STABILITY OF THE BARRIER

ADDITIONAL INFORMATION ON THE SITING PROPOSAL

For the long-term safety of a deep geological repository, it is important to preserve favourable barrier properties for a very long time. This requires ensuring that the rock layer between the repository and the earth's surface is not significantly reduced by fluvial and glacial erosion processes. This document supplements the report on the siting proposal with more detailed information on future erosion.

The first part introduces key data and important factors relevant for the assessment of future erosion in the three siting regions in the form of a cross-section. The second part supplements the report on the siting proposal with simplified scenarios on deep glacial erosion. These scenarios are particularly important for the Nördlich Lägern (NL) and Zürich Nordost (ZNO) siting regions.

In contrast, the most relevant factor for the Jura Ost (JO) siting region is whether the Bözberg hill will maintain its topography in the long term or whether it could be eroded, e.g. in the case of a diversion of the Aare river. For this reason, the third part of this document presents scenarios on the potential evolution of the landscape in this region.

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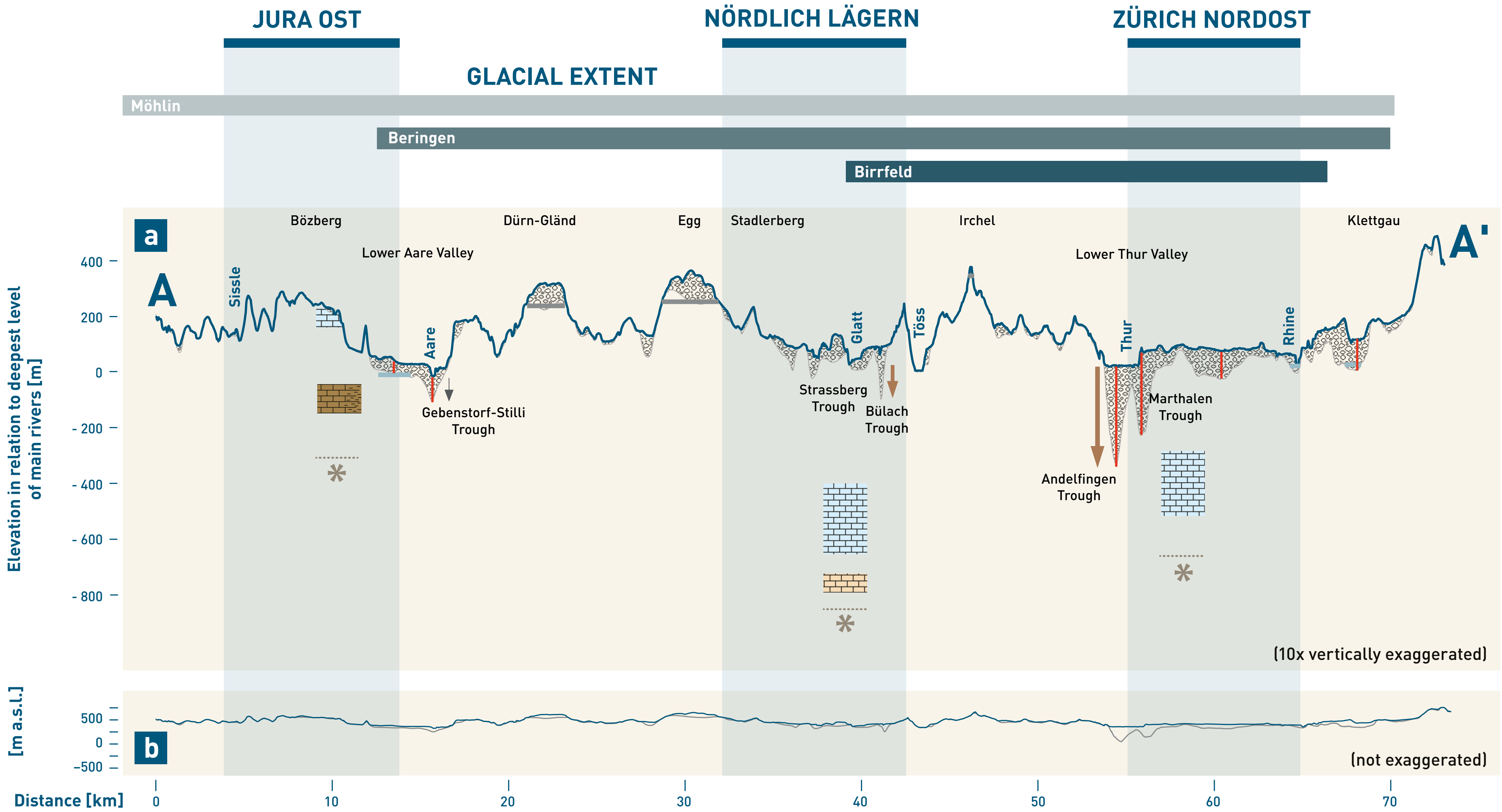
BASIS FOR ASSESSING FUTURE EROSION PROCESSES

The landscape evolution of Northern Switzerland over the last roughly two million years is characterised by river incision and deep glacial erosion. Gravel deposits often cover hills (dark grey lines in Figure 1) and mark the location of former river courses before the surface was eroded during the Quaternary. The depositional age of these gravels was determined with different methods to be around one to two million years. Since then, the main rivers (e.g. Rhine and Aare) have incised around 200 to 300 metres into the rock, i.e. to the deepest river level known today (light blue lines in Figure 1).

Only glaciers were able to erode below this deepest river level. In recent years, Nagra has drilled eleven boreholes into Quaternary sediment, mostly within such glacial troughs (gravel deposits below the light blue line, e.g. Gebenstorf-Stilli or Marthalen Trough).

In the Nördlich Lägern (NL) and Zürich Nordost (ZNO, brown arrows) siting regions, these basins are significantly deeper than in the Lower Aare Valley (grey arrow) in the eastern part of Jura Ost (JO). This observation can be attributed to two factors. On the one hand, the glacial troughs in NL and ZNO were cut into more erodible sedimentary rocks. In contrast, the hard limestone layers in the Lower Aare Valley slow down the erosion process. More erosion-resistant rocks such as these can also be found at greater depths in NL and ZNO, which is why future glacial erosion into these rocks will probably be less deep than observed today in the more erodible rocks. On the other hand, glaciations from past ice ages impacted the three siting regions to varying degrees. The profile and map of the ice extent shown in Figure 1 illustrate these differences based on three important and relatively well-known glaciations in Northern Switzerland (Möhlin, Beringen and Birrfeld). Only the most extensive glaciations reached the JO siting region, and the glaciers were presumably less thick than in NL and ZNO. During the last ice age, the ice cover in ZNO was thicker and more extensive than in NL. Such patterns can also be expected for future glaciations.



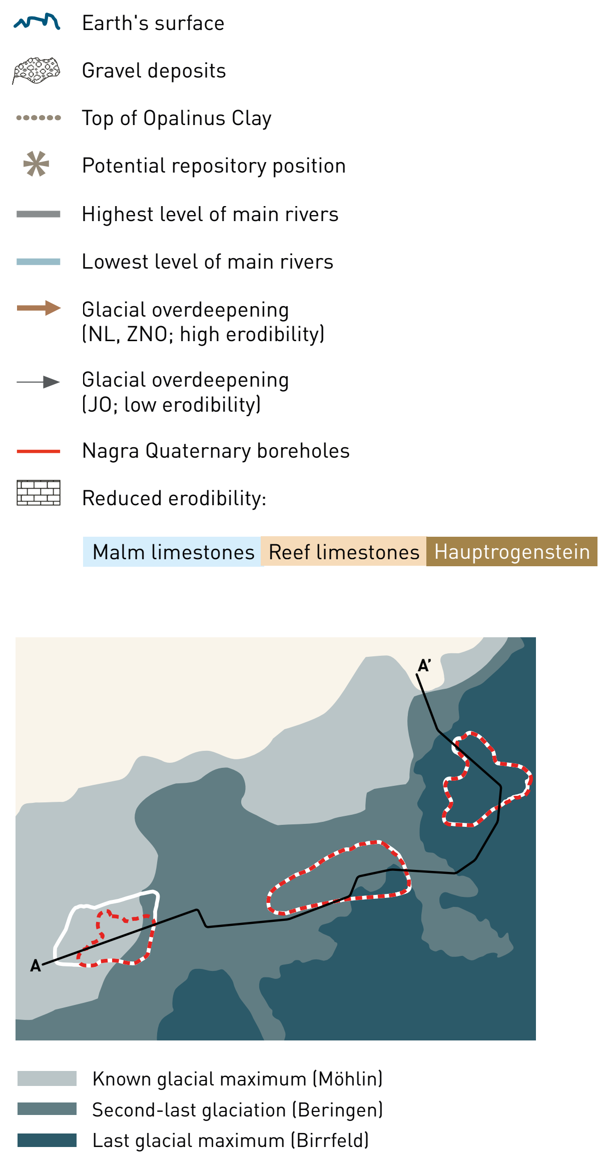


FIGURE 1: Cross-section along the siting regions with the morphological and geological conditions that are key to assessing future erosion processes as explained in this document. The upper profile section is vertically exaggerated 10-fold. The lower part of the figure (b) shows the topography and position of the bedrock surface without exaggeration. The coloured bars above the figure show comparatively well-known extents of earlier glaciations (cf. map on the right). The extent of the Birrfeld glaciation marks the Last Glacial Maximum (LGM) of the most recent ice age around 21,000 years ago. The Beringen and Möhlin glaciations formed during earlier ice ages that probably occurred between 100,000 and 650,000 years ago.

PROTECTING THE BARRIER FROM EROSION

The most important factors that can impact the robustness of the siting regions in terms of erosion are shown in the cross-section in Figure 1:

- Repository depth: Constructing the repository at greater depth increases the robustness of a site towards future erosion processes (river incisions, degradation of the local topography and deep glacial erosion – see Figure 2 and the corresponding text box below for a definition of these terms).

- Local topography (topography above the deepest level of the main rivers): Future river courses primarily orient themselves along this local topography. However, particularly in conjunction with glaciations, valleys could form transversely to existing hills ("glacially diverted channels" as shown in model scenarios for JO, see Figure 5). Jura Ost exhibits the most pronounced local topography. Here, the location of the future river network is perceived to be more stable than, for example, in eastern NL or in wide parts of ZNO. However, changes of the river system cannot be excluded in the JO region, either. Such changes are particularly relevant in JO as this siting region has the shallowest repository depth with regard to the local erosion base.

- Glacial extents: In comparison, the JO siting region was less frequently glaciated, the ice is also thought to have been thinner. At present, there are no glacial troughs in JO, which is why the future formation of troughs is considered to be very unlikely. However, such a scenario cannot be excluded entirely, for example in connection with the formation of a glacially diverted channel through the topography of the Bözberg hill (cf. model scenarios for JO, see Figure 5). Due to the comparatively shallow depth of the repository, an incision down to the disposal level in case of a large glaciation is then more likely in JO than in the other two siting regions.

  In comparison, the eastern part of NL and the ZNO region were more frequently exposed to glaciations in the past. Glacial troughs reaching a depth of up to 200 metres below the present-day local erosion base can be found in both siting regions. South of ZNO, these troughs even reach a depth of nearly 300 metres below base level. However, these deep troughs cut into comparatively soft Molasse rocks.

- Erodibility of the rock column above the Opalinus Clay: greater thicknesses of more erosion-resistant rocks (Malm limestones, reef limestones and Hauptrogenstein in Figure 1) above the repository increase the robustness of a site to erosion, especially with regard to future deep glacial erosion. JO has only a thin layer of Malm limestone and, in addition, the Hauptrogenstein is replaced with rocks that are richer in clay minerals and less resistant to erosion ("Klingnau Formation") in eastern JO. This is the least favourable situation. Conditions are most favourable in eastern NL (thick Malm and reef limestone ("Herrenwis Unit"), followed by ZNO (thick Malm limestones).

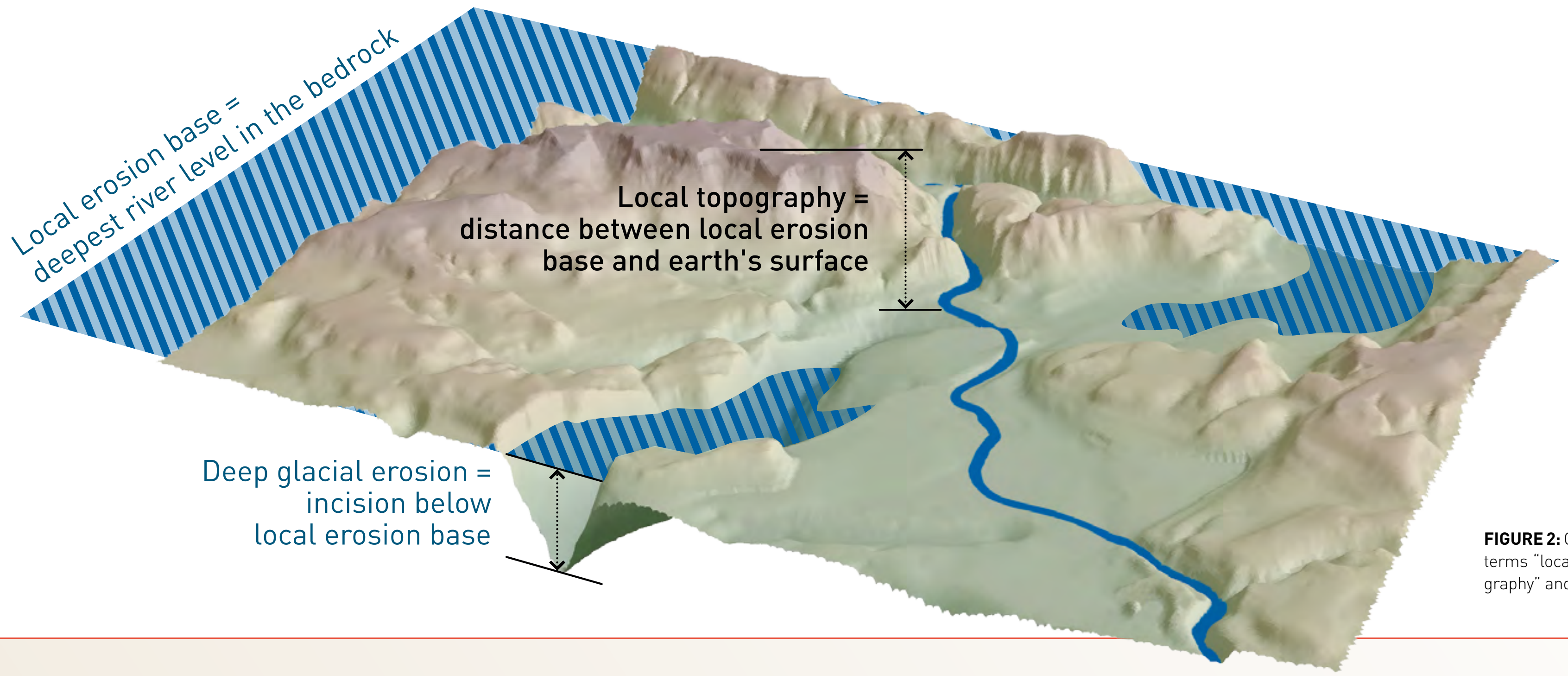


FIGURE 2: Conceptual image linking the terms "local erosion base", "local topography" and "deep glacial erosion".

EROSION PROCESSES

Rivers from different catchments and undergoing different precipitation patterns continuously change the earth's surface. Main and tributary rivers cut into the landscape, transport sediment and deposit this, for example, in floodplains. Over the course of time, rivers respond to numerous influencing factors, in particular the uplift or subsidence of the rock or surface, or climatically driven changes in water regime. Rivers can thus carry large or small amounts of sediment. Where sediment is abundant, it can fill riverbeds. Rivers can also cut through previously deposited gravel, thus reaching the underlying rock. The graded (or longitudinal) profile of the river courses typically exhibits decreasing gradients from the upper to the lower course, but flatter and steeper river sections frequently alternate. This can be explained, for example, with the varying erosion resistance of the rocks along the river.

In many parts of Northern Switzerland, the Aare and Rhine rivers still flow over a gravel bed dating back to ice ages; here, the previous deepest bedrock incision level has not yet been reached again. However, this level is widely known from numerous borehole investigations. By linking these measurement points along the main rivers, it is possible to obtain the local erosion base. When this base level changes, the river responds immediately.

The proportion of consolidated and unconsolidated rocks located above the local erosion base is called local topography (Figure 2). Future river courses primarily orient themselves along this local feature of landscape evolution. Only glaciers can erode below the local erosion base (see box on deep glacial erosion, Figure 3).

HOW DOES EROSION BENEATH A GLACIER OCCUR?

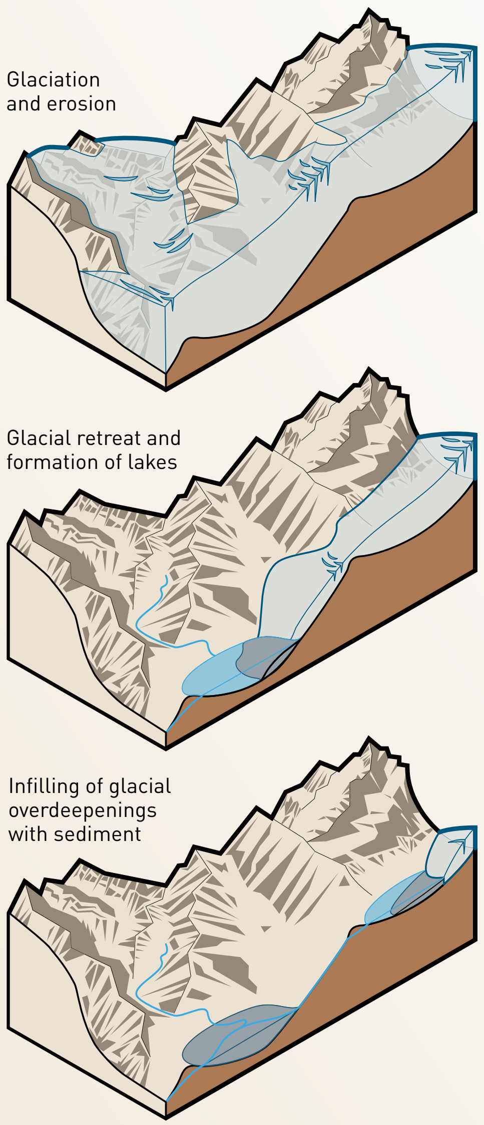
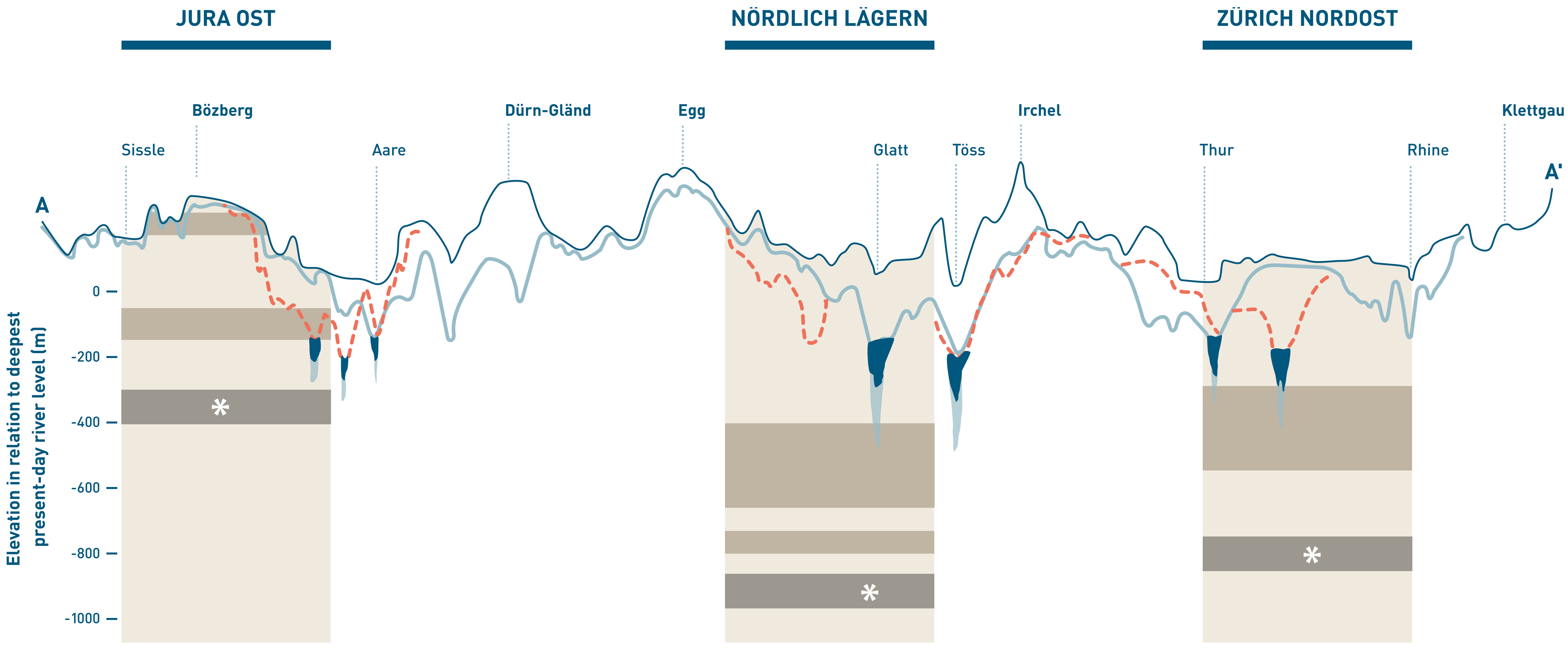


FIGURE 3: Conceptual image of glacial overdeepenings below a glacier and after its retreat (modified after Cook, S.J. & Swift, D.A. (2012): Subglacial basins: their origin and importance in glacial systems and landscapes. Earth Science Reviews 115, 332- 372. doi:10.1016/j.earscirev.2012.09.009).

Erosion beneath a glacier occurs when rocks carried along by the ice abrade the bedrock below, when frozen rocks are torn out of the bedrock, and when the bedrock is impacted by debris in the flowing water below the ice. As water and sediment below the glacial ice can move along adverse slopes, continuous glacial erosion can incise below the local erosion base. As a result, so-called overdeepenings (or overdeepened troughs, topographic depressions) can form in the glacial bed. When the glaciers retreat, these fill with water, forming lakes.

MODEL SCENARIOS OF FUTURE DEEP GLACIAL EROSION

For a better overview, the graphic on erosion in the report on the siting proposal presents only future river incision and the associated evolution of the local topography. To supplement the information in the report, the following figure shows example scenarios with glacial troughs that erode below the future river level. By covering the full range of scenarios, it is possible to link uncertainty in topographic evolution with that of glacial incision (Figure 4). The analyses show that each siting region has areas that are well-protected from long-term erosion. In this context, the situation in Nördlich Lägern is considered to be the most robust, particularly due to the large disposal depth and the presence of comparatively thick erosion-resistant rocks above the Opalinus Clay.



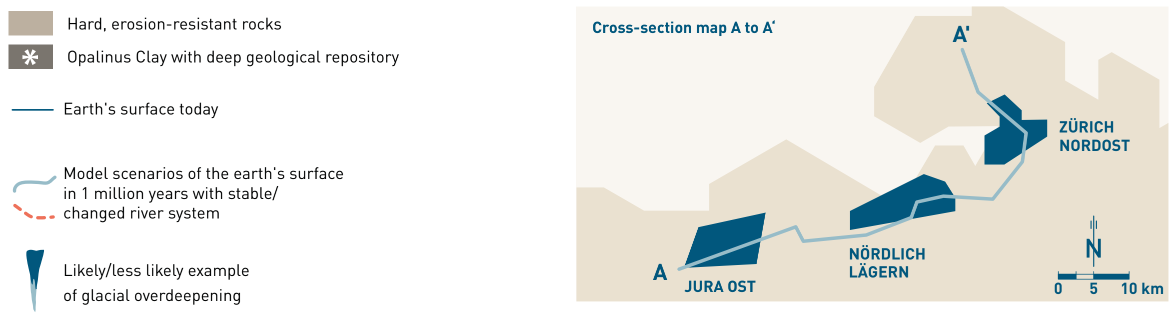


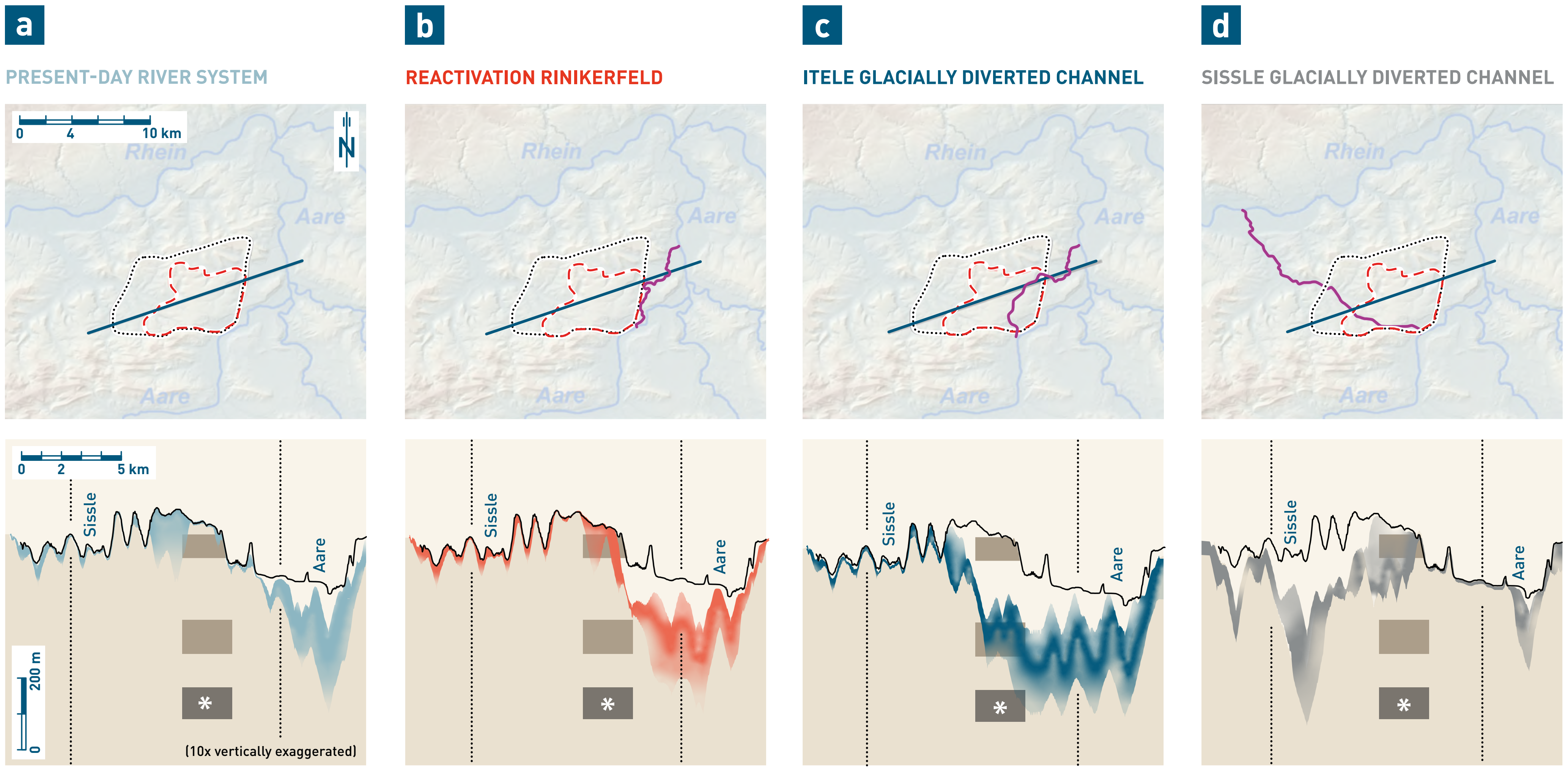
FIGURE 4: Selected model scenarios of future landscape evolution coupled with examples of troughs due to deep glacial erosion. For easier understanding, only the more likely cases of river incision are presented without a bandwidth. For the glacial troughs, more probable and less probable depths of features are indicated. The cross-section is depicted in tenfold vertical exaggeration.

SUPPLEMENTARY SCENARIOS FOR THE LANDSCAPE EVOLUTION IN THE JURA OST SITING REGION

In the context of deep geological disposal, local topography describes the proportion of consolidated and unconsolidated rocks found above the local erosion base. Future river courses primarily orient themselves along these local landscape elements. Rivers are more likely to migrate within a shallow landscape or to flow where they are confined by valleys. Undercutting of valley flanks by the river can lead to mass movements and lateral erosion of the landscape. Particularly in the context of glaciation, it is also possible that new valleys will break through hills (so-called glacially diverted channels).

In Jura Ost, over one third of the rock column that would protect a potential repository (Bözberg hill) is located at a higher elevation than the adjacent Aare river. If future uplift and erosion rates turn out to be very high, the possibility cannot be excluded that the repository could eventually lie above the river level. In contrast with the other siting regions, the stability of the barrier in Jura Ost thus strongly relies on the preservation of the local topography (Bözberg). This is why supplementary landscape evolution scenarios for JO over the next million years were developed, as exemplarily shown in Figure 5.

Scenarios (b), (c) and (d) serve as examples and are not equally likely. A diversion of the Aare through the Rinikerfeld west of the Brugg hill (b) is comparatively likely. Such a scenario could occur, for example, if a future glacier that forms in the Lower Aare Valley delivers large amounts of sediment, thus filling the existing topographic step. Both in Northern Switzerland and worldwide, analogue situations can be found for such a scenario near the ice front. In contrast, scenarios (c) and (d) are classified as significantly less likely to occur. They could be conceivable in particular in the context of a large glaciation. Although not considered likely, scenarios featuring a relocated river system combined with high rates of incision would lead to a decrease in the long-term stability of the barrier in the Jura Ost siting region. In the case of the other two siting regions, river migration scenarios have no relevant impact on the long-term stability as the repository is located at greater depth. In this respect, the Nördlich Lägern siting region has the greatest safety reserves.



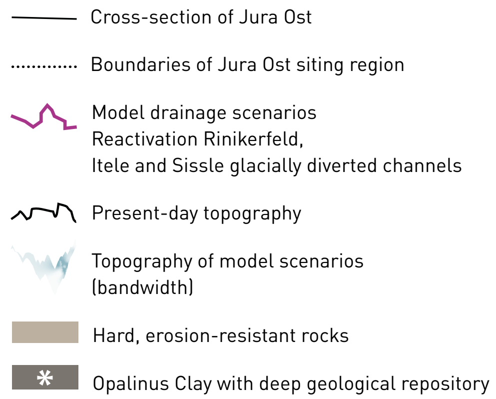


FIGURE 5: Supplementary scenarios for the landscape evolution in the Jura Ost siting region after 1 million years. Figure section (a) shows the most likely scenario with the present-day drainage system of the Aare and Rhine rivers, (b) is a scenario where a former river course (the Rinikerfeld channel) at the eastern edge of the siting region is reactivated, (c) shows the scenario of a glacially diverted channel in the area of the Itele valley and (d) a scenario featuring a glacially diverted channel in the Sissle area. In the Sissle scenario, the Aare cuts through the siting region, and the Limmat and Reuss rivers also discharge in this direction.

Nagra | National Cooperative for the Disposal of Radioactive Waste
Hardstrasse 73 | 5430 Wettingen | Switzerland
T. +41 56 437 11 11 | info@nagra.ch | nagra.ch