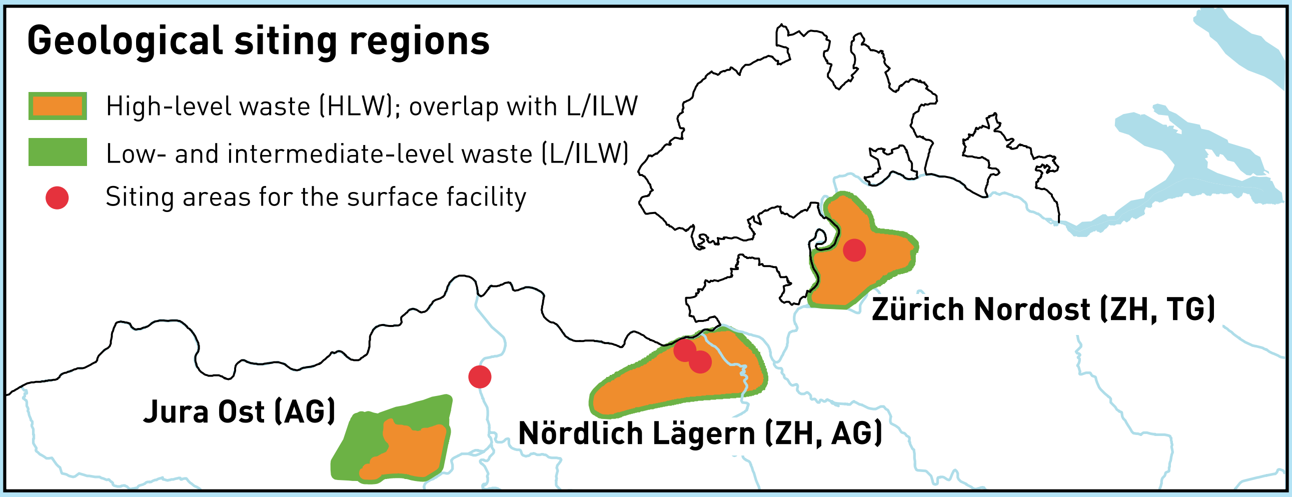
erosion

long-term geological evolution and deep geological repositories

nagra. we care

Imprint

About this brochure



The "Sectoral Plan for Deep Geological Repositories" defines the three-stage procedure for selecting siting regions for deep geological repositories in Switzerland. Thirteen criteria were specified in the Sectoral Plan for identifying possible siting regions and subjecting them to a safety-based comparison. One of these criteria concerns future erosion and its significance for the long-term safety and stability of a deep geological repository. Several factors are considered that are manifested to varying degrees in the siting regions. These include the depth of the Opalinus Clay host rock (see Glossary), the erosion resistance of the overlying rock and the topography. In addition, the locations of the potential siting regions are investigated with regard to past and future glaciations. Nagra developed scenarios for all the siting regions to estimate how deep the Opalinus Clay must lie to be protected from future erosion processes. These scenarios were based on an analysis of past topographic evolution, in particular the incision rates of major rivers and the effects of glacial overdeepening.

In the coming years, the geology of the three potential siting regions Jura Ost, Nördlich Lägern and Zürich Nordost will be investigated in more detail, also with a view to revising and refining the erosion scenarios. The results will provide input for the comparison of the siting regions in Stage 3 of the Sectoral Plan.

Erosion – long-term geological evolution
and deep geological repositories
Nagra publishes special brochures
on radioactive waste management at irregular intervals
October 2018

Introduction

Erosion is the wearing away of rock. It plays a significant role in the long-term evolution of the geological barriers of a deep geological repository for radioactive waste. It has to be ensured that the waste emplacement rooms are protected from exposure until the radioactivity has decayed to a harmless level. Understanding the past is necessary to be able to evaluate the future impact of erosion in different scenarios.

Deciphering the past...

In order to derive future developments in erosion processes, scientists look at how the topography has changed over the last approximately two million years and the influence of alternating cold and warm periods. Each of these cycles lasted between 41 000 and 100 000 years. During the cold cycles, glaciers created valleys and overdeepenings in Switzerland (see pp. 15 ff.) that still shape today's landscape. The Zürich region was covered by glaciers at least fifteen times in the last two million years. In the three potential siting regions Jura Ost, Nördlich Lägern and Zürich Nordost, the evolution of the local base level of erosion over the past two million years was reconstructed by investigating gravel deposits (see pp. 10 ff.) The local base level is determined by the elevation of major rivers such as the Rhine, Aare or Danube. Local rivers and hillslope processes such as landslides are in turn oriented to these major rivers. The past deepening of rivers is considered to have been caused, for example, by uplift of the bedrock or increased water flow due to climate changes. In the last five to ten million years, the fastest and most marked lowering of the local base level in Northern Switzerland was caused by a change in the regional river systems. Northern Switzerland originally drained in the direction of the Danube and was later captured by the Rhine. The Rhine flowed at a significantly lower level than the Danube, leading to a significant and rapid lowering of the base level.

Figure 1
The Rhine Falls close to Schaffhausen cascade over a cliff consisting of comparatively erosion-resistant, hard and massive limestones.
Photo: Beat Müller

… to gain an insight into the future

The future extent of the incision of major rivers into the bedrock cannot be precisely predicted. This is why different scenarios are being evaluated, which include various assumptions regarding the uplift rate of the bedrock, climate developments and erosion rates (see p. 8).

Climate development has a significant impact on glaciers and the erosive force of major rivers, but also on local erosion processes (smaller rivers or landslides). Many possibilities are being considered to predict how the climate will evolve in the future, with the most likely scenario considered to be the continued alternation between cold and warm periods. Model calculations for the climate for the next 130 000 years indicate that a major ice age with glaciers advancing into the Alpine foreland – i.e. the location of the siting regions – is not to be expected for at least another 50 000 to 60 000 years. Because of the global warming caused by anthropogenic CO_2 emissions, this might also happen at a significantly later time (see pp. 6 ff.). In either scenario, the glacial advances would occur at a time when the majority of radioactive substances in a deep geological repository have already decayed away (see pp. 18 ff.).

Glaciers mainly follow the course of old valleys, which causes the valleys to widen and deepen. The formation of completely new valleys that are deeper than the base level of erosion is also considered (see pp. 10 ff.).

Sufficient depth for a geological repository

By looking at various erosion and climate scenarios, it is possible to determine the minimum depth for the Opalinus Clay host rock in which Switzerland's radioactive waste will be disposed of. The host rock will thus be sufficiently protected from erosion processes. In Stage 2 of the Sectoral Plan for Deep Geological Repositories, various scenarios were investigated for the development of the major rivers and deep glacial erosion.

Figure 2
The Aletsch Glacier is retreating due to global warming.
Photo: Danieloizo | Dreamstime.com

Erosion

Erosion is a process that alters the earth's surface over long periods of time and has to be considered when evaluating the long-term safety of a deep geological repository.

Erosion is a fundamental part of the rock cycle (see box on page 9). It is understood to mean the mobilisation and removal of crushed and chemically altered rocks, unconsolidated rocks or soils. Rocks can be eroded by different mechanisms; the most significant forces are water, ice, wind and gravity.

Erosion can act area-wide (denudation), or rivers and glaciers can form incisions and valleys. Rivers and glaciers alter the earth's surface over thousands of years, but there can also be rapid events such as rockslides that can mobilise large amounts of rock within seconds.

The rate of erosion depends on different factors such as climate, the properties of the rocks or on bedrock uplift.

Climate and erosion

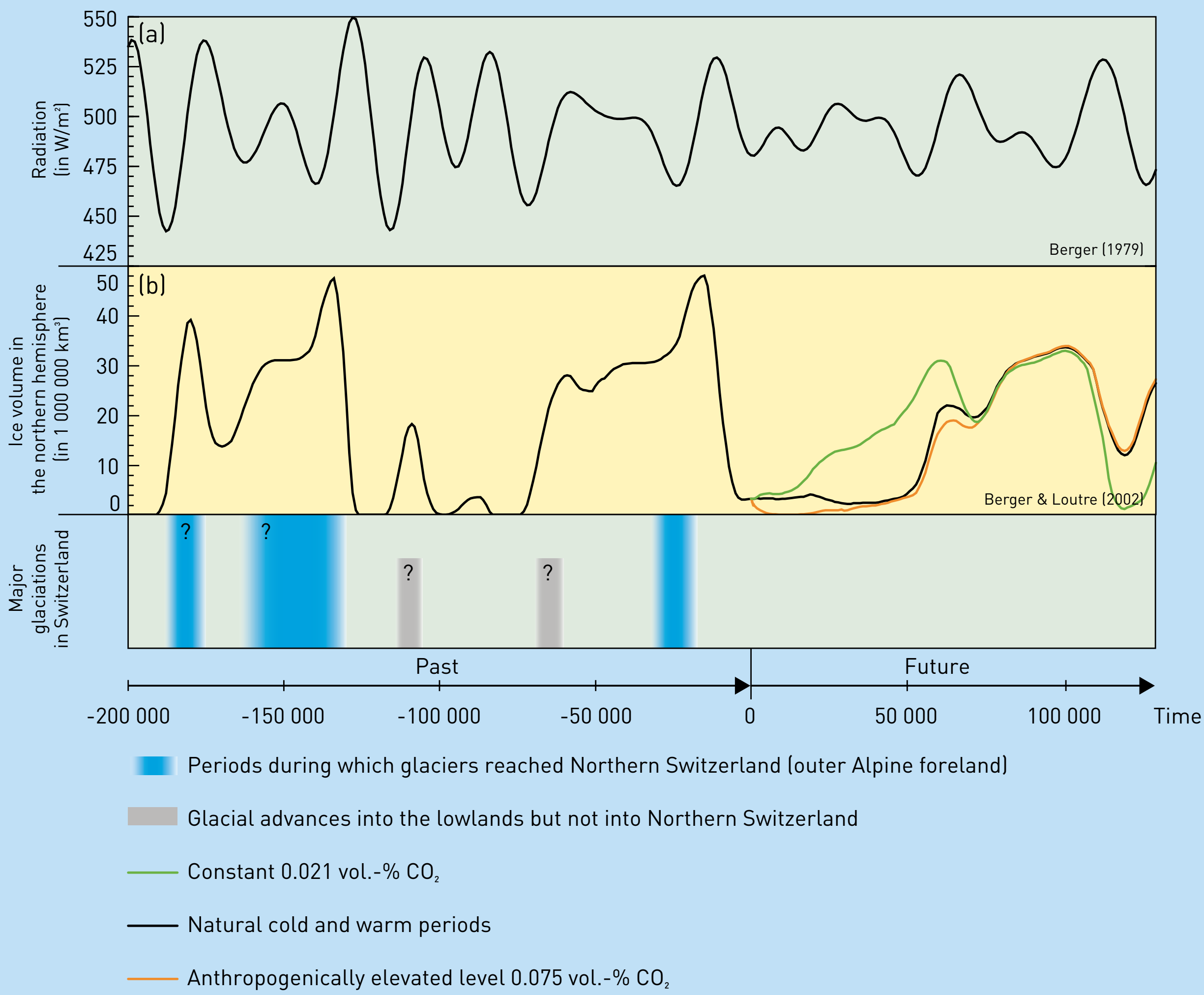
Climate is an important control mechanism of erosion; whether conditions in an area are hot and wet or cold and dry significantly impacts erosion rates. Climate development is determined to a considerable degree by the varying solar radiation caused by fluctuations in the earth's orbit and axis. These fluctuations are one of the causes of alternating cold and warm periods. The climate is also affected by complex interactions between the atmosphere, oceans and different organisms such as corals or trees.

The CO_2 concentration plays a central role throughout. While it is possible to calculate future solar radiation relatively accurately, the future evolution of the level of CO_2 in the atmosphere is very uncertain. Other factors that affect the climate are also not accurately predictable (see box on page 7).

Climate models

Over the next million years, the climate will probably be marked by alternating cold and warm periods. Solar radiation for any given location on earth can be calculated over long periods of time (a). Based on model calculations, the next major ice age is not expected for at least another 50 000 to 60 000 years (b). The level of CO_2 emissions caused by human activities is an unknown factor. High concentrations of this greenhouse gas could postpone the next ice age even further into the future. Numerical models have been used to investigate how varying levels of CO_2 affected the ice volume in the northern hemisphere (b). To address the uncertainties inherent in climate development, the effects of alternative climate developments (e.g. permanently hot and humid) on future erosion in Northern Switzerland are also investigated.

Solar radiation and computer simulations of the ice volume in the northern hemisphere in the last 200 000 years to 130 000 years into the future



Rock properties and erosion

The rock type determines how resistant it is to different types of erosion. Crystalline or calcareous rocks are generally more resistant to erosion than argillaceous or sandy ones. A glacier can, for example, more easily erode Molasse rocks (see Glossary) than the harder, underlying Malm limestones.

A further factor determining erosion resistance is the solubility of the different minerals in a rock. This determines how quickly a mineral can be dissolved by water. Limestones, for example, are more soluble than quartzes.

Uplift and erosion

The Alpine region is presently being uplifted by around one millimetre annually compared to Northern Switzerland. The uplift rates decrease from the Alps towards the Swiss Plateau. By contrast, the Upper Rhine Graben north of Basel is subsiding slightly (see Figure 3). In general, the uplift of the bedrock influences the rate at which erosion "works", i.e. its velocity. The incision of rivers usually progresses more rapidly in regions with higher uplift.

Uplifting of the terrain can have various causes. The uplifting of the Alps could be a direct result of the collision of the Eurasian and African tectonic plates. Another possibility is that the earth's crust is pressed down due to the weight of a glacier. After the glacier retreats, the earth's crust rebounds. Examples of this type of uplift can be found in Scandinavia: as a result of melting of the ice sheet, the bedrock is currently uplifting at a rate of up to one centimetre annually.

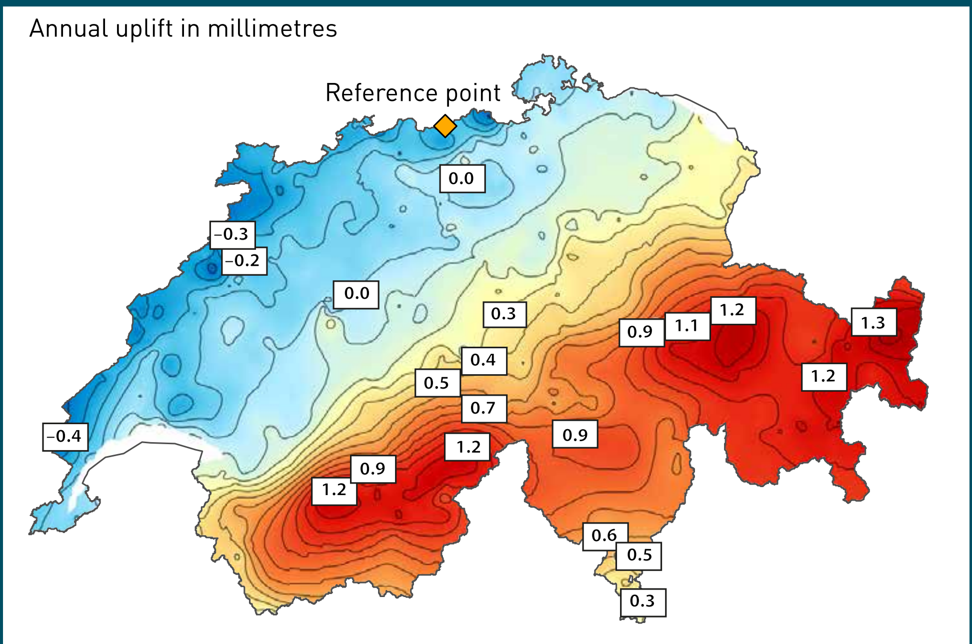
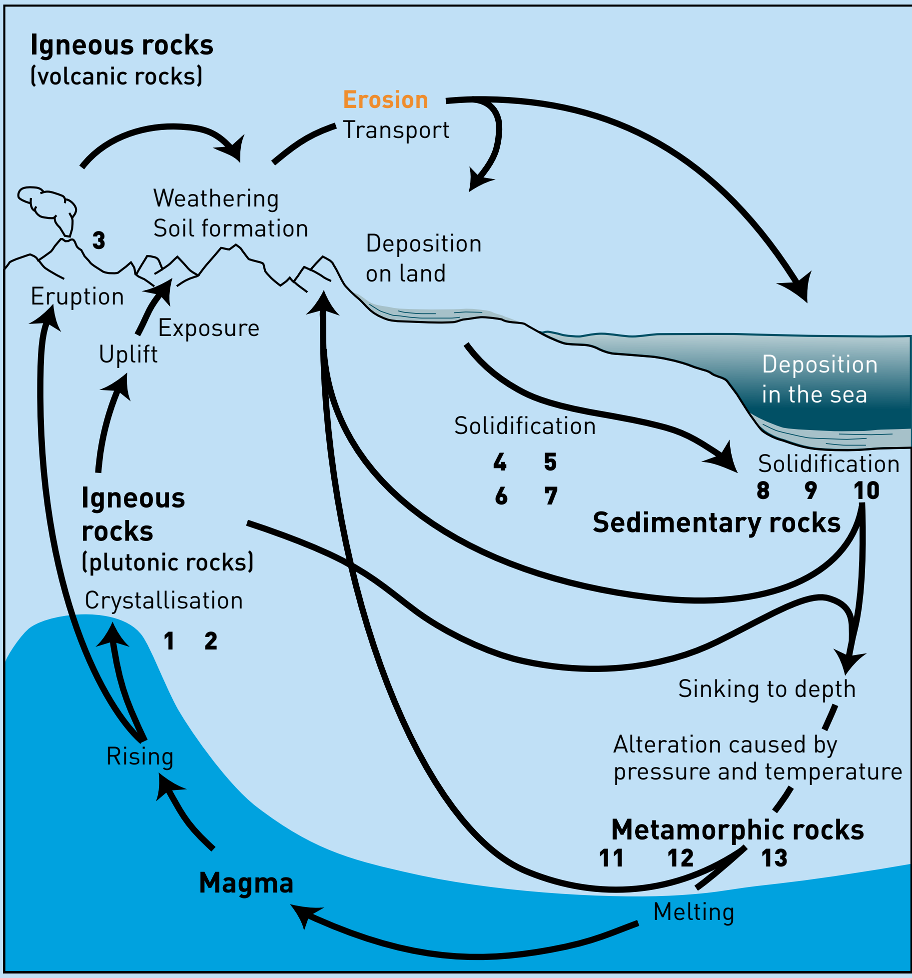


Figure 3
Data from the Swiss national survey for the past 100 years show an annual uplift of the Alps of approximately one millimetre compared to the Swiss Plateau.
Graphic: swisstopo

The rock cycle

The rocks within the uppermost 30 to 60 kilometres of the earth, the earth's crust, are locked in a continuous cycle. Through constant change, rocks evolve from one type into another. Erosion plays a role in this process.

Mountains are formed. They are eroded and rocks are removed. Where the debris is deposited, it forms sedimentary rocks. All rocks can eventually sink to great depths where they are exposed to increased pressures and temperatures that alter or melt them into metamorphic rocks. When the molten rock (magma) solidifies at depth or at the earth's surface it becomes igneous rock. The cycle then begins anew.



Examples of rocks

1 Granite
2 Aplite & lamprophyre
3 Basalt
4 Nagelfluh
5 Sandstone
6 Molasse marl
7 Verrucano
8 Claystone
9 Limestone
10 Anhydrite & gypsum
11 Gneiss
12 Schist
13 Marble

(Source: Iwan Stössel)

Rivers

Rivers are powerful landscape architects. Whether they are major rivers such as the Rhine or small streams, they all shape the topography.

Before man intervened, the major rivers of Switzerland continuously changed their course. Water overflowed and flooded large parts of the land. The riverbed shifted rapidly in some cases – for example as a result of these flooding events – or slowly over the course of many years. Rivers can remove the bedrock through physical and chemical processes. These include the mobilisation, transport and chemical dissolution of rock. River sediments can be identified by their characteristic form; due to stones knocking together in the water and the riverbed, they often have a rounded shape. Old river courses can be recognised in the terrain by the rocks that have been deposited.

Erosion by rivers

The base level of erosion is the deepest point below which a river cannot incise. On a large scale, this point is where the river joins the sea, but it can also be where it flows into a lake. From its source to its base level, the river tends to establish a graded profile and tries to balance irregularities in this through erosion or by depositing sediments. Areas that lie above the profile have a higher potential for erosion, while rivers lying below it tend to deposit sediments.

Small rivers and processes such as landslides or debris flows occurring on a slope orientate themselves to the closest major river and do not erode beneath its level. The elevation of the main rivers thus determines the local base level of erosion, to which the development of the terrain is oriented (see Figure 4).

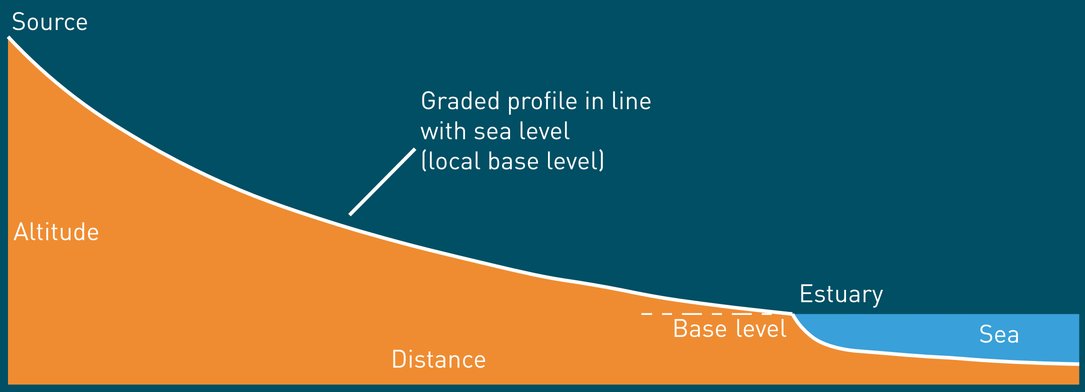


Figure 4
Ideal graded profile of a river (Source: Press & Siever 2003)

What influences the base level?

Various factors control the local base level:

Tectonic **uplift or subsidence** of the terrain can result in the river cutting into the terrain or depositing sediment. If uplift outweighs erosion, the result is a steeper graded profile. By contrast, the profile flattens out if erosion is stronger than uplift.

The type, size and volume of **sediments** carried by a river influence its erosive force. If the volume and grain size increase, the river can abrade the bedrock more strongly. Once it reaches a certain volume and size, sediment transport increases. However, if there is too much sediment or if the material is too large to be transported, it will be deposited on the riverbed.

The **climate** also influences the gradient of a river. High amounts of precipitation increase erosion and sediment transport in a river. A humid climate with a lot of precipitation leads to stronger erosion and thus to a deeper local base level.

The significance of river courses

Shifting watersheds can also lead to incision by rivers (see Figure 5). One example is the redirection of several rivers into the Rhine and thus into the North Sea. Many of Northern Switzerland's rivers used to flow into the Danube and from there into the Black Sea. The catchment area of the Rhine is still growing today compared to that of the Danube, which can be explained by the fact that the Rhine (altitude approx. 390 m a.s.l. at Schaffhausen) flows at a significantly lower level than the Danube (approx. 650 m a.s.l. north of Schaffhausen).

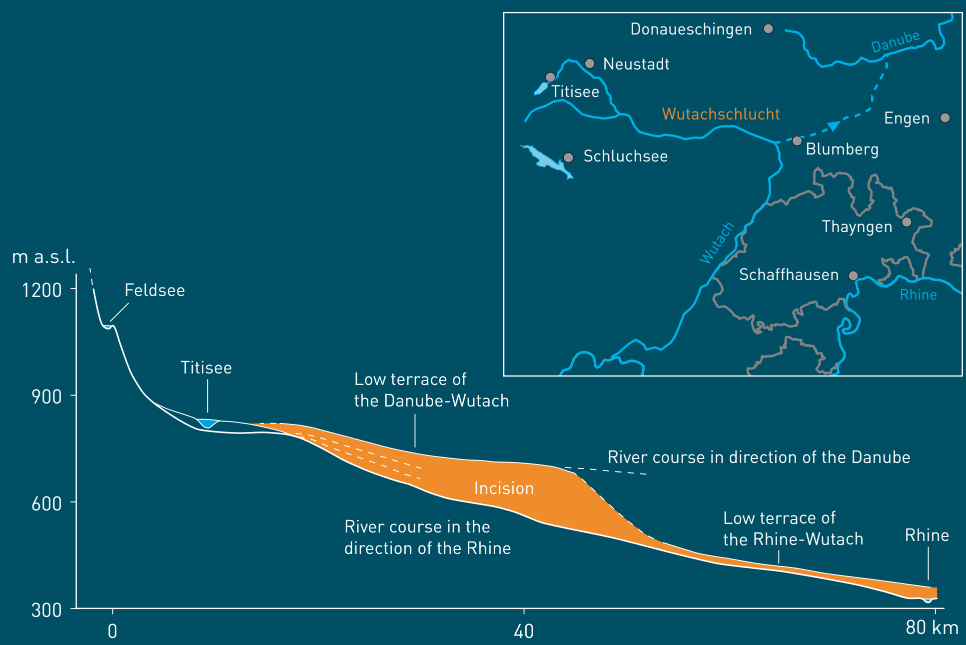


Figure 5
The most recent redirection of a river occurred approximately 18,000 years ago: Close to Blumberg, the Wutach was redirected towards the Rhine. The Wutach Gorge was formed as a result of the ensuing incision.
(Source: Einsele & Ricken 1993)

River terraces provide clues

Terraced landscapes provide evidence of past river incisions. Fluvial terraces are topographic steps that can usually be found on both sides of a river. These steps are formed during river incision, for example as a reaction to the uplift of the earth's surface or an increase in the erosive force of the river. When a river carries more sediment than it can transport based on its flow rate, unconsolidated rocks fill the riverbed again. The stepwise incision of rivers is documented by gravel deposits in Northern Switzerland (see Figure 6). Old gravels can be found, for example, on the Irchel ridge close to the Tössegg or on the Cholfirst ridge south of Schaffhausen. These deposits allow past river incisions to be reconstructed.

The geological clock ticks differently

Existing gravel deposits show that, during the past roughly two million years, the rivers in Northern Switzerland incised between 150 and 300 metres deep into the rock. Knowledge of previous incisions of major rivers was considered when deriving erosion scenarios. The information provided input for delimiting and evaluating the disposal perimeters in Stage 2 of the Sectoral Plan for Deep Geological Repositories.

Glacially diverted channels form

Glaciation can be associated with significant and rapid changes in local river courses. An existing valley can be cut off or filled by moraines, ice or alluvial fill, thus forcing the water to find a new path. In the past, this led to the formation of new valleys in a short time. One example is the breakthrough of the the Rhine between Rüdlingen and the mouth of the Töss. This valley was formed during the last glaciation when a moraine formed between Rüdlingen and the Rafzerfeld. Previously, drainage was from Rüdlingen to the west directly into the Rafzerfeld (see Figure 7).

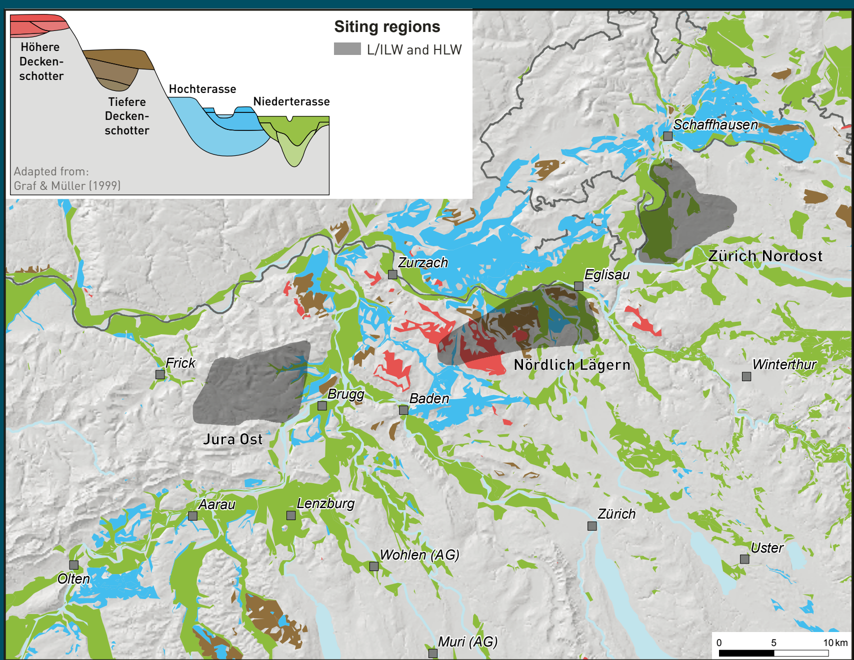


Figure 6
In Switzerland, alluvial terraces exist at different elevations due to the stepwise incision of rivers. Generally, the highest terraces ("Deckenschotter" or "Cover Gravels") are older than the lower "Hoch- and "Niederterrassen" (high and low terraces). They provide evidence of past incision processes. The wide distribution of the "Niederterrassenschotter" ("Low Terrace Gravels") can be seen (green). Not much remains of the higher "Deckenschotter" (red). (Source: Nagra 2014)

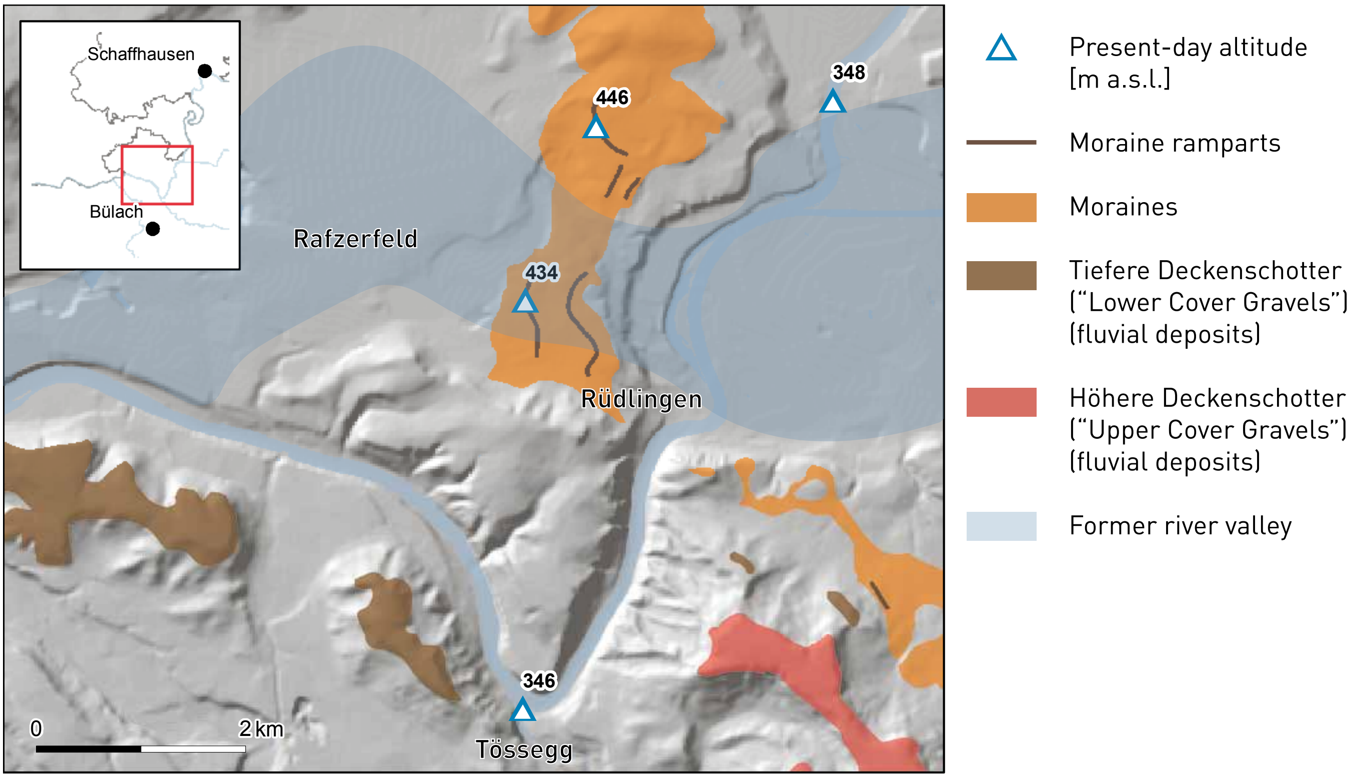


Figure 7
Breakthrough of the Rhine between Rüdlingen and the Töss estuary. Moraine deposits dammed the river and redirected it towards Tössegg at the lowest point in Rüdlingen. This was followed by rapid incision. (Source: Nagra 2014a)

The same types of rocks that were formed in the past are still formed today

Fluvial sediments with characteristic rounded gravels and sandy sections can be found both in today's riverbeds and in old sediments.

"Höhere Deckenschotter" gravel deposits

Present-day fluvial deposits of the Rhine

Glaciers

Glaciers are ice masses formed from snow. Large parts of Switzerland were once covered by glaciers and traces of these can still be found in today's landscape features.

How are glaciers formed?

Glaciers are formed when the amount of snow that falls exceeds the amount that can melt. As a result, the pressure on older layers of snow increases, the snow alters to firn and finally to glacier ice. This process can take several years. Once the ice mass is high enough, it begins to flow downhill and a glacier is formed.

How are glaciers structured?

The glacier gains mass in the accumulation area (see Figure 8). The gain in new glacier ice in this zone outweighs the proportion that is lost mainly by melting ice. In the ablation area, the glacier loses mass due to melting.

How does a glacier erode?

Various types of erosion processes are possible beneath a glacier. For example, a glacier can mobilise frozen rock from the bedrock, or the rocks that it carries along can abrade the bedrock. Erosion can abrade the bedrock more deeply than the local base level.

Traces left by ice

When a glacier retreats and exposes the underlying rock, it leaves behind characteristic landscape features such as moraines or lakes (see Glossary).

The ice masses of a glacier also create new valleys or deepen or alter existing ones. Due to their shape, these valleys are termed tunnel or U-shaped valleys. They typically have steep walls and a flat valley floor. Pronounced U-shaped valleys such as the Lauterbrunnen valley can be found in the Alps (see Figure 9).

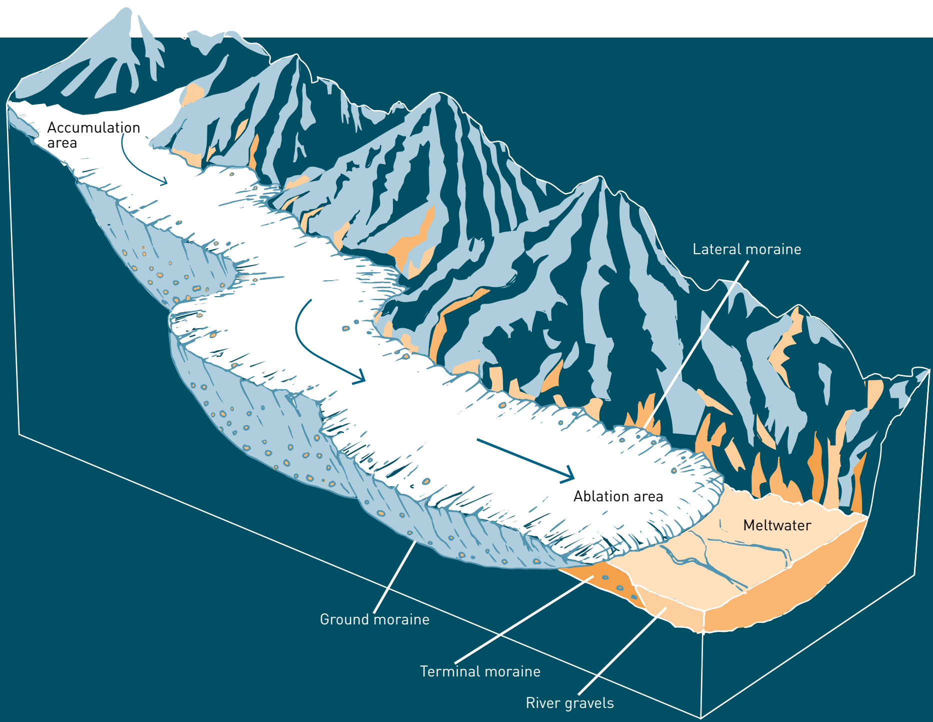


Figure 8
Schematic structure of a glacier (Source: Press & Siever 2003 | Julia Buschbeck – scientific illustration)

Ice-age overdeepenings

When large amounts of meltwater flow beneath a glacier, a strong erosion process is set in motion. Due to the ability of the glacier ice to move water and sediments along adverse bed slopes, continuous erosion can lead to formation of so-called "overdeepened troughs" in the glacier bed (see pp. 16ff.) These can be up to several hundred metres deep. Their depth depends on various factors such as rock type, water flow, flow rate and the thickness of the glacier. The actual impact of these factors on the formation of "overdeepenings" is the subject of present-day research.

Once a glacier retreats, any overdeepenings it has formed will be filled with water. Lake Lucerne and Lake Zürich are good examples of this. The overdeepenings are filled again over long time periods (thousands to tens of thousands of years) by sediment transported mainly by alpine rivers into the lakes.

Information from boreholes shows that large glacial overdeepenings in Northern Switzerland typically have a depth of 100 to 300 metres. Overdeepenings in the vicinity of the siting regions for high-level waste (HLW) are still being examined. Seismic studies were conducted for this purpose and, starting from 2019, deep exploratory boreholes are planned (see pp. 20f.)

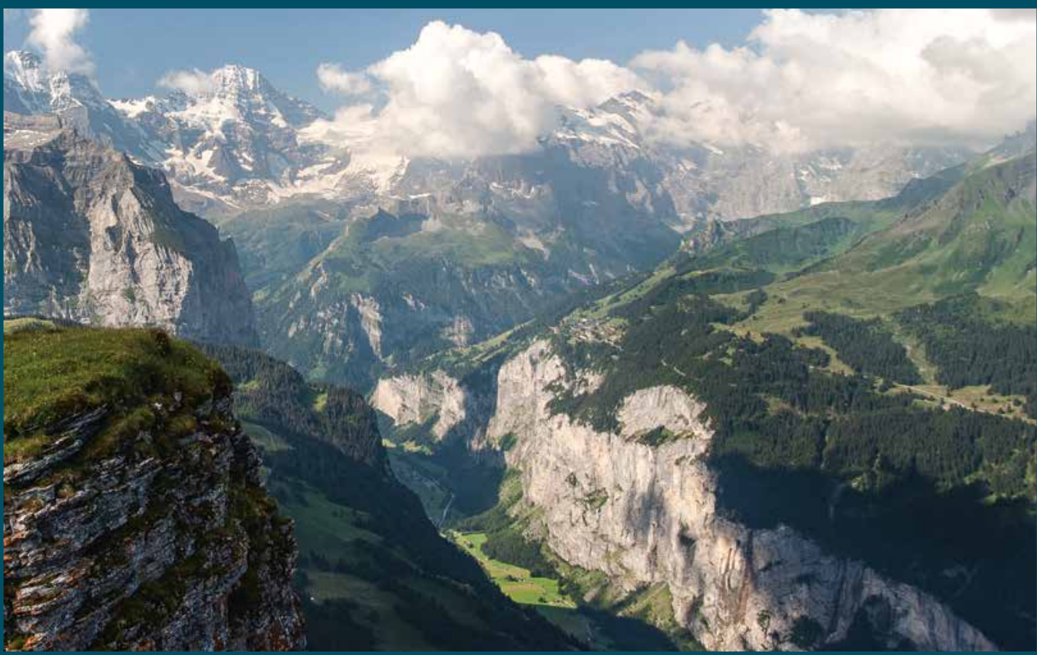
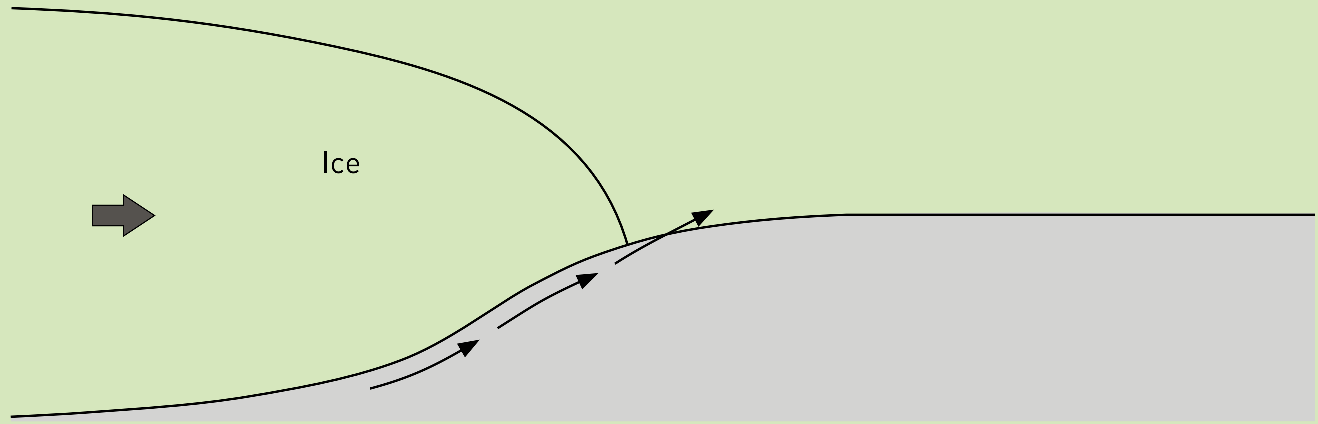
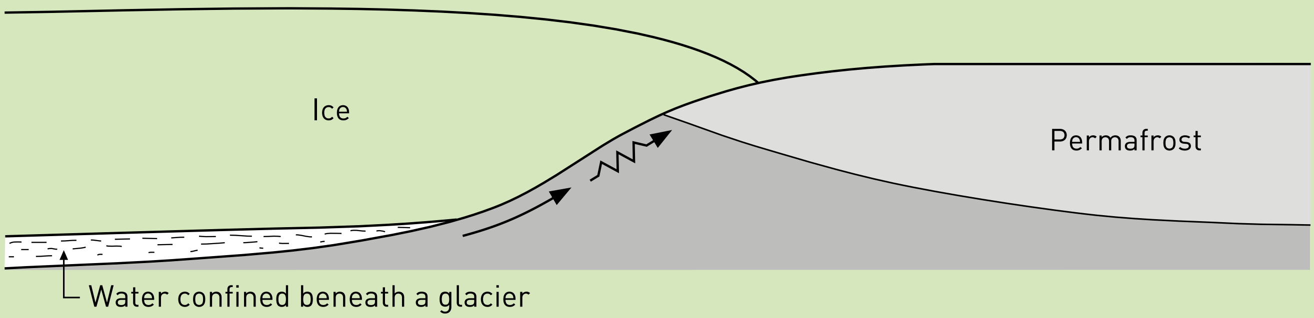


Figure 9
The Lauterbrunnen valley is a classic U-shaped valley with steep walls.
Photo: Jakub Jirsák | Dreamstime.com

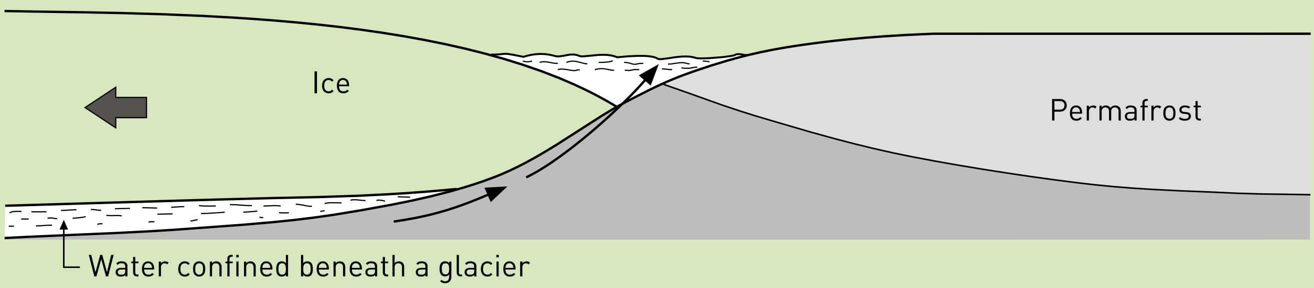
How glacial overdeepenings are formed



When a glacier advances during an ice age, the large pressure gradient below the ice causes high water drainage rates and erosion rates. This can lead to formation of glacial overdeepenings.



In dry-cold climate conditions, permafrost can form around the glacier. The permafrost soil and the glacier can then freeze together, causing the meltwater below the glacier to dam up.



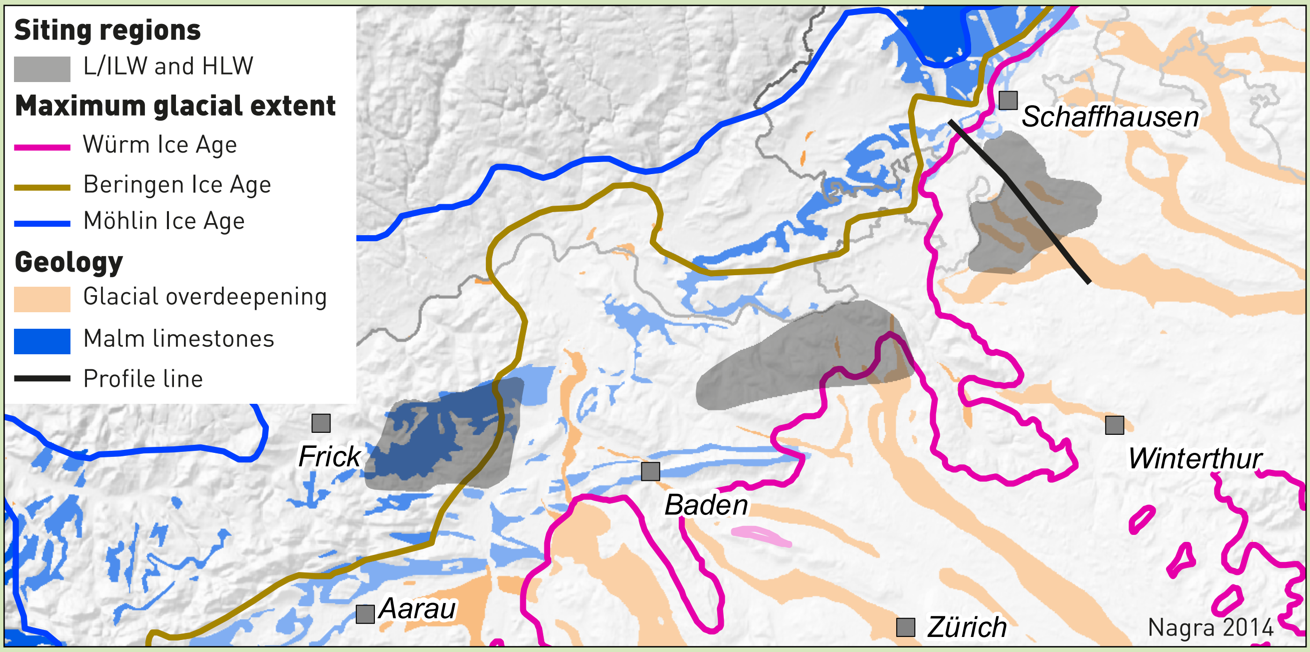
When the climate becomes warmer again, the glacier retreats and the permafrost begins to thaw. As a result, the dammed water underneath the glacier can escape. This causes intensive erosion and can lead to the formation of glacial overdeepenings.

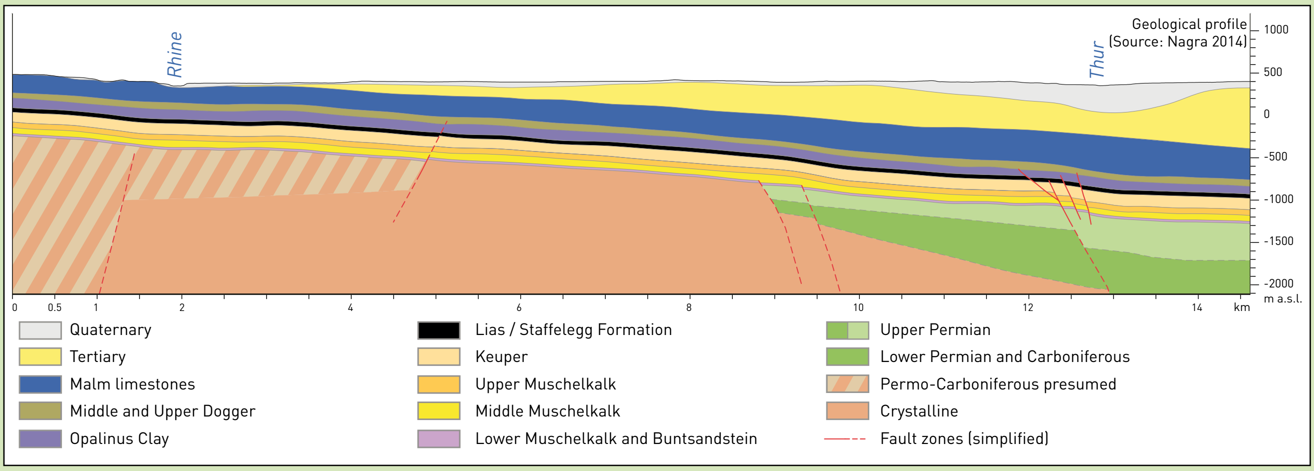
(Source: Piotrowski 1994 and Hooke & Jennings 2006)

A factor in site selection

The glaciers formed during the ice ages cut into the Molasse (see Glossary) of the Swiss Plateau where they formed glacial overdeepenings, which were later filled again with unconsolidated rock. Future glaciers will tend to follow pre-existing valleys. Particularly if there are no pronounced valleys to follow, however, new overdeepenings might be formed.

Glacial overdeepenings were taken into account when defining the boundaries of the disposal perimeters for the repositories. For high-level waste, a distance of at least 500 metres between the bottom of larger glacial overdeepenings and the Opalinus Clay was observed. The rock overburden consists inter alia of thick limestone layers (Malm limestones; see figure below) that are more resistant to deep glacial erosion (see Glossary) than the overlying Molasse layers.





Erosion and deep geological rep

To define siting regions where the host rock lies at the optimum depth, it is necessary to make assumptions about future erosion.

Various scenarios are being examined to understand future erosion processes. They do not allow exact predictions to be made but enable a widely based scientific discussion. Different assumptions are made regarding climate evolution and erosion rates. The purpose of these scenarios is to determine how deep the Opalinus Clay host rock must be to ensure that a deep geological repository is sufficiently protected from erosion on the long term.

In Stage 2 of the Sectoral Plan, the following aspects were considered when defining the disposal perimeter for a deep geological repository:

- Even removal of the terrain by rivers and slope processes
- Evacuation of loose sediment and further deepening into the bedrock by future glaciations
- Formation of new valleys (glacially diverted channels) and new glacial overdeepenings in connection with future glaciations

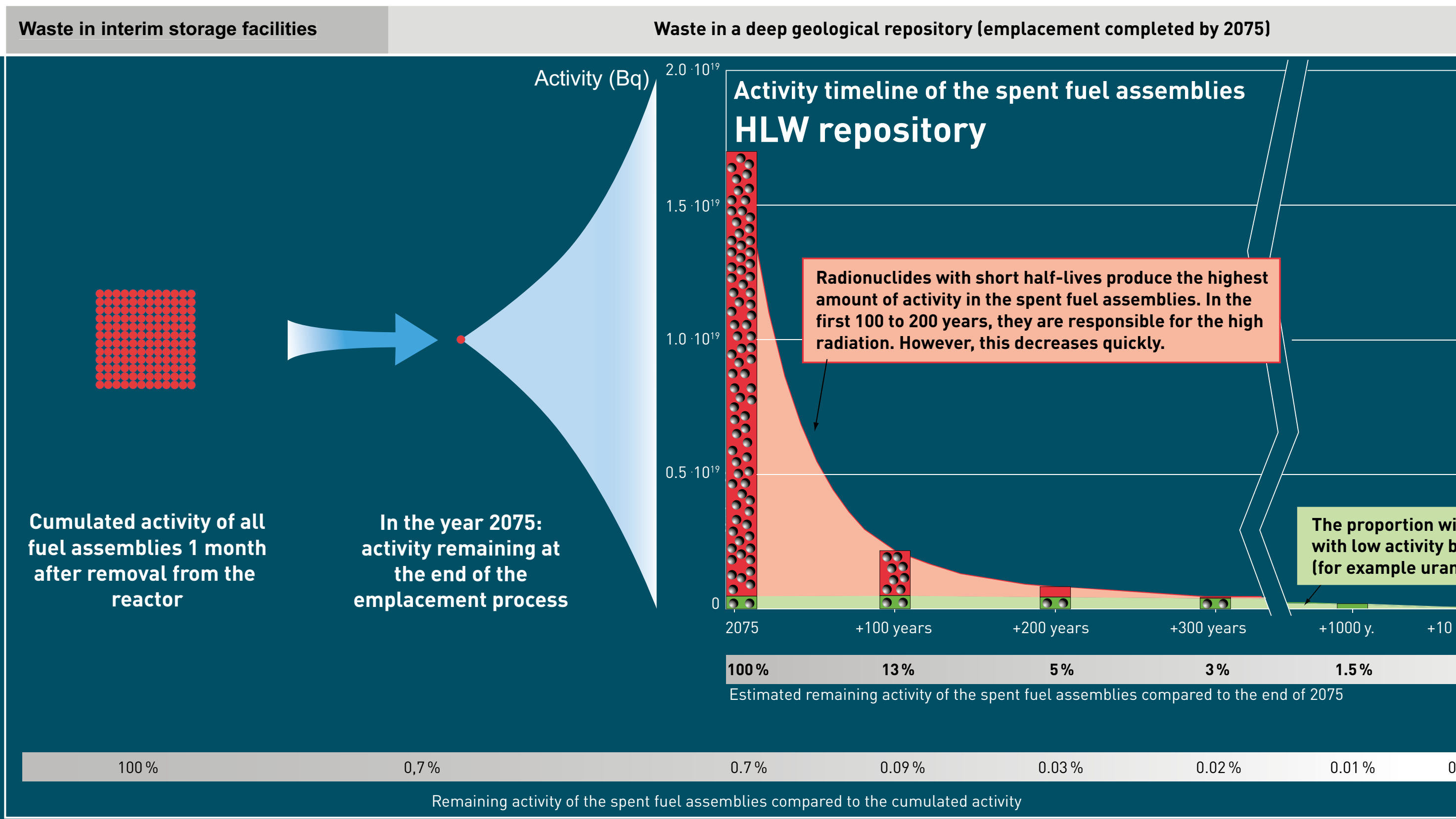
Incision of the major rivers

The assumption in these scenarios is that the terrain will continue to uplift and that major rivers will continue to cut into the bedrock. These rivers create a local base level, so that erosion processes caused by flowing water or slope processes are not possible beneath this level.

The basis for estimating the future incision of the major rivers is provided by an understanding of past developments.

Glacial overdeepenings

In the Alps and their vicinity, glacial overdeepenings and valleys are usually pronounced and thus provide glaciers with a clear flowpath. In flat terrain,



ositories

tributaries or entire overdeepenings form more easily. Switzerland's northern Molasse Basin (see Figure 12, page 24) has overdeepenings that were emptied and refilled several times, but it also contains new overdeepenings and new tributaries of glacial overdeepenings. The past shows that these processes may occur again in the siting regions at some point in the future.

For this reason, deep glacial erosion was considered in two respects when drawing the boundaries of the disposal perimeters of the siting regions in Stage 2 of the Sectoral Plan – for Nördlich Lägern and for Zürich Nordost:

- With regard to the further deepening of existing overdeepenings, the minimum distance between the bottom of the larger troughs and the Opalinus Clay has been set at 500 metres.
- With regard to the formation of new overdeepenings, in the area of the reference disposal perimeters (see Glossary) for high-level waste, a minimum distance of 450 metres to the current local base level (of erosion) has been set.

In the past, the Jura Ost siting region was less frequently covered by glaciers than the other two siting regions. In the future, an ice cover will also occur considerably less frequently here and will be less thick. For the time period under consideration of one million years, the possibility of a glacially diverted channel or a glacial overdeepening occurring through the middle of the siting region is still taken into account. A minimum distance of 200 metres will be maintained to the local base level.

Formation of new channels

The formation of glacially diverted channels associated with glaciations is important for erosion of the terrain. When this type of channel forms, the incision process proceeds relatively quickly. Predicting where new channels will form is possible only to a limited extent. Glacially diverted channels do not, however, incise into the terrain below the local base level.

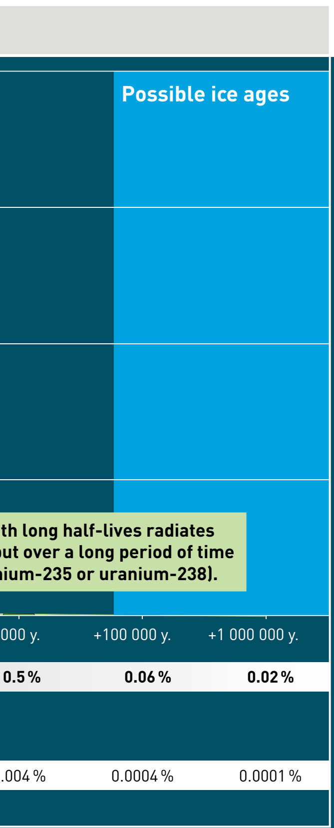


Figure 10
Activity timeline in a deep geological repository for high-level waste. Significant glacial advances in the Alpine foreland are not expected to occur for at least another 50 000 to 60 000 years. By then, a considerable part of the radioactive substances in a deep geological repository will have already decayed.

How long must the waste be contained?

The largest proportion of radioactive waste decays rapidly. After about three hundred years, the radiation level of the waste in a deep geological repository is only a few percent of what it was at the end of emplacement. The radioactive substances with long half-lives radiate less strongly but over a longer period of time.
After 200 000 years, the high-level waste (HLW) is about as radiotoxic as the corresponding amount of natural uranium ore that was mined to produce the fuel assemblies. After 30 000 years, low- and intermediate-level waste (L/ILW) has the radiotoxicity level of granite.

Geoscientific investigati

Nagra is conducting geoscientific investigations in the remaining siting regions to review and further develop future erosion scenarios.

Nagra is investigating the bedrock of the remaining siting regions with methods such as 3D seismics and exploratory boreholes. The latter are scheduled to begin in 2019.

From 2015 to 2017, 3D seismic surveys (see Glossary) were conducted in the siting regions Jura Ost, Nördlich Lägern and Zürich Nordost. 3D seismics provide spatial images of the rock layers underground. The data are analysed and the findings provide input for the future process stages.

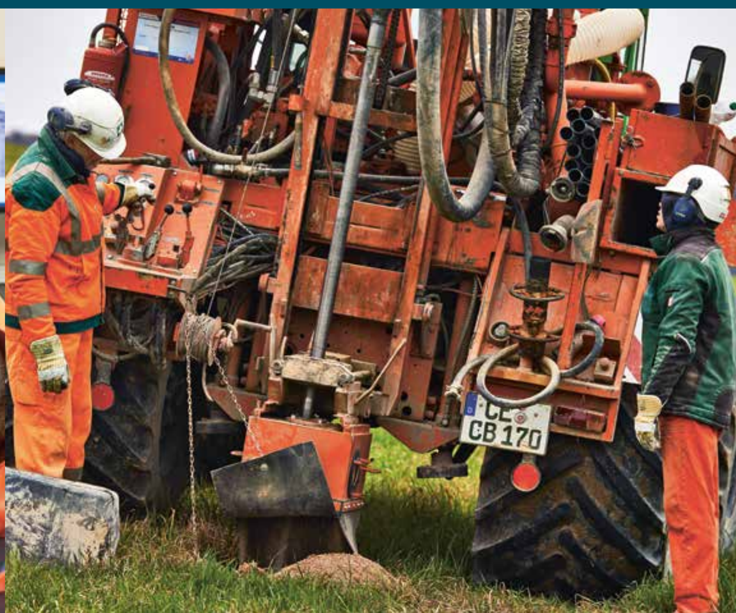
Exploratory boreholes provide comprehensive information about the properties of the host rock and the water-bearing strata. They also help to calibrate previous seismic measurements.

Focus also on erosion

The deep boreholes will provide more accurate information on the depth of the Opalinus Clay, which is relevant for evaluating the protection of a repository from future erosion. Among other investigations, Nagra is drilling Quaternary boreholes in Northern Switzerland in 2018 to study erosion processes in the area. The data collected from these boreholes – in the unconsolidated rocks of overdeepenings – are used to provide an insight into past erosion processes and to predict future developments. Based on this, the existing erosion scenarios will be reviewed and refined in Stage 3 of the Sectoral Plan for Deep Geological Repositories.

Other methods include geological mapping and the investigation of outcrops. Outcrops are places such as quarries where rocks are visibly exposed at the earth's surface. The investigation of outcrops helps in reconstructing future landscape evolution, in particular the impact of erosion.

3D seismics: monitoring in a mobile measuring unit; © photo: Beat Müller



Impulse seismics: drilling a blast hole; © photo: Beat Müller

ons

The results will be considered in the safety-based comparison of the siting regions in Stage 3 of the Sectoral Plan. The goal of these investigations is to create a reliable database for the general licence applications (see below).

What is the next step?

Based on the geoscientific investigations, Nagra will announce the siting regions for which it will prepare general licence applications around 2022. These could be either for a separate repository for HLW and L/ILW or for a combined repository.

Nagra is expected to submit the general licence applications around 2024. To further specify the surface infrastructure needed for a deep geological repository, Nagra plans again to collaborate with the siting Cantons, regions and communities. The submission of the general licence applications is followed by a review by the authorities and a wide public consultation. The decision of the Federal Council is expected for around 2029.

Parliament must approve the decision. The decision of Parliament, in turn, is subject to an optional national referendum. If a referendum is called, the Swiss voters will decide on the sites for deep geological repositories around 2031.

Borehole; photo: © Comet Photoshopping, Dieter Enz

Rock description; © photo: Nagra

Conclusions

The future topography in the geological siting regions will be shaped mainly by rivers and glaciers. The Opalinus Clay will be protected from erosion by the overlying rock layers and sufficient depth.

Rivers

Different scenarios for the future development of the local base level of erosion are derived from studies of past and present river systems. These scenarios differentiate between a repository for L/ILW and one for HLW (different timescales for safety assessment), as well as between the siting regions.

Glaciers

Glacial overdeepenings that have cut 200 to 300 metres deep into the Molasse can be found in the siting regions Nördlich Lägern and Zürich Nordost. Overdeepenings in harder limestones as found between the Molasse and the Opalinus Clay are rare and not as deep.

Developments in the past show that erosion primarily occurs in existing valleys and overdeepenings and that it can deepen or widen these further. However, new overdeepenings can form in regions where the terrain is flatter. For this reason, erosion scenarios consider both the deepening or widening of existing glacially diverted channels and overdeepenings as well as the formation of new ones.

Situation in the siting regions

The siting regions that will undergo further investigation in Stage 3 of the Sectoral Plan (Jura Ost, Nördlich Lägern, Zürich Nordost) have the following characteristics regarding future erosion:

The siting regions Nördlich Lägern and Zürich Nordost were more frequently covered by glaciers than Jura Ost, and these two regions also have glacial overdeepenings. Due to their relatively flat terrain surface, new overdeepenings could also form relatively easily. The reference disposal perimeters proposed in Stage 2 lie at least 550 metres

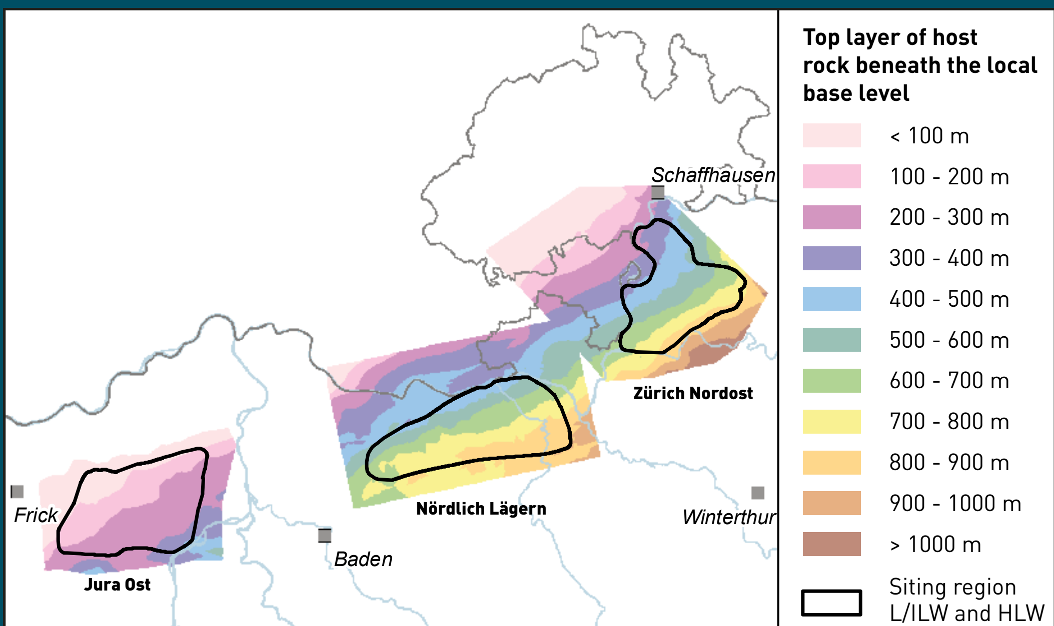


Figure 11
Location of the top layer of the Opalinus Clay host rock beneath the local base level (Source: Pietsch & Jordan 2014)

(Nördlich Lägern) and 450 metres (Zürich Nordost) below the local base level. In both siting regions, it is possible to locate the disposal perimeters at an even greater depth (see Figure 11). In addition, thick layers of limestone are located above the Opalinus Clay; these have a high erosion resistance compared to the marls and sandstones of the Molasse.

Regarding future erosion, the situation is somewhat different in the Jura Ost siting region. The Opalinus Clay is not located as deep in Jura Ost as it is in the other siting regions. In the proposed disposal perimeter, the Opalinus Clay lies at least 200 metres below the local base level. The Bözberg Plateau was, however, covered by glaciers only a few times and these were also significantly less thick. The likelihood that new glacial overdeepenings will form during the relevant future time period is therefore considered low, but the formation of a new valley was considered as an erosion scenario. This is based on the assumption that the lower Aare Valley is closed as a result of a glaciation and that the Aare will flow through a new valley that passes through the siting region. Even in this pessimistic scenario, the repository will not be exposed in the next million years.

All three siting regions are therefore protected from erosion for a sufficiently long period of time.

Where can a deep geological repository be constructed?

In principle, all the siting regions fulfil the strict safety requirements of the Federal Government and are suitable for the construction of deep geological repositories. The Swiss Federal Nuclear Safety Inspectorate (ENSI) confirmed this in April 2017 in its expert review.

In the next stage of the process, the siting regions will be investigated in more depth and compared with one another. Based on safety considerations, Nagra will then propose the most suitable sites for the construction of the deep geological repository.

Glossary

Activity
The number of spontaneously decaying atomic nuclei of a radioactive substance per second.

Deep glacial erosion
The formation of deep rock channels and overdeepened valleys below the ice of foreland glaciers.

Depth of disposal zone
A deep geological repository provides spatial separation of radioactive waste from the human environment. The disposal zone must be deep enough to ensure that the host rock and the radioactive waste are sufficiently protected from erosion.

Disposal perimeter
The disposal perimeter comprises the area of host rock underground in a geological siting region that is considered the most suitable in terms of safety for the construction of a deep geological repository. Reference disposal perimeters were used in the safety-based comparison in Stage 2 of the Sectoral Plan for Deep Geological Repositories.

Glacially diverted channel
When a river is dammed or a valley is filled with gravel (by a glacier or by tills/gravels deposited proglacially), a glacially diverted channel can form. In this case, the water tries to find a new path to bypass the obstacle.

Erosion
The wearing away of rocks and soil through the action of water, ice, wind and gravity.

Glacial overdeepening
Overdeepenings, some of which extend to considerable depth, exist in the valleys of the Swiss Plateau. They are filled with unconsolidated rocks (sand and gravel) that were eroded from the glaciers to beneath the base level of today's rivers. The impact of such features is taken into consideration in the site selection process.

Half-life
The time period in which the amount and thus also the radioactivity of a specific radionuclide decreases to half its original value.

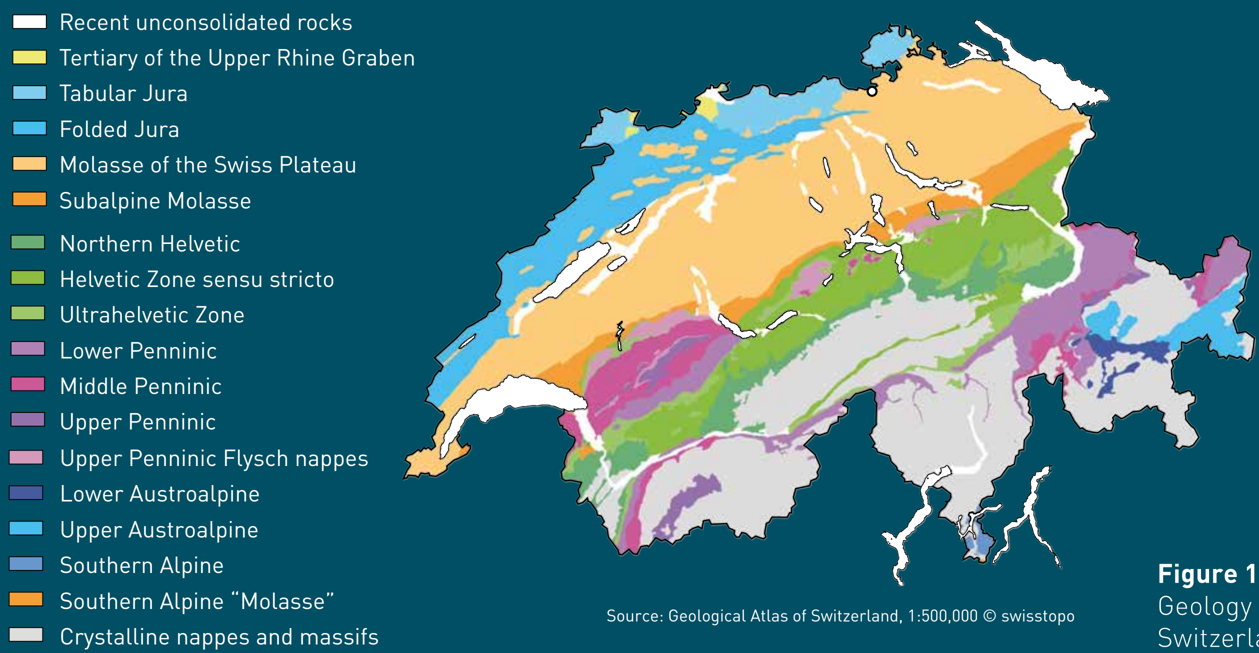


Figure 12
Geology of Switzerland

Host rock
The emplacement rooms of a deep geological repository are constructed in the host rock. It contributes significantly to the retention of radionuclides.

Molasse
Debris eroded from the Alps (see Figure 12).

Moraine
Sediments deposited by glaciers consisting of different rocks and grain sizes, ranging from clay to large blocks.

Opalinus Clay
Host rock selected in Switzerland for the safe containment of radioactive waste. The Opalinus Clay was deposited in a shallow sea during the Jurassic period some 173 million years ago.

Radionuclide
Unstable atomic nucleus that decays spontaneously, causing the emission of radiation. Radionuclides can either occur naturally or be artificially produced.

Radiotoxicity
The toxicity of radioactive substances when they penetrate the human body.

Sectoral Plan for Deep Geological Repositories
The site selection process for a deep geological repository is implemented in three stages as specified in the Sectoral Plan for Deep Geological Repositories. It complies with the Nuclear Energy Act and the Spatial Planning Act (see Figure 13).

Seismics
Seismic measurement methods produce images of the geological underground using artificially generated vibrations.

Time period for consideration
The time period for consideration is the time span used in safety assessments for a deep geological repository. For a HLW repository it has been set at one million years, and for an L/ILW repository it is 100 000 years.

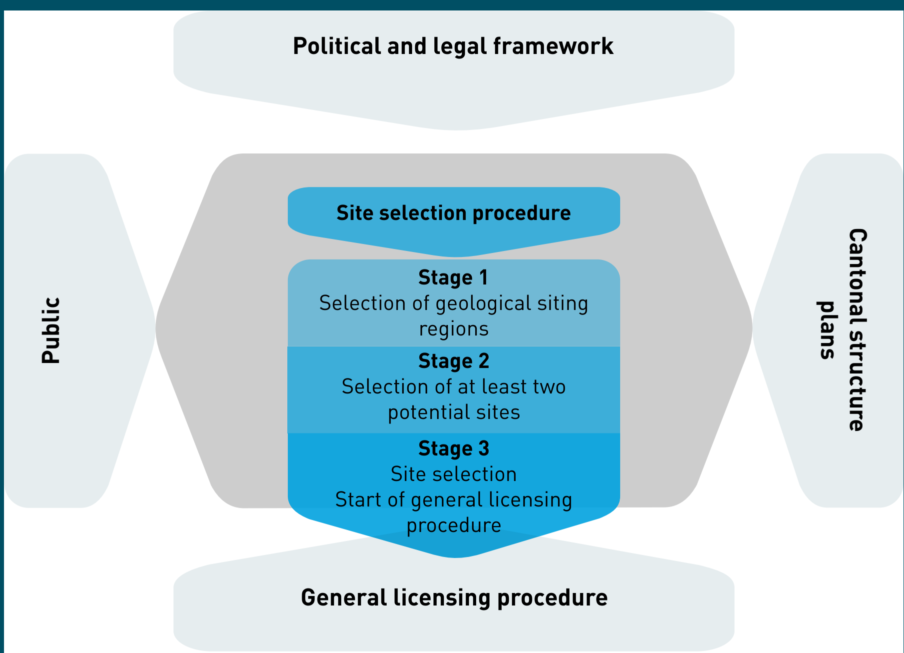


Figure 13
Stages and dependencies based on the Sectoral Plan for Deep Geological Repositories (source: Swiss Federal Office of Energy)

Bibliography

Berger, A. (1979): Long-Term Variations of Daily Insolation and Quaternary Climatic Changes. J. Atmos. Sci., 35, 2362 – 2367.

Berger, A. & Loutre, M.-F. (2002): An Exceptionally Long Interglacial Ahead? Science, 297, 1287 – 1288.

Einsele, G. & Ricken, W. (eds.) (1993): Eintiefungsgeschichte und Stoffaustrag im Wutachgebiet (SW-Deutschland). Tübinger Geowissenschaftliche Arbeiten, Reihe C, 15.

Graf, H. R. & Müller, B. U. (1999): Das Quartär: Die Epoche der Eiszeiten. In: Bolliger, T. (ed.): Geologie des Kantons Zürich. Ott Verlag, Thun, 71 – 95.

Hooke, R. LeB. & Jennings, C. E. (2006): On the formation of the tunnel valleys of the southern Laurentide ice sheet. Quaternary Science Reviews, 25, 1364 – 1372.

Pietsch, J. & Jordan, P. (2014): Digitales Höhenmodell Basis Quartär der Nordschweiz – Version 2014 (SGT E2) und ausgewählte Auswertungen NAB 14-02.

Piotrowski, J. A. (1994): Tunnel valley formation in northwest Germany – geology, mechanisms of formation and subglacial bed conditions for the Bornhöved tunnel valley. Sedimentary Geology, 89, 107 – 141.

Press, F. & Siever R. (2003): Allgemeine Geologie, Einführung in das System Erde, 3. Auflage. Spektrum Akademischer Verlag, Heidelberg – Berlin.

Further reading (available mainly in German)

Nagra (2014): SGT Etappe 2: Vorschlag weiter zu untersuchender geologischer Standortgebiete mit zugehörigen Standortarealen für die Oberflächenanlage – Geologische Grundlagen Dossier III – Geologische Langzeitentwicklung; NTB 14-02.

Nagra (2014a): Erosion und Landschaftsentwicklung Nordschweiz – Zusammenfassung der Grundlagen im Hinblick auf die Beurteilung der Langzeitstabilität eines geologischen Tiefenlagers (SGT Etappe 2); NAB 14-25.

"Standortgebiete für geologische Tiefenlager – Sondierbohrungen für Etappe 3", August 2017

"Radioaktive Abfälle – Woher, wieviel, wohin?", March 2017

"Bohrungen für Quartäruntersuchungen", March 2017

"Langzeitsicherheit – Die Hauptaufgabe der Tiefenlagerung radioaktiver Abfälle", October 2015

"Standortgebiete für geologische Tiefenlager – Sicherheitstechnischer Vergleich: Vorschläge für Etappe 3", January 2015

You can download or order these documents under www.nagra.ch, "Publications".

Nationale Genossenschaft für die Lagerung radioaktiver Abfälle

(National Cooperative for the Disposal of Radioactive Waste)

Hardstrasse 73
Postfach 280
CH-5430 Wettingen

Tel +41 (0)56 437 11 11
Fax +41 (0)56 437 12 07

info@nagra.ch
www.nagra.ch
www.nagra-blog.ch

nagra we care

Brochure 10 / October 2018