channel formation.

The in part still inadequately understood boundary conditions associated with the formation of the channels obviously also determined those areas where no subglacial channels have been identified. Deep channels which formed during the Elsterian glacial period have so far only been identified north of the simplified 0 m isoline at the base of the Quaternary shown in Figure 3, even though the ice sheet extended much farther to the south. As mentioned earlier, no channels of similar depth formed during the Saalian and Weichselian glacial periods in north Germany - which again suggests that other boundary conditions must have existed during the glacial periods which affected the area.

4 Significance of subglacial channels for the long-term safety of geologic repository sites in north Germany

In Chapter 2, it was concluded that ten more ice ages could possibly affect the area during the one million year period considered in this study. And that one or several of these glacial periods could have a similar extent to the Elsterian glacial period. This means that subglacial channels with maximum erosion depths of up to 500 m could also potentially form in the future in unconsolidated Tertiary and Quaternary sediments. However, it is not possible to predict where such channels may form in future. In principle, subglacial channels could therefore form at any locality in north Germany.

This means that in an analogous way to the Gorleben salt dome, the cover rock of other potential geologic repository sites might also be subject to erosive change in future by the formation of subglacial channels. The situation that exists in the cover rock above the Gorleben salt dome is therefore a model for the possible future of other salt and argillaceous rock sites. The existence of a subglacial channel in the cover rock of a potential geologic repository site in north Germany is therefore nothing special, and in the light of the assumed future development of the climate, has to be seen as a real possibility anywhere in north Germany as part of the long-term safety analysis of changes in the cover rock.

In the context of subglacial channels, there are differences between salt and argillaceous geologic repository host rocks associated with the difference in the depth of the emplacement zones. These emplacement zones are defined as being deeper than 800 m when rock salt is used as the host rock. In the case of argillaceous host rocks, however, the most favourable depth of the emplacement zones is considered to start at a shallower depth of 300 m (BGR 2007; Hoth, P., Wirth, H. et al. 2007) and within the particularly favourable zone down to approx. 400 m because of the special host rock properties (cf. Amelung, P., Jobmann, M. et al. 2007; Jobmann, M., Amelung, P. et al. 2006; Uhlig, L., Amelung, P. et al. 2007).

4.1 Sites in salt host rocks

The main period of diapirism affecting most of the salt domes in north Germany occurred during the Cretaceous. During this period of diapiric upward movement, they lost their former sedimentary overburden consisting of Upper Cretaceous rocks (hard sediments in “Pläner” facies or relatively soft sediments in the marl and “Schreibkreide” facies), so that at the present day, the cover rocks overlying the salt domes, as typically represented by the Gorleben salt dome, largely only consist of unconsolidated Tertiary and Quaternary beds. Figure 4 shows an example of a simplified schematic cross-section through a north German salt dome.

Subglacial channels forming in future in similarly structured permeable cover rocks at alternative localities are expected to cut down in a similar way to that already seen today in the Gorleben salt dome (Bornemann, O., Behlau, J. et al. 2008). At the Gorleben site, a subglacial channel eroded Tertiary beds and the remains of the Lower Cretaceous rocks during the Elsterian glacial period so that Elsterian Quaternary channel sediments now also lie directly above the salt rock in parts. The hydraulic pressures which existed when the melt water flowed across the area must have been very high because some parts of the cap rock above top salt became brecciated. Evidence that brecciation of parts of the cap rock was associated with the formation of the channel is available in the form of interbedded sandy layers with pebbles which in parts also reveals the bedding forms typical of flowing water, and have been proven to be of Quaternary age.

The irregular shape of the surface of the salt in the vicinity of the channel resembles the surfaces typical of channels which develop in solid rock. Characteristic erosion features in low permeable hard rocks described by Kor, P. S. G., Shaw, J. et al. (1991) in parts of North America are attributed to extreme drainage events involving large volumes of rapidly draining subglacial melt water. An example of a subglacial channel in north Germany featuring these types of erosion forms is in the Muschelkalk outcrop near Rüdersdorf to the east of Berlin (Schröder, J. H. 1995). A this locality, a channel with a depth of around 50 m and a width of between 5 to 160 m was cut down into the rock in a manner dependent on its hardness, as evidenced today in the rocks which are now exposed at the surface. Analogous channels cut down to depths of up to approx. 50 m into outcropping low permeable and variably hard salt rocks are therefore considered possible for conservative reasons during channel formation. This interpretation is reinforced by the observations made at the Gorleben salt dome. Although top salt in the vicinity of the Gorleben channel still has a relief today which is partially attributable to the development of the channel, it is only slightly deeper than the surrounding top salt surface (Bornemann, O. 1991: enclosure 16). It can therefore be concluded that the rock salt is only affected by slight dissolution and erosion during the processes which caused the formation of the Elsterian subglacial channel. In addition, the erosion of the melt water clearly took place preferentially along the permeable boundary between the cap rock and top salt, as demonstrated by the cap rock breccia. If only unconsolidated Quaternary/Tertiary beds and Cretaceous argillaceous rocks had been present, instead of the „tough" salt dome, the Gorleben channel would certainly have cut down even deeper. This is highlighted by a comparison of the degrees of hardness between rock salts and argillaceous rocks, revealed, for instance, by simple classification according to the Mohs scale of hardness: the north German argillaceous rocks of Quaternary, Tertiary and Lower Cretaceous age are relatively soft. They only reach values of between 1 and 2 on the Mohs scale of hardness. Rock salts have hardnesses of 2.5, and gypsum around 2 - which together with anhydrite is the main constituent of a cap rock. Anhydrite even has a hardness of 3 to 3.6.

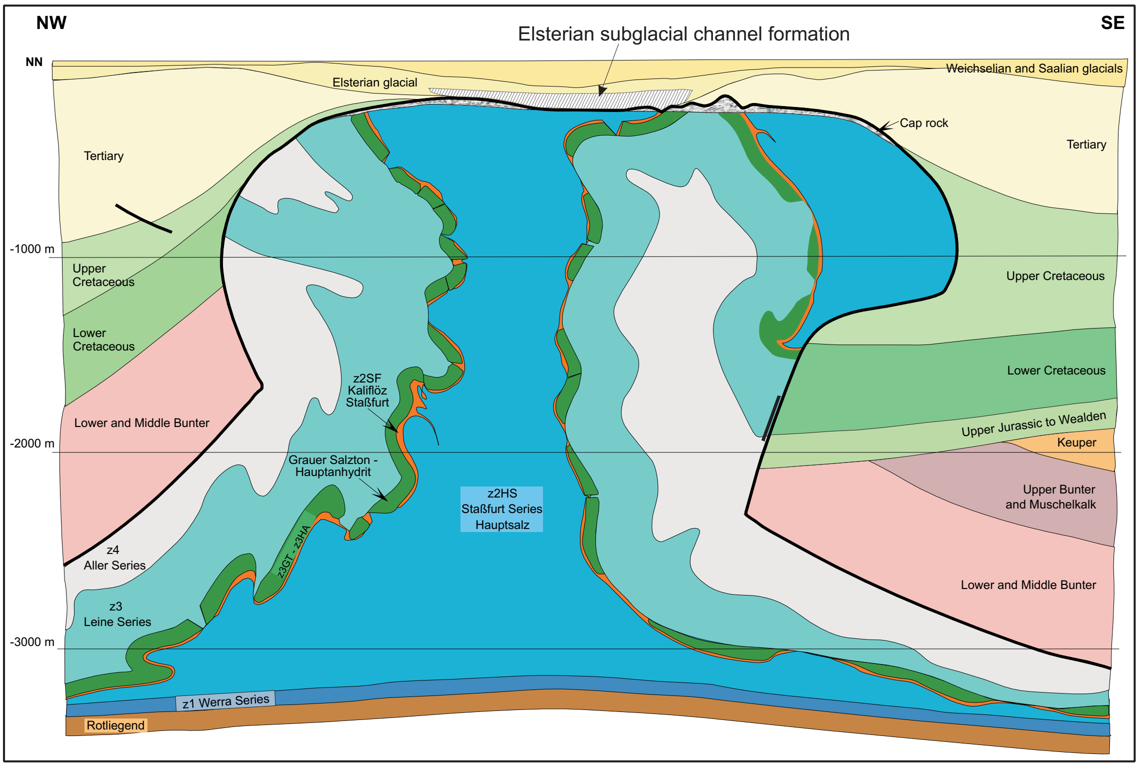

Fig. 4: Schematic cross-section through a salt dome in north Germany (after Bornemann, O. 1991).

4.2 Sites in clay host rocks

The depths to the argillaceous rocks in north Germany which are worthy of investigation lie between > 300 and < 1000 m according to HOTH, P., WIRTH, H. et al. (2007). Figure 5 shows a simplified schematic cross-section through a north German argillaceous rock deposit.

Insofar as the cover rock above the deposit only consists of unconsolidated Tertiary and Quaternary beds, the erosion could not only extend down to a depth of 500 m in the cover rock beds as a result of potential future subglacial channel formation, but also erode the stratigraphically older argillaceous host rock. In principle, this applies to those zones lying to the north of the 0 m Quaternary baseline (Figs. 2 and 3), in which Elsterian subglacial channels formed, and where they could develop again in future according to the forecast of the future climatic conditions. To the south of this line, the formation of channels may only be dependent on the existence of rapidly draining ice lakes (cf. THOME, K. N. 1980), which would only give rise to erosion of the cover rock beds down to minor depths.

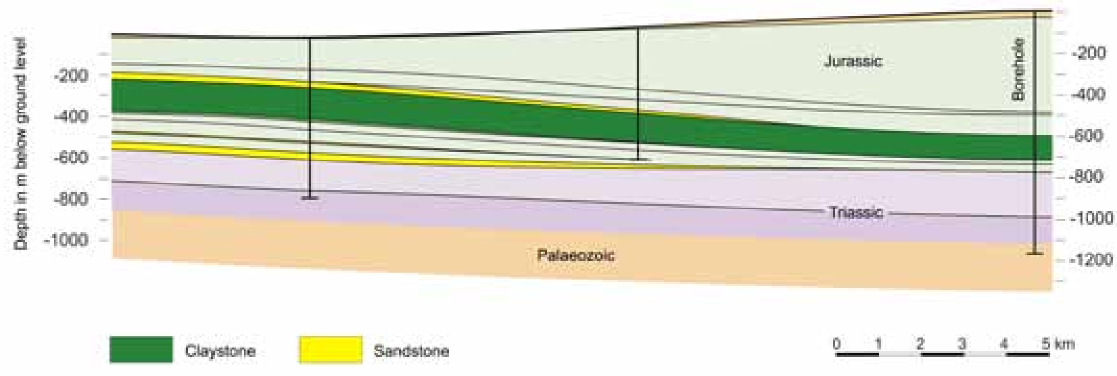

Fig. 5: Schematic cross-section through an argillaceous rock formation in north Germany (from: BGR 2007).

An undisturbed sequence of rocks above the Lower Cretaceous and older argillaceous rocks consists of a sequence of Upper Cretaceous rocks consisting of either hard “Pläner” limestones or softer marls and “Schreibkreide” limestones (details in SDGG 2007). In Denmark, subglacial channels which have cut down to total depths of 50 to 350 m have been discovered (JØRGENSEN, F. & SANDERSEN, P. B. E. 2006) which have also cut down a few tens of metres into Cretaceous limestones within the deeper lying horizons. THIERMANN, A., KOCH, M. et al. (1970) describe a meltwater channel in North Rhine-Westphalia (sheet 3711 Bevergern) which has a width of around 2 km and has cut down into Lower Cretaceous marls 25 to 30 m below today‘s ground level. However, this channel is not genetically comparable to the deep Elsterian subglacial channels to the north of the 0 m Quaternary baseline. Nevertheless, the relatively minor erosion of only a few tens of metres into the calcareous rocks indicates that the harder and low permeable units within the calcareous Upper Cretaceous sequence could protect underlying argillaceous and stratigraphically older potential host rocks to a certain degree from erosion during subglacial channel formation processes.

One of the conditions for this, however, is that the protective Upper Cretaceous rocks are not soft and marly or have not been eroded by uplift now or in the future during the period covered by this study. The dividing line, however, between areas with a stronger tendency to uplift and those with a tendency to subside since the Oligocene corresponds approximately to the 0 m Quaternary baseline. In the Mittelgebirge south of this line, uplift has been around 300 m during the last approx. 30 million years - with up to 600 m in the area around the Harz (LUDWIG, A. O. 2001). The clay deposits worthy of investigation as geologic repository host rocks could therefore lose their protective Upper Cretaceous cover as a consequence of uplift-related erosion in this area in future. By way of contrast, the zones north of this line have undergone subsidence of around 300 m over this period, and the subsidence in the vicinity of the North Sea has even exceeded 1000 m – the tectonism therefore tends to have a protective effect on the zones of interest in this area.

5 Summary and conclusions

An assessment of the change over time of the cover rocks overlying a host rock formation is an integral part of the long-term safety analysis of potential geologic repository sites for high-level radioactive, heat-generating waste (HAW). One of the main influences on the development of the cover rock is the effect of future climatic processes.

The past changes in the climate are used to develop a prediction for the way the climate will develop in the next one million years. This is used to assess the possibilities of deep subglacial channel systems forming again in north Germany during the glacial periods predicted to occur in the future. It is considered possible that ten more ice ages could affect north Germany in the next one million years, of which at least one could have the potential of the earlier Elsterian glacial period, e.g. which led to the formation of a subglacial channel in the cover rock above the Gorleben salt dome. Because it is impossible to predict the location of future subglacial channels, the conditions in the cover rock above the Gorleben salt dome are considered a model for any alternative location in north Germany. Due to the large thicknesses of rock salt which have accumulated in salt domes, the planned depth for geologic repositories in salt has been defined as 800 - 1000 m to rule out any negative effects on a geologic repository associated with the formation of channels in future. The effects of future channel development are also limited by the hardness of rock salt because this is an important parameter for the formation of subglacial channels.

The depth for argillaceous formations considered worthy of investigation as potential geologic repository host rocks is considered to be > 300 m, whereby the zone of particular interest for petrophysical, engineering and economic reasons lies within the 300 to 400 m depth range (cf. AMELUNG, P., JOBMANN, M. et al. 2007; BGR 2007; HOTH, P., WIRTH, H. et al. 2007; JOBMANN, M., AMELUNG, P. et al. 2006; UHLIG, L., AMELUNG, P. et al. 2007). The barrier function of these soft argillaceous formations lying at relatively shallow depths is directly jeopardised by the formation of subglacial channels which can erode down to 500 m, particularly in the absence of hard, calcareous and low-permeable Upper Cretaceous cover rocks. Moreover, the argillaceous formations present in southern north Germany also lie within a zone characterised by significant neotectonic uplift, so that a current favourable Upper Cretaceous formation here could possibly be eroded away during the course of the next one million years looked at as part of this safety analysis.

A comparison of the potential host rocks argillaceous rock and rock salt in north Germany therefore reveals that argillaceous rocks are less suitable for the construction of geologic repositories for high-level radioactive and heat-generating waste than rock salt in salt domes unaffected by extractive mining or other activities. This applies particularly to sites in north Germany where the argillaceous formations worthy of investigation lie at depths of > 300 m to around 500 m.

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