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ARBEITSBERICHT NAB 24-28

Geologic Scenarios for the Evaluation of Earthquake Impact on the Deep Geological Repository

November 2024

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

nagra.

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Nagra Arbeitsberichte ("Working Reports") present the results of work in progress that have not necessarily been subject to a comprehensive review. They are intended to provide rapid dissemination of current information.

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Abstract

The proposed Haberstal site for construction of the Swiss deep geological repository (DGR) is located in one of the seismically quietest zones of Switzerland. Nevertheless, seismic activity is not entirely absent and an assessment of the impact of earthquakes on post-closure safety is requested in the Stage 3 requirements of the Deep Geological Repositories Sectoral Plan.

The Swiss disposal concept addresses the occurrence of future faulting in several ways:

- The repository will be constructed in a ~100 m-thick clay-mineral-rich host rock. The potential disposal zone itself is characterized by the absence of larger-scale faults (i.e. faults mapped by 3D seismic reflection imaging).
- Detailed 3D seismic surveys were conducted to image the subsurface of the site and to identify a zone without faults.
- The potential disposal zone is bounded by regional fault zones to the north and south. These are likely to accommodate potential future deformation due to tectonic processes during the time period for assessment. A safety distance will be maintained to these area-bounding tectonic elements.
- Should faults reactivate or develop in the host rock or in the backfill, self-sealing will seal those features and maintain hydraulic isolation towards bounding formations, including aquifers. The permeabilities of self-sealed faults do not impact radionuclide transport significantly.
- Should smaller-scale safety-relevant faults be penetrated during construction of the waste emplacement tunnels or sealing sections, a suitable safe distance will be maintained to the actual waste containers.
- The frictional properties of the host rock as well as the in-situ stress conditions make it unlikely that a seismic rupture can nucleate. If any deformation would occur, it would be distributed and therefore produce small strains.
- The backfill material will serve as a mechanical buffer against any potential deformation for the emplaced waste packages for high-level waste and spent fuel.

In this report, the occurrence of earthquakes as the part of the assessment basis for the development of a safety case is discussed. As part of this assessment, *features, events, and processes* (FEPs), which could promote the occurrence of earthquakes, or which could be influenced by direct impacts of earthquakes (shaking and displacement), are screened. Further, the safety case relies on key attributes and safety functions of repository features. Potential impacts on these by earthquakes are reviewed to assess any possible impact.

At the surface, the damage due to earthquakes is predominantly caused by the shaking movement induced by the seismic waves. It is well established that at depth, the amplitude of seismic waves is reduced. Unlike structures at the surface, backfilled structures in the underground are unable to shear and deform at levels that would be required to cause structural damage. It is concluded that seismic shaking does not pose a threat for post-closure safety.

The actual rupture, i.e., the displacement discontinuity along the fault activated by an earthquake, could pose a potential threat to post-closure safety as it could create pathways for radionuclides. In three earthquake scenarios the impact of a rupture in different parts of the repository (adjacent to the repository footprint, in the low and intermediate level waste (L/ILW) sealing system, and in the high-level waste (HLW) repository, respectively) are developed and discussed. Features, events, and processes are screened and potential impacts on component-specific safety functions

are qualitatively evaluated to facilitate the treatment of these earthquake scenarios in safety assessment.

If during the construction of the repository, further significant faults would be detected, then the impact of such faults on the safety of the particular repository zone would be investigated. Thus, ruptures through safety-relevant structures and barriers may be actively avoided through maintaining a safe distance to such features or other engineering safety measures. Nevertheless, the developed scenarios cover situations where such measures fail.

In this report we limit the discussion to the detailed development of earthquake scenarios as part of the assessment basis for the safety case. These scenarios will be evaluated in the post-closure safety assessment.

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List of Acronyms

BIH	Baden-Irchel-Herdern Lineament
CRZ	Containment-providing rock zone
DGR	Deep geological repository
ENSI	Swiss Federal Nuclear Safety Inspectorate
FEP	Features, Events, Processes
FMD	Frequency-magnitude distribution
HLW	High-level waste (spent fuel assemblies and high-level waste from reprocessing)
L/ILW	Low- and intermediate-level waste
M_{max}	Magnitude of the largest possible earthquake
PEGASOS	Probabilistic Seismic Hazard Analysis for Swiss Nuclear Power Plant Sites
PRP	Pegasos Refinement Project
SED	Swiss Seismological Service
SF	Spent fuel
WGE	Weiach-Glattfelden-Eglisau Lineament

1 Introduction

The long-term stability of the repository host rock with regard to geological long-term evolution is an important factor for post-closure safety of the deep geological repository (DGR). It needs to be maintained over the time period for assessment. Earthquakes are a phenomenon where stability is temporarily compromised. Therefore, the potential for earthquake processes to compromise post-closure safety needs to be scrutinized.

Earthquakes can perturb the geosphere and elements of the engineered barrier system by two main factors. The first is the actual static displacement on the rupture surface as well as in an adjacent damage zone, potentially branching to neighbouring segments if a complex fault zone is activated. The second factor is the shaking which translates to the cyclic loading of structures through the passing wave train. While the actual displacement is confined to a narrow zone around the slip patch, the zone potentially perturbed by shaking can be spatially quite extensive.

The goal of this report is to develop geological scenarios that describe the potential occurrence of seismicity during the post-closure period at the Haberstal site. The developed geological scenarios will be evaluated in the post-closure safety assessment. The model-based assessment of the performance of the barriers, or performance assessment for short, will determine, if earthquakes have the potential to compromise post-closure safety provided by the Swiss disposal concept (Section 2). If deemed necessary, these scenarios might be propagated to subsequent processes carried out in safety assessment.

To that end, we first review the safety concept and siting of the repository. We then review general earthquake properties and processes (Section 3). Potential sources of earthquakes with relevance to the repository are considered (Section 4). Finally, effects of earthquake processes on the repository are described through a range of scenarios (Section 5).

The impact of earthquakes on post-closure safety has been discussed before as part of the safety case assembled within Project Opalinus Clay (Nagra 2002c). Therein, the future occurrence of earthquakes was discussed based on a phenomenological description and empirical evidence focussing on the effects of passing seismic waves. Specific scenarios where a large rupture creates a transmissive feature were treated as “what-if?” cases for the assessment of the performance of the barriers (Nagra 2002b, Nagra 2002a). It was shown that the effects of hypothetical large transmissive features, e.g., caused by earthquakes, would not impact post-closure safety to an extent that would compromise post-closure safety. Here we update the discussion of earthquake-related phenomena considering recent progress in the field.

We base our description on the thorough site selection process including the description of favourable repository host rock properties (Nagra 2024g), the siting in a zone free of detected faults (Nagra 2024h) and the neotectonic evolution of the region (Nagra 2024f). The repository concept is built upon a multi-barrier system that is balanced to jointly fulfil a range of safety functions (Nagra 2024l). The goal of this report is to consider earthquake processes in the context of the repository concept. Only together, it is possible to appreciate the robustness of the whole repository system against external influences such as earthquakes.

The focus in this report is on the relevance of earthquakes for post-closure safety, i.e., after backfilling of the repository. In this report we develop *geological scenarios* which will then be used in safety assessment to evaluate the robustness of the safety concept regarding earthquake effects. This corresponds to the requirements defined in ENSI (2018a), paragraph 5.1f, to use scenario development methodologies for the assessment of earthquake influences on post-closure safety. This approach contrasts with the assessment of operational safety, which makes use of the probabilistic seismic hazard assessment methodology instead. The reason for using different paradigms is the time period for assessment for the construction and operation of the facility (several decades) compared to that for post-closure safety (up to 1 million years). The potential impacts of earthquakes during the operation phase of the DGR are discussed in a separate report (Nagra 2024c).

Earthquakes are captured by the list of features, events, and processes (Nagra 2024i) and are classified as a potentially disruptive event, thus requiring a closer investigation by generating geological scenarios. Each of these geological scenarios describes a combination out of a sufficiently broad range of earthquakes with varying magnitude to explore their potential impacts on post-closure safety by considering them in safety assessment. The geological scenarios developed in this report are first quantitatively evaluated as part of performance assessment (Nagra 2024o). During performance assessment, it will be considered whether the impacts of the scenario events would have a potentially significant, negative impact on specific claims made regarding the performance of the geologic or engineered barriers. The geological scenarios developed in this report and the results of the corresponding performance assessment inform the development of safety scenarios (Nagra 2024b) and if deemed necessary, the developed safety scenarios will be propagated to the analysis of radiological consequences (Nagra 2024j).

2 Safety concept and siting of the repository

It is important to recognise the safety concept of the deep geological repository before considering the possible impact of earthquakes on post-closure safety. In the following, the geological setting of the repository site and the general safety concept are reviewed in relation to earthquake processes. Only a summary is given in the following. For full descriptions of the safety concept and the provisional design of the repository see Nagra (2024l). The synthesis of the geological situation is contained in Nagra (2024g).

2.1 Safety and repository concepts

The provisional repository design envisages two disposal areas, one for spent fuel (SF) and high-level waste (HLW) and one for low and intermediate level waste (L/ILW), located at the same site in a combined repository (Fig. 2-1). A distance between these repository parts is maintained such that they do not influence each other.

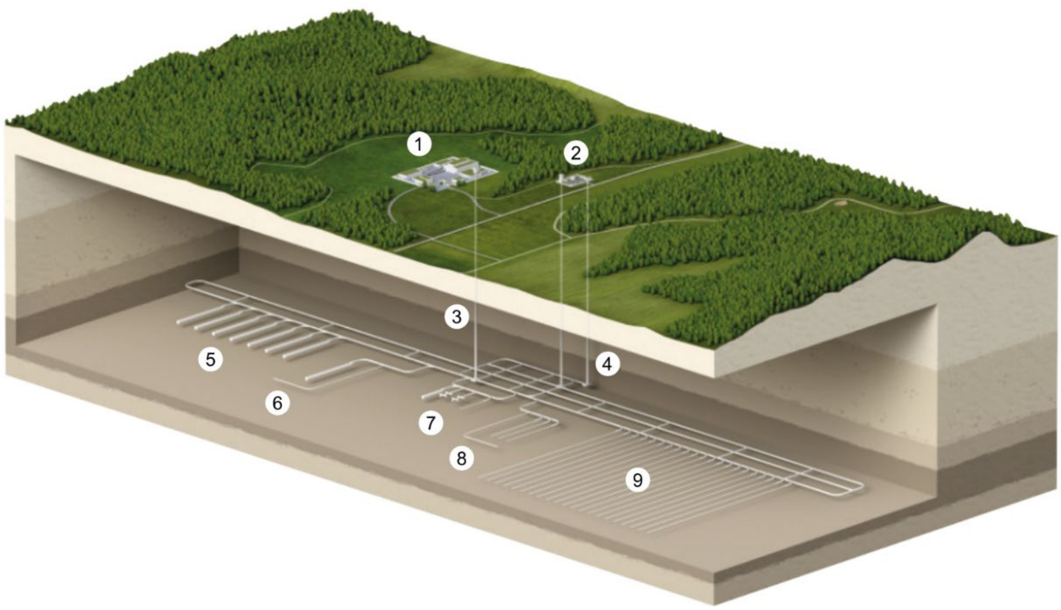

Fig. 2-1: Illustration of the combined repository for SF/HLW and for L/ILW (Nagra 2021)

Legend: 1) Surface facility 2) Auxiliary access facility 3) Access shaft (main access) 4) Operation and ventilation shafts (auxiliary accesses) 5) Main repository L/ILW 6) Pilot repository L/ILW 7) Test areas 8) Pilot repository HLW 9) Main repository HLW.

According to the current repository concept, the underground part of the combined repository will be constructed in Opalinus Clay at a depth of more than 800 metres below the surface. It will include a series of dead-end emplacement drifts for SF and HLW, which are supported by segmental lining elements and annular gap-filling material. The combined repository will also include dead-end emplacement caverns for L/ILW, which will be supported by a tunnel support system consisting of shotcrete towards the Opalinus Clay and an inner-shell tunnel support emplaced by formwork (Nagra 2023).

Waste is disposed of in emplacement rooms, located deep underground, roughly in the middle of the Opalinus Clay host-rock layer, between its confining units. The engineered barriers for HLW disposal consist of SF assemblies with fuel rods and vitrified reprocessed HLW that are packaged in steel canisters. The HLW canisters are emplaced in drifts, which are subsequently backfilled with a compacted bentonite buffer and sealed. For L/ILW disposal, L/ILW waste packages are placed inside waste containers and voids filled with cementitious material. The waste containers are in turn emplaced in caverns that are backfilled with cement-based mortar.

The geological barrier is considered to be of primary importance in the long term, due mainly to the excellent qualities and long-term stability of the CRZ. The CRZ includes the Opalinus Clay, as well as the geological units above or below the host rock that also contribute to radionuclide immobilisation and retardation of release. The Opalinus Clay formation is characterised by:

- A fine and homogeneous pore structure with a very low hydraulic conductivity. This ensures that water movement in this clay formation is limited, and that radionuclide migration is essentially diffusion dominated.
- A high clay mineral content. This results in a high sorption capacity for many radionuclides, thereby delaying their migration through the clay.
- A high self-sealing capacity. This means that any fractures in the clay will rapidly close again.

The geological units above or below the Opalinus Clay include units with a lower or more heterogeneous clay mineral content, participating in the retardation of the radionuclide release.

The geological barrier is complemented by a mutually compatible set of engineered barriers. A key role of the engineered barriers is the minimisation and mitigation of disturbances to the CRZ caused by the waste and its emplacement, including, for example, the effects of heat generated by the waste and the disturbance to the rock caused by the excavation and ventilation of underground openings. The engineered barriers around the HLW waste, with the waste disposal canister playing the central role, are expected to provide a period of complete containment of radionuclides. Although some eventual release of radionuclides and migration through the multi-barrier system cannot be excluded, most radionuclides will remain immobilised in the waste forms and waste containers until they decay.

Furthermore, the radionuclides that are released will migrate only slowly towards the surface environment, with substantial attenuation by radioactive decay of many radionuclides first within the engineered barriers and then, for any that penetrate these barriers, within the surrounding geological barrier.

2.1.1 Safety functions and related safety requirements

Collectively, the multi-barrier system provides the following safety functions:

- S1: Isolation of radioactive waste from humans and the environment;
- S2: Complete containment of radionuclides for a period of time;
- S3: Immobilisation, retention, and slow release of radionuclides;
- S4: Compatibility of the components of the repository system;
- S5: Long-term stability of the multi-barrier system regarding long-term geological and climatic evolution.

These safety functions are used to derive a set of safety requirements on the system components, including the “pillars of safety”.

Analysing whether the barriers meet their various requirements and thus fulfil their assigned safety functions requires an understanding of the events and processes that are likely to affect the repository design over the safety-relevant assessment timeframe; this analysis is termed performance assessment and is documented in Nagra (2024o).

2.1.2 Pillars of safety

The repository features that are the main contributors to the safety functions are termed "pillars of safety". The pillars of safety and their properties are considered well understood and insensitive to perturbations. The pillars of safety are (cf. Fig. 2-2):

- The **repository layout and deep underground location**, ensures, for example, that inadvertent human intrusion is unlikely, and that the repository is not susceptible to geological events and processes relevant to post-closure safety.
- The **containment-providing rock zone (CRZ)**, which, together with the engineered barriers, ensures the containment and retention of the radioactive substances. The CRZ includes the host rock as well as upper and lower confining units. The host rock is characterised by a fine and homogeneous pore structure, extremely low hydraulic permeability, a homogeneous and high clay mineral content and the associated high sorption capacity for many radionuclides. The CRZ is characterised by favourable properties (especially self-sealing ability) for long-term stability, forming a very effective and stable barrier against radionuclide transport and a compatible (physical and chemical) environment for the engineered barriers.
- Both **SF and reprocessed HLW matrix** are chemically stable in the expected environment.
- The **SF and reprocessed HLW disposal canisters** are mechanically stable and corrosion-resistant in the expected environment. They ensure complete containment of the radionuclides for a period of time.
- The HLW emplacement drifts will be backfilled with bentonite. This **bentonite buffer** provides a stable barrier against radionuclide transport, and a suitable physical and chemical environment that enhances the longevity of the HLW disposal canisters. In addition, this buffer offers mechanical support to the host rock after the degradation of the tunnel support. It protects the canisters and compartmentalises the repository by separating them from each other, thereby mitigating the impact of inadvertent human intrusion and reducing the potential impact of the heat release on the retention properties of the CRZ.
- The **L/ILW cementitious near field** promotes sorption of radionuclides, decreases corrosion of metals and inhibits degradation of organic materials, which in turn reduces gas generation. The cement-based backfill can also store a significant volume of gas and provides mechanical stability to the host rock, even after the degradation of the tunnel support.
- The **closure system** includes all the sealing systems and backfill of the shafts in the host rock. Together, these elements form a stable barrier against radionuclide transport. Particularly in the L/ILW repository section, where unfavourable gas pressure buildup might happen in the emplacement caverns, the closure system serves as a gas transport and storage system. The sealing system additionally provides mechanical stabilisation of the host rock. It remains effective even after the tunnel support has degraded. It also contributes to repository compartmentalisation and reduces both the likelihood and the radiological impact of inadvertent human intrusion into the repository.

Each pillar of safety can contribute directly and/or indirectly to the safety functions. For example, the SF/HLW disposal canisters contribute directly to the complete containment of radionuclides, while the surrounding bentonite buffer contributes indirectly as it helps to protect the canisters.

Compatibility between the different pillars is demonstrated by a solid technical and scientific understanding of the geology and engineered components.

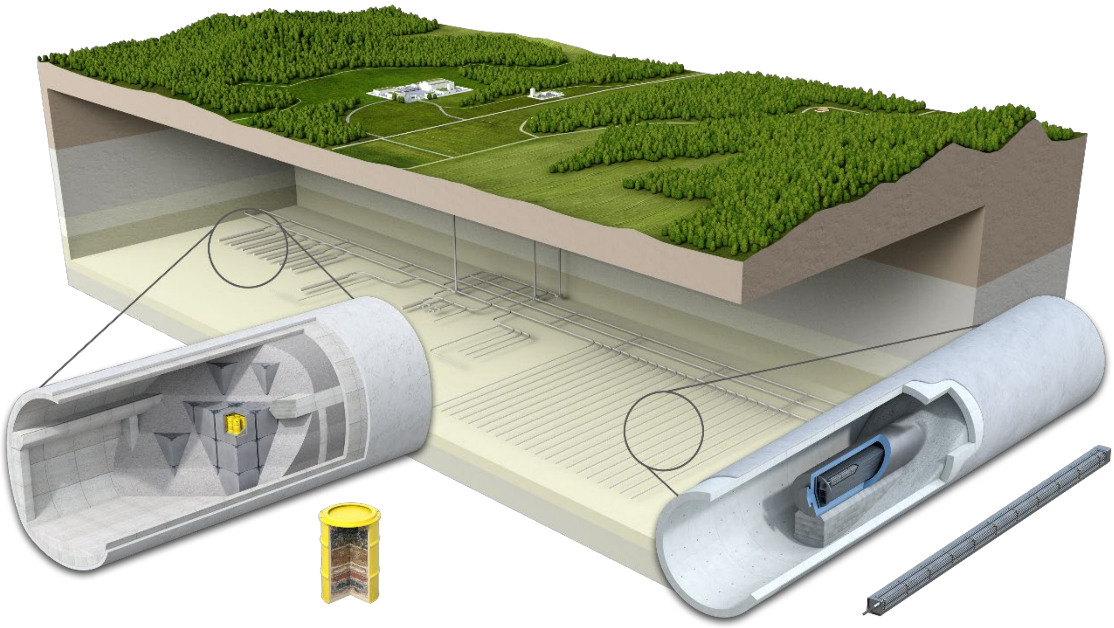

Fig. 2-2: Post-closure safety concept for the HLW and L/ILW repository according to the combined repository disposal project

For the L/ILW repository, as an example, a 200 l drum will be placed in an LC container, which will be emplaced and backfilled with mortar (left). For HLW, as an example, SF encapsulated in a carbon steel canister placed on a bentonite pedestal and backfilled with a bentonite material buffer is shown (right).

2.2 Siting and host rock suitability

Switzerland is regarded as a region with low-to-moderate levels of seismicity. The site lies in the seismically relatively quiet zone of northern Switzerland (Wiemer et al. 2016). At the site faults are well imaged by high-resolution 2D and 3D seismic surveys and considered for site selection and preliminary placement of the repository structures (Nagra 2024a).

The potential disposal zone is bounded by complex E-W striking systems of faults to the north and south. The area in between is free of seismically resolvable discrete faults, which makes it a suitable site for placement of a repository (Nagra 2024h). During the geological past, deformation has localised on faults and regional fault zones, which acted as weak zones and have repeatedly been reactivated, as is a common phenomenon in continental crust (Townend & Zoback 2000). It is expected that also during the next million years deformation will mainly localise in these existing faults. The creation of new tectonic zones or fault zones is regarded as very unlikely during the next million years. Thus, avoiding identified tectonic structures is the best strategy to avoid the impact of future deformation and ruptures on post-closure safety.

During construction of the main repositories detailed geologic investigations will be performed to identify features that could impact post-closure safety. The repository structures are placed according to the interpretation of the 3D seismic imaging to avoid any seismically mappable faults, i.e., a fault that is large enough to be visible on 3D seismic surveys (Nagra 2024h). In the unlikely case that any structures are found and deemed a potential threat to post-closure safety, the canister emplacement can be adopted accordingly.

The Opalinus Clay host rock shows less common small-scale fracturing than neighbouring more competent units as indicated by the deep drilling campaign, 3D seismics and outcrop examples (Nagra 2024g). Furthermore, compared to the more competent units above and below, deformation in Opalinus Clay tends to be accommodated in a distributed manner which limits the large-scale connectivity of features. Consequently, the comparably minor share of deformation that might affect the areas away from the main tectonic zones is expected to be distributed and will mainly affect pre-existing smaller-scale structures. Such diffuse zones of deformation are also less likely to rupture in a single large event. The rheologic and frictional properties of the Opalinus Clay inhibit seismic rupture and promote distributed deformation (Nagra 2024g).

Self-sealing in the backfill material, the host rock, and clayey rocks of the CRZ will occur on relatively short time scales should a fracture form. Sealed fractures are hydraulically indistinguishable from the rock matrix (Nagra 2024g, Nagra 2024o). Any created hydraulic transmissivity should therefore be only temporary.

The engineered barrier system, with the bentonite backfill in the SF/HLW drifts (Nagra 2024l) can act as a mechanical buffer between the host rock and the waste packages. Any deformation would be distributed within the soft backfill material rather than directly transmitted to the stiff waste canisters. This decreases the localised deformation at the canister and thus the likelihood of a canister breach.

2.3 Expected evolution of the repository

The expected evolution of the repository after backfilling and closure is described in Nagra (2024i). The aspects of the expected evolution with relevance for earthquake processes are summarised in the following section.

Engineering aspects

The siting decision for placing the repository fields is based on high resolution 3D seismic images. Detected faults are avoided and a respect distance maintained. During construction, geologic characterisation will ensure that critical sections of the repository, in particular the locations for emplacement and sealing sections, do not contain tectonic structures that could host significant localised deformation during the time period for assessment. The distance of waste emplacement rooms and waste packages to each other is optimised such, that repository-induced effects do not significantly change the state of stress in the CRZ. Waste emplacement rooms are backfilled with bentonite material (SF/HLW) or cementitious mortar (L/ILW), and access tunnels are backfilled with previously excavated material. A redundant system of seals is used to close the facility and mitigate radionuclide transport outside of the CRZ.

Evolution of repository

Gas generation takes place due to corrosion and degradation of organic materials in the caverns. Some of this gas dissolves in porewater within and around the caverns, with the remainder accumulating within the caverns, increasing the gas pressure and limiting further inflow of water. Desaturated conditions persist for several tens of thousands to hundreds of thousands of years, until gas generation ceases. Some gas may enter the rock but will migrate through it without causing damage. Fractures in the excavation-damaged zone however will self-seal also in partially saturated conditions.

In the HLW part, resaturation is much quicker due to much lower gas production rate, high capillary pressure and despite high heat production from the waste. The increases of temperature and gas production will lead to increases in pore pressure and gas pressure, and thus to changes of the effective stress conditions. The magnitude of these can be predicted through modelling and the system will be optimised such that activation of faults or creation of fractures is mitigated (Nagra 2024o).

External effects

The tectonic boundary condition of the site is characterized by an intra-plate setting with very low strain rates, close to instrumental detection limits. The tectonic deformation is expected to be low during the time period for assessment (Nagra 2024g). Faults north and south of the prospective repository have been reliably imaged by the 3D seismic survey. These will serve as weak zones where deformation localises, potentially leading to natural earthquakes. However, the creation of new faults during the time period for assessment is very unlikely. Since the deposition of the Opalinus Clay ca. 170 million years ago, tectonic strain has been largely localized to the regional fault zones, while the low strain areas foreseen to host the repository have taken up no relevant deformation. This held true also during the more recent deformation phases including the formation of the Jura Fold-and-Thrust Belt. It is therefore considered unlikely that relevant new faults are created during the time period for assessment.

Secondary processes, such as erosion and glaciations have the potential to change the state of stress, particularly at shallow depth of the repository, such that they could influence the occurrence of earthquakes (Nagra 2024f). During glaciations the vertical stress component will increase with commensurate changes to the horizontal stresses. Such alteration of the stress regime could potentially cause, currently inactive faults to become active (Nagra 2024d). In future warm phases post-glacial rebound might lead to an activation of yet another set of faults.

This glacial-interglacial cycle has been ongoing since the Quaternary period, and it is assumed that during those cycles the different fault sets that would be activated in future cycles were already active in past cycles (Nagra 2024f). Hence, the faults that are active at different phases of these glacial-interglacial cycles are documented in the geologic record. If there are any seismically mappable faults, that were active at different phases of glacial-interglacial cycles, they are mapped.

Erosion driven by rivers and glaciations will locally decrease the overburden, potentially leading to stress changes. Due to the long timescales of these processes, it is not expected to significantly change the pattern of fault activation.

2.4 Overview of the repository safety assessment

The principles, procedures, and methods necessary to assemble the safety case for the proposed repository are described in Nagra (2024m). The evidence, knowledge, assessment tools and methodologies developed or acquired in support of site selection and safety assessment form the assessment basis. It contains the understanding for the geosphere, the engineered barrier system, the waste forms and their respective interactions as well as natural and repository-induced processes. The present report is considered part of the assessment basis.

Post-closure safety assessment consists of the following three main processes, result of which support demonstration of post-closure safety (Nagra 2024m):

- **performance assessment**, in which the thermal, hydraulic, mechanical, and chemical evolution of the repository system is analysed,
- **safety scenario development**, which entails the identification and description of a set of safety scenarios that capture uncertainty in initial state and subsequent evolution of the repository system over time, and
- **Analysis of radiological consequences**, which consists of an evaluation of radionuclide release rates to the surface environment as a function of time.

To ensure completeness of safety assessment, Nagra maintains a comprehensive database that encompasses all features, events, and processes (FEPs) relevant to the Swiss deep geological repository (Nagra 2024i). FEP databases are a standard tool in safety assessment of DGRs (Nuclear Energy Agency 2019). They provide a database that aims to cover all FEPs that may be relevant to the repository and its environment. Various completeness checks with international FEP lists were performed to ensure its completeness.

In this report, we use the Nagra FEP database to guide a systematic assessment of the potential effects of earthquakes on post-closure safety. To that end, the Nagra FEP database (Nagra 2024i) was screened. FEPs that are associated with the occurrence of earthquakes were identified. FEPs can either contribute to the occurrence of earthquakes (discussed in Sections 3 and 4) or be affected by the occurrence of earthquakes (discussed in Section 5). Throughout the text, described FEPs are linked to their respective index number in the Nagra FEP database. The list of FEPs with relevance to the subject of this report and a reference to the relevant section of this report is given in App. A.

The impacts of the potential effects identified in this report on a set of claims regarding the functionality of each component of the multi-barrier system and the functionality of the entire disposal system will be determined by performance assessment. The results of the performance assessment informs the subsequent processes carried out in safety assessment.

3 Seismological background

The phenomenon of earthquakes can be decomposed into a sudden displacement along a discrete surface in the Earth's crust, i.e., a fault, and the waves that are radiated from this rupture that travel through the Earth's body and along its surface. The hazard that is associated with earthquakes can thus be differentiated into a rupture hazard from the displacement discontinuity itself and a shaking hazard away from the earthquake source where seismic waves interact with infrastructure and the geological environment.

For completeness of the report, a brief overview of earthquake mechanics in general and some specific aspects of the seismic activity in Switzerland is provided in the following section. Then, the largest events to be considered on presently unknown structures are discussed.

3.1 Earthquake mechanics

To understand the potential impact of earthquakes on post-closure safety, it is important to reflect on some characteristics and empirical relationships that can be used to describe them. Arguably the most important property of an earthquake is its strength, which can be quantified by magnitudes. One type of magnitude is the moment magnitude, defined as $M_W = 0.67 \log_{10} M_0 - 6.07$ where the seismic moment M_0 is in units of Nm. M_0 is defined as the product of the average displacement d, the rupture area A and the shear modulus μ. To account for the enormous range of earthquake sizes, the magnitude scale is logarithmic.

The exponential-scale nature of earthquakes is also reflected in the magnitude-frequency relation, also known as Gutenberg-Richter relation, shown exemplarily for Switzerland in Fig. 3-1. Small earthquakes occur much more frequently than large events, with about a factor of 10 between the number of events with a magnitude difference of approximately one. The exact ratio of earthquake rate of different magnitudes is given by the b-value, defining the slope of the Gutenberg-Richter relation.

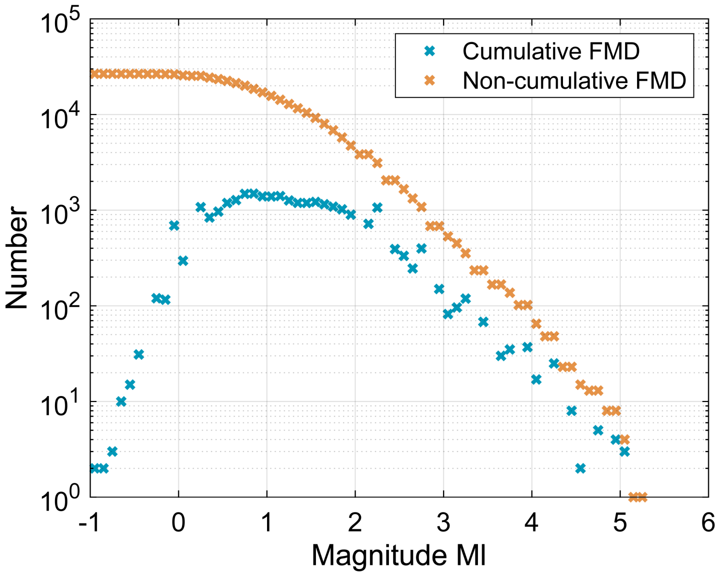

Fig. 3-1: Frequency-magnitude distribution (FMD) of earthquakes in Switzerland determined for local magnitudes in the period 01.01.1975 – 30.09.2023

Data from the ECOS-09 catalogue (Fäh et al. 2011) and updates thereof.

During an earthquake, tectonic stress built-up on the rupture surface is released. The so-called stress drop of an earthquake roughly describes this released stress on the rupturing fault. It has been observed that the average stress drop of earthquakes is scale-invariant, i.e., it is about the same for earthquakes from the laboratory scale to the largest tectonic events (Kwiatek et al. 2011). Based on such observations, earthquakes are often described as a self-similar process, which means there is apparently no fundamental difference between the processes that produce and that occur during large or small earthquakes (Kanamori & Brodsky 2004). This allows derivation of further scaling relations that describe the earthquake mechanics of small and large earthquakes.

The relationship between earthquake magnitude and displacement, as well as the size of the rupture (here diameter of a circular rupture area) is shown in Fig. 3-2. From that figure, for an earthquake of magnitude 4, a displacement on the order of 1–10 cm over a slip patch of about 1-3 km can be estimated. To derive the scaling relations drawn in Fig. 3-2 the earthquake process is simplified to a rupture on a circular fault (Eshelby 1957). For this model, the relation of fault size l, i.e., the diameter of the circular fault, to the seismic moment of the earthquake is given by $l = (7/4\ M_0\ \Delta\sigma^{-1})^{-1/3}$, where M_0 is the seismic moment and $\Delta\sigma$ is the stress drop. The mean displacement d is related to the stress drop by $\Delta\sigma = \mu d/l$, whereby a shear modulus μ has to be assumed (Stein & Wysession 2003). For the relations shown in Fig. 3-2, stress drop is assumed to vary independent of earthquake size between 0.1 to 10 MPa (Kanamori & Brodsky 2004, Allmann & Shearer 2009), corresponding to the diagonal lines. For the shear modulus μ, a value of 30 GPa is used, which is a typical value for the crystalline basement in the Earth's crust. This is much higher than the shear modulus of the Opalinus Clay host rock (Nagra 2024g). Although this model is very simplified, and some variations of stress drop in relation to fault types have been found (Allmann & Shearer 2009), it works well including for large earthquakes. Only the very largest subduction events ($M_W > 7$) appear to show different scaling, potentially related to geometric effects of the extremely large rupture surfaces (Denolle & Shearer 2016).

We are using these scaling relations later to infer the size of earthquakes that may be produced by currently unknown or undetected faults (Section 3.3.1) and to estimate the potential displacement along a presumed slip patch of a scenario event (Section 5.2).

Various phenomena lead to localised deformation in the volume surrounding the main rupture. Distributed deformation (Petersen et al. 2011, International Atomic Energy Agency 2021) is thought to occur co-seismically and involves activation of pre-existing structures away from the principal fault (Thompson Jobe et al. 2020). Strain and stress changes in the surrounding rock volume due to the discrete displacement (King et al. 1994). This is one of the driving processes for the occurrence of aftershocks (Freed 2005, Richards-Dinger et al. 2010). Further away from the earthquake source, dynamic stresses by the seismic waves are also perturbing the system temporarily, potentially leading to triggered seismicity (van der Elst & Brodsky 2010).

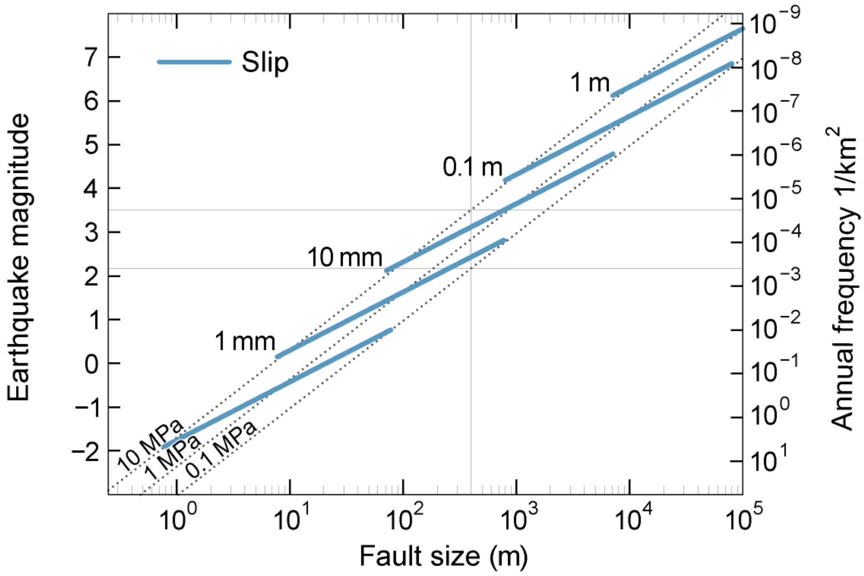

Fig. 3-2: Relationships among various parameters of earthquakes, independent of their mechanism, that describe their self-similar scaling

The larger the earthquake, the larger the rupture and slip, depending on the stress drop in a particular earthquake. Observational data indicate that earthquake stress drops range between 0.1 and 10 MPa (Zoback & Gorelick 2012). The fault size indicated along the abscissa corresponds to the size of the fault segment (length or width) that slips in a given earthquake. Thin lines denote the largest possible event on presently unmapped faults (Section 3.3.1). The right-hand ordinate refers to the earthquake occurrence as discussed in Section 3.3.2.

3.2 Seismic hazard in Northern Switzerland

Switzerland has a very well documented historical record of seismicity. It dates back several hundreds of years for felt seismicity. Fig. 3-3 shows a map of Switzerland with observed seismicity and modelled occurrence rates of large earthquakes (swissnuclear 2013). The areas of highest seismic activity are the region around Basel, the canton Valais, and eastern sections of the country. The north-central area of Switzerland, containing the site[1], is among the areas with the lowest determined seismic activity. Still, some seismicity exists in this region and small earthquakes were recorded also close to the site[2].

Northern Switzerland can be considered a tectonically active, but low-strain area. Presently, horizontal deformation rates measured by the permanent stations are on the same order as the associated error ellipses (Nagra 2024f). In areas within the continental interior, faults behave differently than along plate boundaries, where they are constantly loaded and break quasi-periodically (Li et al. 2009). In low-strain areas, loading is often shared by complex sets of interacting faults that are spread across a large area. Individual faults can be inactive for long times.

[1] FEP 3.1.1 – Siting, design and implementation – Repository site

[2] FEP 14.8 – Geological processes and events – Seismic activity

Existing faults provide zones of weakness that often guide deformation in low-strain areas (Sykes 1978). Importantly, a variety of weak fault plane orientations can be activated under the same applied stresses. Earthquakes along repeatedly reactivated faults might result in complex rupture patterns and leave distributed, rather than simple cumulative traces within the landscape (Landgraf et al. 2017). Thus, low deformation rates with long recurrence intervals and distributed faulting pose significant problems in detecting faults from geomorphological evidence; a fact that is further enhanced by surface processes and anthropogenic overprint.

Northern Switzerland experienced glacial and periglacial climatic conditions during several periods in the Quaternary. Potential records of pre-Holocene faulting are expected to be obscured by area-wide erosion, overprinted by deposition, or confused with ice- or freeze related features, rendering a landscape-based analysis of active faulting difficult (Hammer et al. 2019). Given the complexities for low-strain areas as highlighted above, the potential for faulting in areas not presently known to be active needs to be acknowledged.

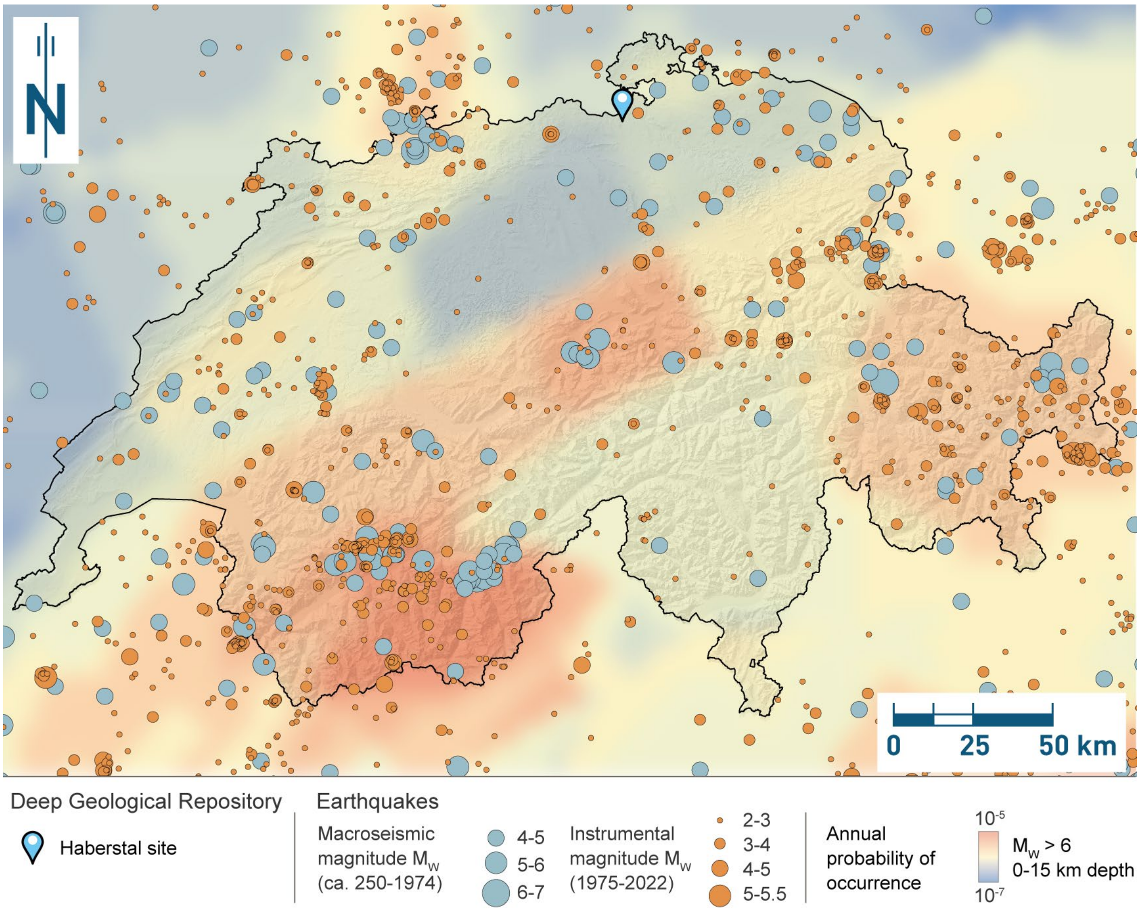

Fig. 3-3: Recorded earthquakes (historical and instrumental) and modelled probability for earthquakes with $M_W > 6$ to occur in Switzerland, determined in the framework of the PRP project (swissnuclear 2013)

The background colour indicates the annual probability of occurrence for earthquakes with $M_W \geq 6$ in an area of 0.05° longitude × 0.05° latitude (ca. 21 km^2) for hypocentral depths < 15 km.

3.2.1 Seismic hazard assessments

For the operation of nuclear facilities in-depth assessments of the seismic hazard are prescribed (ENSI 2018b). A series of probabilistic seismic hazard assessment studies were performed in the PEGASOS and Pegasos Refinement Projects (PRP) for the Swiss nuclear power plants. These projects followed the strictest guidelines (Level 4) of hazard analysis procedures as defined by the American Senior Seismic Hazard Analysis Committee that have since been updated based on the experiences collected during those assessments (NRC 2012). The results of PRP (swissnuclear 2013) were later joined with the hazard model of the Swiss Seismological Service (Wiemer et al. 2016) and prescribed by ENSI for the application to the Swiss nuclear power plants (Proseis 2015). These studies form an important basis for any seismic hazard assessment for locations in Switzerland.

In typical applications of probabilistic seismic hazard assessments, the performance periods of assessed structures are rarely more than 100 years. For nuclear installations ground motions with return periods of about 10,000 years must be considered. For the time period for assessment of 1 million years for the DGR, the validity of such probabilistic assessments is questionable. The seismic record (including instrumental and historic evidence) does not span more than a few hundred years. In contrast, the return period of the largest ground motions, that may dominate the hazard, is on the order of 10,000 years or more. It is obvious that the seismic record thus only represents a short snapshot of the seismic history and any extrapolations of it towards the period for assessment is associated with large uncertainties (Schmedes et al. 2005, Fäh et al. 2009). A standard probabilistic treatment of these uncertainties would not be sufficient to meaningfully capture the range of possible evolutions. Consequently, a probabilistic assessment of the seismic impact on post-closure safety is avoided in this report. Instead, we take the existing state-of-the-art probabilistic assessments as a starting point for a scenario-based assessment. Such a scenario-based assessment of the impact of earthquakes on post-closure safety was also prescribed in ENSI (2018a). Geological scenarios were developed that capture the full range of possible future evolutions with respect to seismic activity impacting the repository.

As will be discussed later in this report (Sections 3.4 and 5.1) the probability of exceeding a specific level of ground motion is not the determining factor for the impact of future earthquakes on post-closure safety. Instead, radiologic consequences may only arise if an earthquake rupture occurs in or near the repository (Sections 5.2–5.4). Thus, here we focus on the occurrence of earthquakes rather than on the ground motions produced by them.

3.3 Earthquake sources

The occurrence of earthquakes is bound to fault zones. Here we assume that no new faults of appreciable size are to form in the presently undisturbed prospective repository zone during the period for assessment. While there is no guarantee, the geological record since deposition of the host rock ca. 170 million years ago, does not indicate that any significant deformation has occurred. Thus, there is no obvious reason to assume that significant deformation will occur during the time period for assessment. During the siting process, 3D seismic surveys were acquired, processed and interpreted in detail to image the subsurface and find locations where the host rock is undisturbed (Nagra 2024h). The identified faults, here termed *seismically mappable*, will be avoided, and a respect distance maintained.

3.3.1 Potential impact of presently unknown fault structures

The identified faults and their geometric properties allow an estimation of the largest potential seismic events they may host. Conversely, we may also determine the largest events for which hosting faults were not reliably identified thus far. We call these faults *sub-seismic* here. For the setting of the 3D seismic surveys conducted at the site, it was determined that faults with a minimal vertical throw of 5 m were detected (Nagra 2024h). Using empirical relationships between the length of a fault trace L and the accumulated displacement D_{max}, we can derive the size of potentially unmapped faults and further the maximum size of an earthquake on such faults.

It has been shown that there is a linear relationship between the length of a fault trace L and the accumulated displacement D_{max} as $D_{max} = \gamma L$. For a wide range of fault sizes, including the scales discussed here, the coefficient of proportionality takes a typical value of $\gamma = 0.025$ (Bergen & Shaw 2010). Conservatively assuming $D_{max} = 10$ m for a complete set of seismically mappable faults, we can estimate the maximum length of potentially undetected faults (sub-seismic faults) to 400 m. The scaling relations that relate earthquake rupture length to slip shown in Fig. 3-2 can then be used to infer M_W in the range [2.1, 3.4] and slip in the range [0.5 mm, 4.8 cm].

Therefore, the largest fault that might potentially have been missed[3] in the seismic investigations is assumed with a dimension of 400 m in length and 10 m in throw. This would, as a maximum, relate to a potential earthquake on the order of M3.4.

3.3.2 Earthquake frequency

In the next step we consider how often such a hypothetical, maximum earthquake of M3.4 would occur. We base this on the existing assessments of the source term collected during the probabilistic hazard assessment studies, bearing in mind the limitations of the representativeness of the earthquake catalogues that were used as input data for the time period for assessment, as discussed above. Nevertheless, this will serve as a first-order estimate of the rate at which small earthquakes, for which hosting features are unknown at this stage, are expected to occur in the repository zone in the absence of further information.

Fig. 3-4 shows the annual rate of earthquakes of magnitude 4 and larger within a 25 km radius around the Beznau nuclear power plant according to different earthquake hazard models (Proseis 2015). During the PEGASOS project, the four different expert groups included both the Beznau nuclear power plant and the Haberstal site in the same source zone (Nagra 2004), and we assume here, that the modelled seismicity rates are transferable from Beznau to the repository site. In these source zones, seismicity is modelled to occur uniformly, and there is no further discrimination between locations above faults or away from them. From Fig. 3-4 and taking the mean SED model, a M5 event would be expected with a rate of about 0.002 yr^{-1} in a region of 25 km radius (an area of 1963 km^2), which is equivalent to 10^{-6} yr^{-1} km^{-2}. Note the uncertainty, that is associated with these estimates. The mean rate of M5 events estimated by the Swiss Seismological Service and the PRP expert groups varies by approximately a factor of three and the 95% confidence interval for this earthquake rate spans about an order of magnitude.

In agreement with the Gutenberg-Richter relationship (Section 3.1), M4 events are estimated to occur with about 10 times higher rate and so forth for smaller events. For the M3.4 events, i.e., the largest events that we cannot deterministically exclude currently (see Section 3.3.1), we have to extrapolate the relationship from Fig. 3-4 to smaller magnitudes. Assuming $b = 1$, the extrapolation of the M5 rate yields about $4 \cdot 10^{-5}$ yr^{-1} km^{-2}, with a 95% confidence interval spanning $2 \cdot 10^{-5}$ yr^{-1} km^{-2} to $7 \cdot 10^{-5}$ yr^{-1} km^{-2}. The mean rate corresponds to about one M3.4 or larger event every 25,000 years in a given area of 1 km^2. This estimate does not account for the

[3] FEP 11.1.10 – Geological setting – Undetected features

distribution of hypocentral depths. Typically, event hypocentres are distributed evenly between 1 to 10 km depth, with fewer events at greater depth and no events are expected in the top 1 km (Proseis 2015). Here we do not introduce further assumptions on the depth distribution of seismicity in the repository footprint. However, it is plausible, that only a fraction of seismic events of M3.4 or smaller, and hence with rupture dimensions less than 400 m, that were to occur within the footprint of the repository, would actually reach the depth of the repository. Most events would have their rupture confined to the strata well below repository depth.

More importantly, this estimate also disregards the distribution of earthquake hosting faults. The repository will be placed in a zone that does not show signs of faulting. Because the nucleation of earthquakes is generally bound to faults, an absence of faults (above a certain size) implies that no earthquakes (above a commensurate size) can occur.

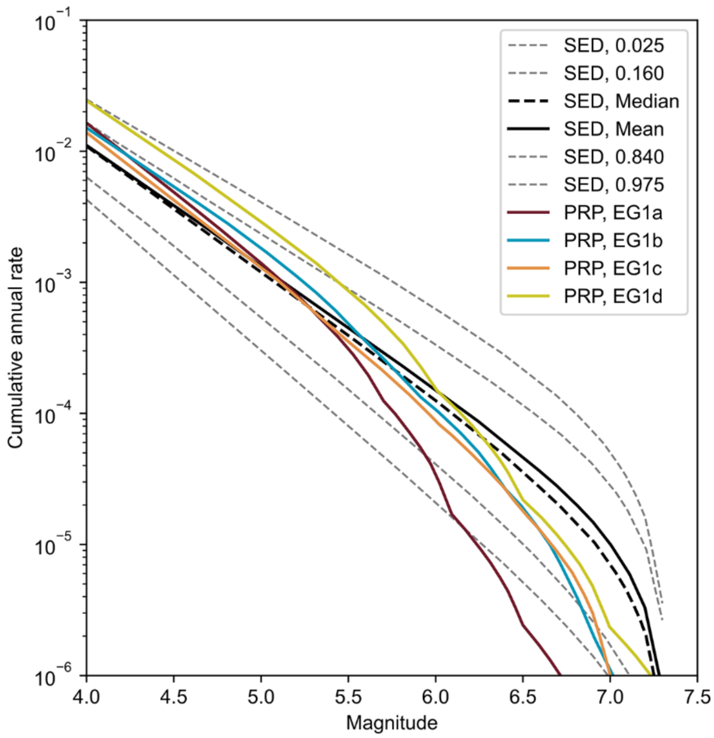

Fig. 3-4: Estimations of the (mean) annual rate of an earthquake above a given magnitude within a 25 km radius around the Beznau nuclear power plant (Proseis 2015)

The SED model (Wiemer et al. 2016) including the 95% confidence interval is shown next to the estimates obtained by four different expert groups of the PRP project (swissnuclear 2013).

3.4 Earthquakes in underground facilities

Most of the damage associated with earthquakes results from the seismic wavefield as it interacts with infrastructure. The impact of seismic waves on underground structures differs from the observed impacts at the surface. The impact of seismic waves on underground structures such as tunnels has been well studied. It is generally observed that underground structures bear less damage than above-surface structures, with less damage at greater depth (Pratt et al. 1978, Hashash et al. 2001).

Because the underground structure is contained in the surrounding rock, the response of a tunnel to shaking is dominated by the surrounding ground response rather than by the properties of the tunnel structure itself. Underground structures are unable to deform beyond the elastic response due to the passing waves. Those are on the order of kilopascals and thus much below the static loads from the surrounding rock. During the post-closure period the repository is backfilled further preventing any damage.

In addition, ground motions at depth are significantly smaller than at the surface. In the absence of site-specific data, ground motions at depth can be assumed to be a factor of approximately 2 smaller than ground motions at the surface. However, the specific conditions at the site and of the frequency content of the incoming wave determine the actual difference in amplification between a location at depth and the surface (Hallo et al. 2022). These relationships will be further investigated during preparation of a construction license. A seismometer installed at repository level in the Bülach-1 deep borehole (Spillmann et al. 2022) will be used to compare the response at the repository level with that at the surface. Preliminary observations at Bülach indicate that ground motions at repository depth are indeed about half of those at the surface (Fig. 3-5). The specific site response for the geological conditions at the repository site will be determined once sufficient data was collected and will be considered in the design of underground structures. We refer to Nagra (2024c) for additional discussion of the site amplification at depth.

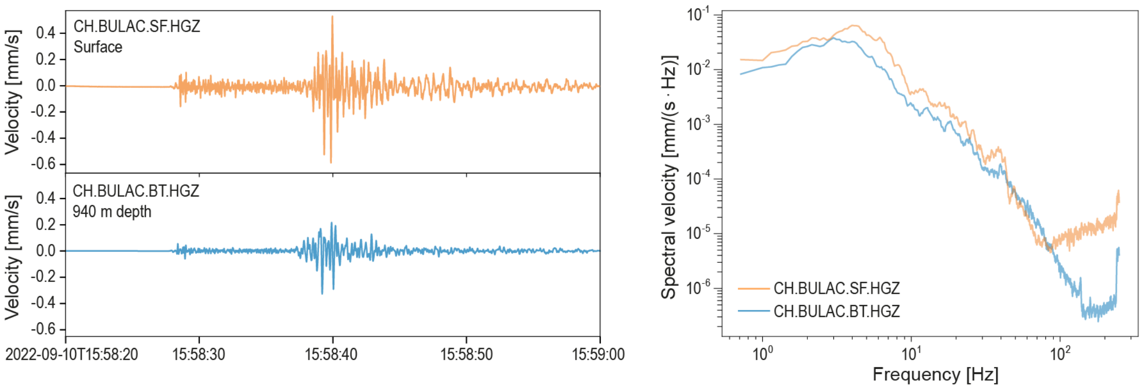

Fig. 3-5: Comparison of waveforms (bandpass 2-30 Hz) and smoothed S-wave spectra of the Mw4.7 earthquake near Mulhouse of September 10, 2022 recorded at the surface (BULAC.SF.HGZ) and at 940 m depth (BULAC.BT.HGZ) in the borehole Bülach-1

4 Geologic setting with respect to future seismicity

Understanding future strain localization is key to assessing the effects of active tectonics on the integrity of the barrier. The strain accumulation history observable within the rock volume of consideration is a product of the entire geological history. Most importantly, the strain localization history suggests a strong control on future strain localizations by precursory structures. Evidence demonstrating this is found on all observational scales, i.e., seismic mapping scale, outcrop scale, borehole-scale, and microscopic scale (Nagra 2024g). The phenomenon of strain localization along pre-existing structures is the rationale behind the characterization of present-day strain accumulation and the siting process, including the placement of underground structures.

The level of seismic activity in Northern Switzerland is low, which is typical for an intra-plate region where surface deformation is generally very low or absent[4] (Nagra 2024f). Earthquakes are caused by stresses and strain accumulation in the Earth's crust. Understanding the state of stress can help to identify which structures are critically stressed, such that small stress changes may be sufficient for activation, and which structures are oriented such that their future activation is less likely[5].

The current stress regime[6] and hence the pattern of seismic activity[7], is thought to be active since the cessation of folding of the Jura fold-and-thrust belt[8] (Nagra 2024f). This regime is overprinted by glacial cycles, that lead to changes of the stress field due to time-varying ice loads[9] on the surface and due to erosional processes (Nagra 2024f, Nagra 2024e). Together, these make up the source for potential transient changes to the tectonic stress field[10] relevant for the time period for assessment. Features active during these glacial cycles are contained in the geologic record and where already mapped or will be mapped during construction of any underground structures, respectively.

4.1 Inventory of faults at the site

The site is located tectonically between the Baden-Irchel-Herdern (BIH) Lineament in the south and the Weiach Flexure related to the Siglistorf Anticline in the north. These two regional fault zones are located above the boundary of the Constance-Frick Permo-Carboniferous through. The Constance-Frick Trough is characterised by a half-graben geometry with the main fault located in the south most probably underneath the BIH. The Permo-Carboniferous Trough and the related regional fault zones are a dominating tectonic feature in Northern Switzerland (Nagra 2024g). Both the Siglistorf Anticline and the BIH strike roughly ENE-WSW (Fig. 4-1).

The ENE-WSW-striking Weiach-Glattfelden-Eglisau Lineament (WGE) is a highly segmented nearly vertical fault is located south of the Siglistorf-Anticline. It forms the northern limit of a tectonically quiet area to the south (Fig. 4-1). Seismic interpretation indicates a basement rooting of the WGE. The Eglisau Fault and the Zweidlen Fault strike roughly NW-SE thus in a typical so

[4] FEP 14.1 – Geological processes and events – Regional vertical movements
FEP 14.2 – Geological processes and events – Regional horizontal movements

[5] FEP 14.18 – Geological processes and events – Fault reactivation and formation of new faults
FEP 11.1.7 – Geological setting – Local stress regime

[6] FEP 11.1.6 – Geological setting – Current regional stress regime

[7] FEP 14.8 – Geological processes and events – Seismic activity

[8] FEP 14.7 – Geological processes and events – Neotectonic activity

[9] FEP 15.2.4 – Climatic processes and events – Ice sheet effects (loading, melt water recharge)

[10] FEP 14.17 – Geological processes and events – Evolution of regional stress regime

called "Hercynian" orientation. The trace length of all aforementioned faults decreases upwards in the stratigraphic sequence.

The area in between the WGE and the BIH is free of seismically mappable faults, which makes it a suitable site for placement of a repository (Nagra 2024h). We refer to the interpretation of the 3D seismic survey in Nagra (2024h) for a detailed discussion of the resolved features and their structural relationships.

During the geological past, deformation has localised on existing local faults and regional fault zones, which acted as weak zones and have repeatedly been activated. It is expected that also during the next million years deformation will mainly localise in these (Nagra 2024f). The creation of new regional or local fault zones is regarded as very unlikely during the next million years and not further considered.

Earthquakes generally start at greater depth than the proposed repository depth. In fact, earthquake hazard models for Switzerland consider the top 1 km aseismic (Proseis 2015), i.e. no seismic rupture initiates at such shallow depth. Larger events, with rupture surface extents of several kilometres, have the potential to propagate a rupture to the surface or close to it. Such events need sufficiently large fault planes which can be reliably detected by seismic methods. The absence of such large faults in the proposed area of the repository lets us exclude the possibility of a large rupture through the repository zone.

There is a persistent centre of weak, shallow seismic activity near the town of Eglisau (Nagra 2024f). The seismic activity underneath Eglisau is located northeast of the WGE and possibly related to the Eglisau Fault, in a zone where smaller NW-SE trending faults abut against faults that run parallel to the Permo-Carboniferous trough. Specifically, the seismicity is located on several small structures which are distinct from the WGE (Nagra 2024f).

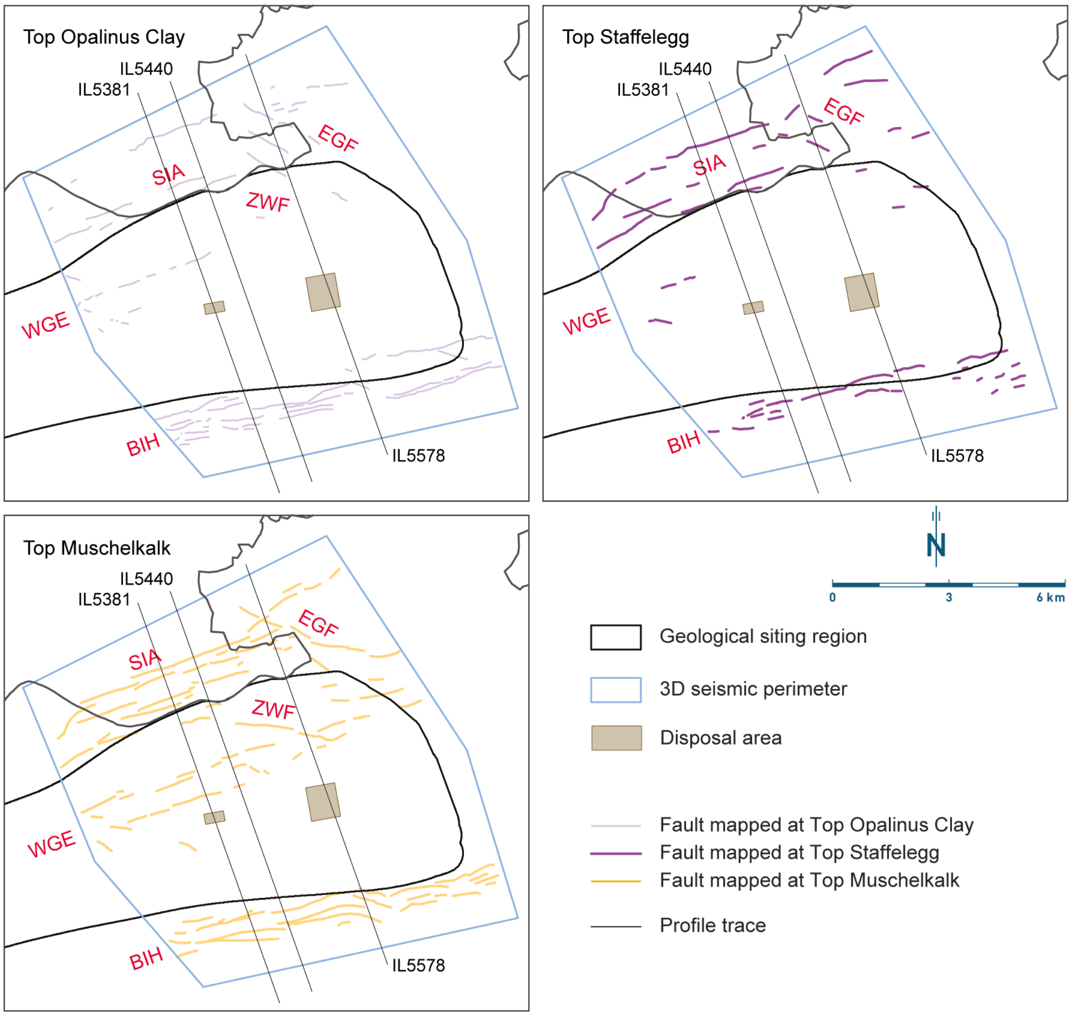

Fig. 4-1: Fault map on the levels Top Muschelkalk, Top Staffelegg, Top Opalinus Clay with the proposed disposal areas

Profile traces correspond to sections shown in Fig. 4-2. Disposal areas correspond to the provisional design of the repository.

Regional tectonic elements are the Siglistorf Anticline (SIA), the Weiach-Glattfelden-Eglisau Lineament (WGE), and the Baden-Irchel-Herdern Lineament (BIH). The Zweidlen (ZWF) and Eglisau (EGF) faults are considered local faults.

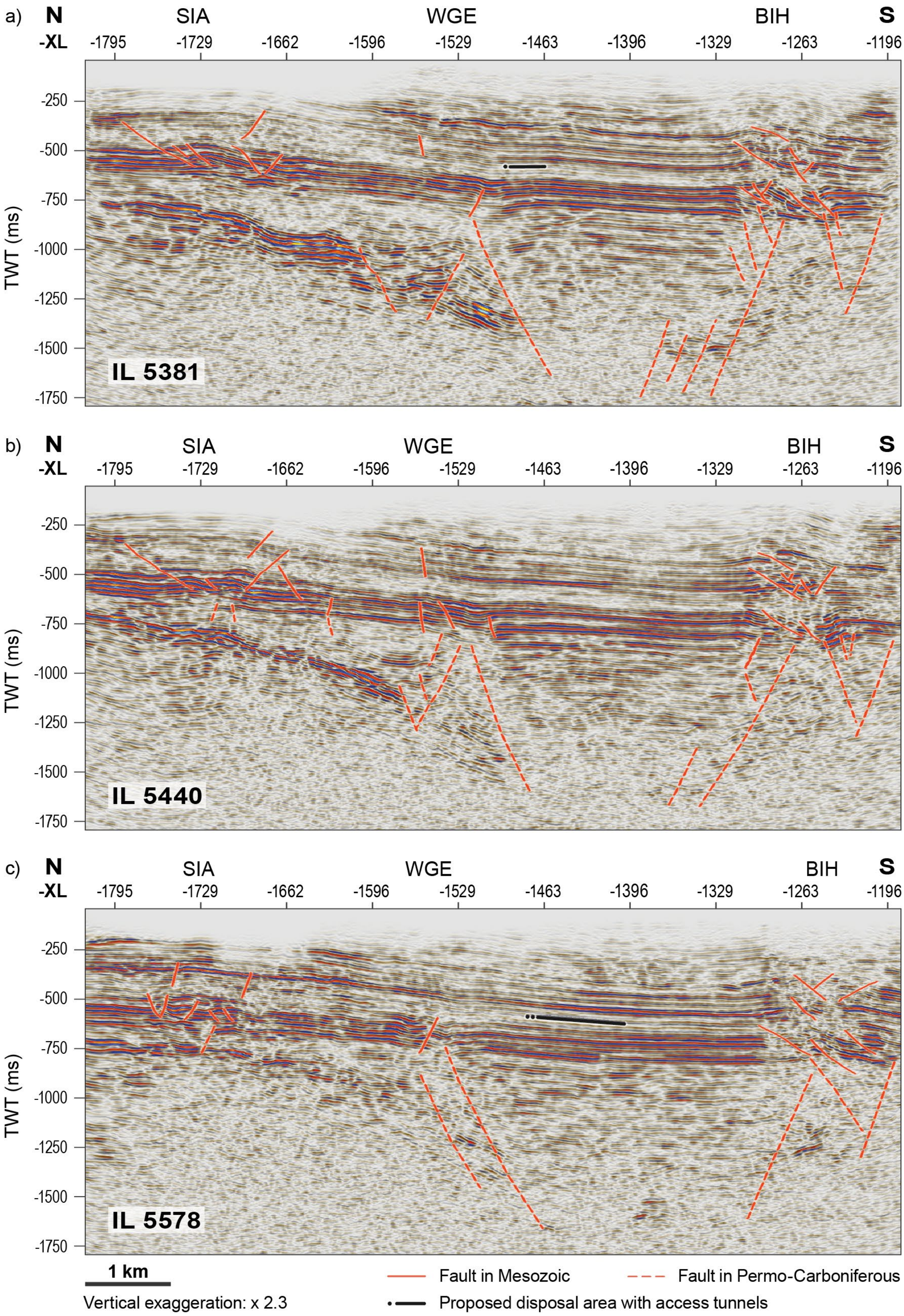

Fig. 4-2: Pre-STM-ref zero phase seismic in-lines through (a) the L/ILW disposal area, (b) the central access, (c) the HLW disposal area with fault interpretation in the Mesozoic and the Permo-Carboniferous deposits

4.2 Geomechanics and deformation processes in the host rock

Besides the placement of the repository and its structures in a zone free of seismically mappable faults, the host rock itself has important properties that contribute to stability towards tectonic processes and hence promote post-closure safety. The host rock properties with relation to earthquake processes are briefly discussed below. Further information on geomechanical properties and deformation behaviour can be found in Nagra (2024g).

Opalinus Clay is a relatively soft rock, with relatively low bulk and shear moduli compared to the more competent rocks in the underburden and the overburden. The stiffer and more competent units (e.g., Malm limestones) carry larger lateral tectonic stresses, and exhibit a more distinct brittle behaviour (Nagra 2024g). This limits the build-up of major differential stress in Opalinus Clay and explains that deformation expressed by fracturing primarily occurs in the more competent layers.

Another characteristic of the mechanically less competent Opalinus Clay and confining units is that brittle deformation is accommodated by strong segmentation, where individual segments are often not connected by a discrete structure ("soft linked"). This applies along fault strike but also in vertical direction across layers of different mechanical properties. For example, it is frequently observed that discrete displacements observed on seismic imaging in the overburden and/or underburden cannot be observed in the softer Opalinus Clay. Hence the localised deformation in the competent units transitions into a more distributed deformation in the softer Opalinus Clay (Nagra 2024g). This process impedes the formation of large, localised displacements[11] necessary for large-scale faults.

The favourable elastic and plastic properties of Opalinus Clay are complemented also by its frictional properties. Subjected to shear loads, the rock exhibits velocity-strengthening behaviour rather than velocity-weaking behaviour observed in typical seismogenic rocks (Nagra 2024g). This means that the sliding friction between the two sides of a discontinuity increases as the sliding velocity increases. This behaviour tends to lead to slow and distributed deformation rather than "catastrophic" failure in a fast, localised rupture (Orellana et al. 2018).

But even if fracture propagation and fault growth was to occur in Opalinus Clay, it has the capacity to self-seal (Nagra 2024g). Self-sealing means that potentially elevated hydraulic transmissivity associated to faulting will be reduced to such an extent that they have no significant impact on radionuclide transport through the rock.

4.3 Potential for induced seismicity

The phenomenon of human-induced seismicity has been observed in a wide array of settings that involve large-scale loading or unloading of the Earth surface (Grünthal 2014, Grigoli et al. 2017). Seismicity can accompany rock extraction or tunnel advancement (Husen et al. 2012) but can also occur from fluid injection (Schoenball & Ellsworth 2017) or from changes to surface loads, such as reservoir impoundment (Talwani 1997). Mining-related seismicity has been observed on all scales and is strongly dependent on the setting of a mine and industrial operations applied (Grünthal 2014).

Induced seismicity generally occurs in response to changes of subsurface stresses (Grigoli et al. 2017). Empirically stress changes necessary to induce seismicity vary widely. Based on the concept of a critically stressed crust, there are faults close to failure for which minor stress perturbations are sufficient to trigger a seismic event. Accordingly, seismicity has been reported through induced stress changes less than 100 kPa (Barbour et al. 2017) at hypocentral depth.

[11] FEP 11.1.8 – Regional fault zones

However, a smaller footprint of the pressure perturbation also reduces the likelihood of triggering a critically stressed fault.

Related to the DGR, induced seismicity may occur as a result of perturbed effective stresses due to (a) the excavation process or (b) other forcing produced by repository-induced effects such as the heating or gas production by the emplaced waste packages[12]. Mining-related seismicity would be related to construction activities only. A conservative assessment of the potential for mining-related seismicity was performed by Rinaldi & Urpi (2020). Their study suggests no relevant potential for mining-related seismicity, with maximum moment magnitudes less than -1.

4.3.1 Potential for induced seismicity caused by repository-induced effects

Changes to the effective stress around the DGR are related to the increased temperature for heat producing SF/HLW and the generation of gas, particularly by the L/ILW. Both, the rock matrix and the pore fluid expand in response to heating. The expansion of the rock matrix gives rise to an instantaneous change of total stress in the vicinity of the heated rock (thermo-mechanical response). The pore fluid has a larger coefficient of volumetric expansion than the rock skeleton. The thermal expansion of the pore fluid leads to a transient increase of porewater pressure[13], corresponding to a reduction of effective stress in the host rock (thermo-hydraulic response). The dissipation of porewater overpressure is controlled by the hydraulic diffusivity of the rock, resulting in a delayed propagation of the thermo-hydraulic perturbation.

Gas production adds to the pore pressure and changes the effective stresses analogously[14]. However, spatially the gas pressure is much more confined to the actual structures of the repository, whereas the thermal pulse extends beyond. Pressure from gas production is significant only after the thermal pressure pulse has largely dissipated. The two processes do not overlap in time (Nagra 2024i). Design measures will be taken to limit the gas pressure and to ensure that no loss of mechanical integrity of the engineered or geologic barriers will occur in the post-closure period (Nagra 2024o).

The choice of a very low permeable host rock for the DGR entails pressure built-up due to repository-induced effects. It is conceivable that thermal loading could change the subsurface stresses such that faults in the vicinity of the repository get activated by these thermally moderated stress changes (Urpi et al. 2019). Thermal heating is a rather slow process, and the thermal perturbation will propagate to significant distance only several decades after waste emplacement. Likewise, the stress perturbations from thermal pressurisation travels slowly, but potentially reaching on the order of a kilometre away laterally from the emplacement drifts after several hundred years. The spacing of waste emplacement rooms and waste packages will be chosen such that changes of the state of stress in the CRZ due to repository-induced effects is limited.

Because the permeability in the rock units below the host rock, particularly the Muschelkalk aquifer, is high, any thermally-induced pore pressure changes are dissipated. The hydraulically permeable formations effectively decouple the potentially seismogenic deep sedimentary and crystalline units from the repository-induced effects. This mitigates the potential for thermally induced seismicity in these formations.

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[12] FEP 2.2.4 – Common FEPs – Pore pressure
FEP 13.3.4 – Repository-induced effects – Induced seismicity

[13] FEP 13.3.3 – Repository-induced effects – Thermally-induced pore pressure increase

[14] FEP 13.3.5 - Repository-induced effects – Gas-induced pore pressure increase
FEP 13.3.6 – Repository-induced effects – Pore-pressure-induced stress changes, fracturing and fault re-activation

With adequate characterisation of relevant structures during the excavation of the repository and its emplacement rooms, induced seismicity can be adequately managed and its impact on post-closure safety mitigated.

Conclusion

Induced seismicity can arise in nearby faults due to the thermal load and thermo-hydro-mechanical coupling. Thermal stresses are decoupled by the aquifers and do not reach greater depth where larger and potentially unknown faults could get activated. The rock mechanical behaviour of Opalinus Clay does not favour seismic rupture, and thus critical stress changes are expected to be released by distributed aseismic deformation. Self-sealing properties will ensure that the hydraulic barrier will remain intact. The impact of induced seismicity on post-closure safety can be mitigated by adherence to appropriate respect distances.

4.3.2 Potential for induced seismicity unrelated to the repository

Induced seismicity may occur also from other activities independent of the repository. For example, future human actions (Nagra 2024k) that involve injection or production of fluids for extraction of geothermal heat, extraction of hydrocarbons, and underground storage of gas may cause seismicity[15].

For aspects of post-closure safety, we would be concerned about tectonic structures that could be reactivated through these processes. In this report, we treat all seismically mapped fault zones as potential sources of seismicity. Hence, potential induced seismicity from activity unrelated to the repository is implicitly included in the treatment of natural seismicity.

Conclusion

Induced seismicity from processes unrelated to the repository cannot be excluded. However, their impact is implicitly included in the natural seismicity assessment, thus no specific further considerations are required.

[15] FEP 17.2.2 – Future human actions – Geothermal exploitation
FEP 17.3.2 – Future human actions – Liquid waste and gas injection

5 Geological scenarios for future earthquake activity

The repository site is located in one of the seismically quietest regions in Switzerland with a relatively low seismic hazard rating. Discontinuities that potentially could host earthquakes were in the centre of attention during the evaluation of the 3D seismic survey conducted at the site, but none could be identified on seismic scale.

In this section, we describe and qualitatively evaluate the potential effects of earthquake ruptures on the safety of the DGR based on a range of geological scenarios (Fig. 5-1). These are developed under consideration of potential earthquake sources and potential vulnerabilities of the repository. We begin with earthquakes in the regional context that sends wavetrains through the repository (Section 5.1). We continue with hypothetical earthquake sources close to the repository (Section 5.2), and in specific sections of the repository (Sections 5.3 and 5.4). Significant differences between the L/ILW and HLW repository parts exist in terms of their temporal evolution, e.g., gas pressure and temperature, and their engineered barrier system. Hence, independent geological scenarios are developed for each repository part.

To derive geological scenarios based on the size and distance of the earthquake rupture to structures of the repository we define an "influenced zone". This zone is defined by the rupture plane and with a margin of one rupture length in all directions. This definition of the influenced zone is conservative and roughly coincides with the zone in which aftershocks are triggered by static stress changes (Richards-Dinger et al. 2010). The influenced zone also fully contains the zone where secondary rupture, i.e., co-seismic activation of lesser faults during the rupture of the main fault, may occur (Petersen et al. 2011). Some examples of hypothetical scenario events are drawn in Fig. 5-1 to illustrate this concept.

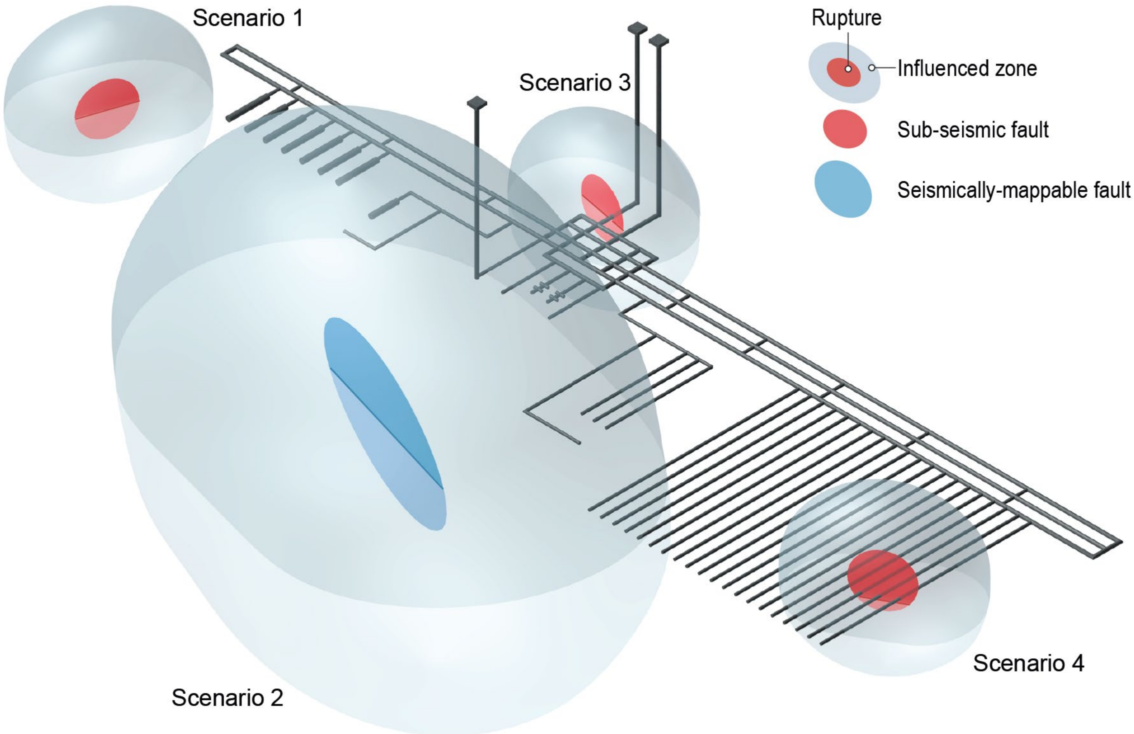

Fig. 5-1: Schematic definition of the geologic scenarios discussed, defined by the size of their rupture planes and influenced zones and given their position relative to repository structures (schematic, not to scale)

Seismically mappable faults are assumed to be known, while sub-seismic faults are currently not known. Scenario 3 would be a rupture on a sub-seismic fault in the L/ILW repository and its gas storage system, while Scenario 4 describes a rupture on a sub-seismic fault in the HLW repository.

For each of the following geological scenarios, we are giving a phenomenological description of the processes with potential relevance for post-closure safety. Then, there is a section each for all FEPs that are relevant to the respective scenario followed by a section that specifically lists the involved key attributes & component-specific safety functions, according to Nagra (2024b). The quantitative assessment of any radiologic consequences of the developed geological scenarios will be conducted within the performance assessment workflow (Nagra 2024o).

5.1 Scenario 1: Seismic shaking from far-field earthquakes

Scenario 1 is a regional or remote earthquake that sends seismic waves through the repository. Here we consider events that occur more than about one fault length away from repository structures to be in the far-field (Fig. 5-1). An example of such an event would be the M6.7 Basel earthquake of 1356. The return period of the Basel earthquake has been estimated to be on the order of 2000 years (Meghraoui et al. 2001). It is reasonable to assume that such events will occur relatively frequently during the post-closure period and this scenario is considered part of the expected repository evolution.

Most of the damage that is caused by earthquakes in general is produced by the seismic waves. In response to the seismic wavetrains, buildings are sheared and brought to failure. In the underground, and more so in back-filled tunnels and waste emplacement rooms, the elements of the engineered barrier system are locked in place by the backfill, unable to be sheared significantly and hence unable to be brought to failure by passing seismic wave trains (Section 3.4). The dynamic stresses of earthquake waves are on the order of kilopascals (Brodsky & van der Elst 2014), thus on a similar order as are the solid earth tides, and not significant for the structural integrity of building materials or components of the engineered barrier system. Further, seismic shaking is strongly reduced in the subsurface relative to the surface. Nonetheless, possible FEPs that need to be considered are the potential for liquefaction and changes to water conducting features in the CRZ. They are subsequently discussed.

Liquefaction

Liquefaction is ground failure that can be observed in unconsolidated sandy soils. The seismic waves lead to a compaction of the unconsolidated components of the ground which squeezes water out of the pores and leading to liquefying of the soil. Building supports such as foundations may lose its integrity which may lead to severe destruction.

Liquefaction occurs in unconsolidated sediments (silts and sands) that easily compact during seismic shaking. Liquefaction is not observed in clayey sediments, as the clays strongly reduce permeability, inhibiting seismic compaction as well as provide cohesion to the rock or soil (Youd 2003). Further, liquefaction can only occur under fully saturated conditions. Because the backfill, the seals and the engineered barrier system for the HLW repository is made up primarily of swellable clay materials, liquefaction can be excluded as a phenomenon of concern for the HLW repository (Pusch 2000). The cementitious materials employed in the L/ILW repository are not subject to liquefaction.

Changes to aquifers

It is commonly observed that large earthquakes are followed by changes of the ground water system. Among the more common observations are:

- Changes to the water level in wells (transient and static),
- Changes to the discharge rate of ground water sources and
- Changes to the tidal response of ground water wells.

Many of these observations were made at significant distance to the rupture. The nature of these hydrological changes is not fully understood. For example, a change in stream discharge must either be associated to a change in permeability along the flowpath, a change in hydraulic gradient or both (Wang & Manga 2010). Potential processes and models to invoke these are, e.g.:

- Static elastic strains in the crust caused by earthquakes and subsequent dilation or contraction of cracks,
- Enhanced permeability produced by seismically induced fractures and
- Undrained consolidation and liquefaction.

The observed changes relate to the shallow ground water system and aquifers. The Opalinus Clay, however, will provide sufficient hydraulic separation from such aquifers and from high hydraulic transmissivity features which may be affected by temporary changes of permeability. The profiles of natural tracers in the porewater indicate long-term stable hydrochemical boundary conditions. That is, such changes did not occur or were too short lived to be resolvable with these profiles (Nagra 2024g). Finally, all of these effects are observed only during a short period (days to months) following such large earthquakes. Since large earthquakes are rare at the site, with inter-event times of hundreds of years or more, such short-lived changes are unlikely to affect post-closure safety.

Features, Events, Processes

The effects of a Scenario 1 event may have minor influence on the regional hydraulic system[16]. But such effects are usually short-lived and do not impact the barrier function of the CRZ. Liquefaction generally is a potential impact of geological events[17] but will not occur in the overconsolidated host rock or in the repository backfill due to high clay content and partial saturation over long periods.

Key attributes & component-specific safety functions

No key attributes or component-specific safety functions are influenced by a Scenario 1 event.

Conclusion

As part of the safety concept, the repository will be backfilled. Structures are confined within the formation and differential shearing is very limited in its potential to cause structural damage. The effect of the shaking is that of the solid stresses of the passing waves which are typically on the order of kilopascals only. Hence, the shaking by regional earthquakes is not expected to lead to damage of the engineered barrier system. Although occurring many times within the time period for assessment, the shaking from regional or further away earthquakes is not expected to impact post-closure safety.

5.2 Scenario 2: Rupture with the influenced zone in the repository footprint

Scenario 2 is a rupture where the influenced zone overlaps with structures of the repository, but the main rupture does not go through any structures. A Scenario 2 event could, e.g., be a hypothetical M6 or larger event on the WGE or a smaller event on a sub-seismic fault within the general footprint of the future DGR but not cross-cutting any tunnels. The locations and throws of large faults in the sedimentary column are very well known at the site. Hence, we do not assume that a rupture of several kilometres size could form in the footprint of the repository where no faults were imaged by the 3D seismics. As of today, there has been no recorded earthquake in the seismic catalogue (Fig. 3-3) that would correspond to Scenario 2 or any of the other scenarios described below, based on the proposed location and layout of the repository (Nagra 2024a).

The possible impacts on post-closure safety for hypothetical large events are discussed using two constructed scenarios, based on a hypothetical large joint rupture of the WGE and associated faults. The WGE is a regional fault zone and may be associated with the northern bounding fault of the Constance-Frick Permo-Carboniferous trough (Fig. 4-1). The approximately 9-km-long WGE is broken up into segments no longer than about 2 km in the region of interest.

Two specific scenarios are considered, corresponding to the source descriptions of the PEGASOS project (Nagra 2004) and PRP (swissnuclear 2013). The issue of the largest possible earthquake in each source zone was discussed by different expert groups. The problem of assessing the magnitude of the largest possible event M_{max} is an important component of probabilistic seismic hazard assessments. In PRP the expert groups used distributions for the description of M_{max} in each source zone. There is uncertainty as to whether to consider the bounding faults of the Permo-Carboniferous trough as inactive and hence unable to be reactivated or whether the bounding faults have to be considered active and could be an earthquake source.

[16] FEP 11.2.2 – Geological setting – Effective hydraulic properties

[17] FEP 10.2.10 – Access structures and sealing system – Impact of geological events and processes

Note that the scenarios discussed below are constructed scenarios and do not necessarily reflect a formally determined assessment of the existing structures to produce large earthquakes, including the size of the source faults and their status as active or inactive. The scenarios rather serve to illustrate the potential effects of a large earthquake close to the repository. We consider the scenarios to fully cover the range of possible impact of potential events on the post-closure safety of the DGR.

Specific scenario: Large earthquake on the Weiach-Glattfelden-Eglisau lineament

For the first scenario, we assume a hypothetical M6 earthquake with a rupture patch of 9 km length and an average displacement of 0.5 m (based on scaling relationships, see Section 3.1). This would mean, that all known segments of the WGE rupture jointly in a single event. It is assumed that longer faults bounding the Permo-Carboniferous trough, east and west of the WGE, do not participate in the rupture.

Even though the fault is steeply dipping, a reverse mechanism would be expected in the current stress field (Nagra 2024n). Slip would be assumed maximum somewhere in the centre along the rupture patch and taper off to the edges. The rupture is assumed here to extend through the Malm and Muschelkalk deep aquifers. A disturbance of the regional aquifer systems such as changes to hydraulic heads and groundwater composition in the aquifers could occur. If both aquifers are displaced, then so would be the Opalinus Clay. However, because of soft linkage behaviour (Section 4.2), deformation would be most likely in a distributed fashion, similarly as described in Roche et al. (2020).

It is to be expected that not all deformation would occur along the main strand of the fault. Secondary displacement, or distributed displacement, on smaller faults must be expected. The width of the zone where such distributed displacement can occur is on the order of a kilometre, but only at very few locations would distributed displacement actually develop (Petersen et al. 2011). The magnitude of displacement would typically be 2 to 3 orders of magnitude smaller than on the main rupture surface (Petersen et al. 2011). Such a displacement is consistent with that determined for presently unknown faults (Section 3.3.1). Further, also this distributed displacement is expected to localize on zones of weakness, i.e., pre-existing features, as suggested by empirical evidence (Thompson Jobe et al. 2020). The undeformed block to the south of the WGE, that is proposed to contain the repository zone, is assumed to remain largely intact. We assume that no new faults and fractures would be created that are not already present in the rock. The rare case where such distributed displacements goes through structures of the repository is contained in Scenarios 3 and 4 for the L/ILW and HLW repositories, respectively.

Static stress changes will occur in the rock adjacent to the rupture plane due to the unloading of the rupture surface and the accumulated slip. They decrease quickly in amplitude as ~r^2 (Okada 1992). In addition, due to the low shear modulus of the OPA, the static stress changes at repository level are expected to be much lower than in the stiffer load-bearing formations above and below.

A freshly ruptured fault is thought to bear a certain transmissivity that follows from the displacement of two matching rough surfaces. Experimental evidence from experiments performed in the Mont Terri Underground Research Laboratory suggest that self-sealing of small displacement occurs on the timescale of months to years (Bock et al. 2010, Nagra 2024g). But also for very large displacements in excess of 1 m, self-sealing is a relatively quick process as shown for the M7.9 Wenchuan earthquake (Xue et al. 2013). This is in accordance with other observations related to the hydrogeologic system following earthquakes, described in Scenario 1.

Scenario for a M_{max} event on the bounding fault of the Permo-Carboniferous trough

The interpreted 3D seismic survey suggests some degree of structural control of the bounding fault of the Permo-Carboniferous trough on the segments of the WGE (Nagra 2024h). Thus, for the absolute endmember case of conceivable seismicity, we assume here that a M_{max} event starting on the bounding fault of the Permo-Carboniferous trough would continue onto the WGE.

For the scenario, we assume a hypothetical M7.5 earthquake with a rupture patch of 100 km length and an average displacement of 1 m (based on scaling relationships, see section 3.1), but average displacement could reach up to 5 m for a high stress drop event of smaller extent. A similar metre-scale displacement would be expected also through the host rock on the WGE adjacent to the repository.

The relevant processes do not change compared to the previous M6 scenario. Distributed displacements of up to several centimetres could occur in the repository zone (Petersen et al. 2011), as described in the previous scenario, and is expected to localize on zones of weakness, i.e., pre-existing features. The displacements there would still be bound by the dimensions of the inventory of features. Thus, distributed displacements are still in the range of displacements assumed for currently unknown features (Section 3.3.1). However, given the well-imaged potential repository zone, we exclude the possibility that a rupture with metre-scale displacements would run through the repository.

We refer to Scenarios 3 and 4 for the L/ILW and HLW repositories, respectively, for the potential impacts on key attributes and component-specific safety functions perturbed by such distributed displacement.

Features, Events, Processes

The effects of a Scenario 2 event would affect the CRZ surrounding the repository, laterally and vertically. This area could be affected by increases of permeability, and thus a reduction of the performance of the CRZ[18]. Ruptures through the Opalinus Clay, but outside of the footprint of the repository, and in the clay-rich CRZ would be expected to self-seal within months to a few years (Nagra 2024g)[19]. Elevated temperature (to the degree expected to occur due to repository-induced effects) does not impact self-sealing capacity. However, a temporarily elevated transmissivity must be expected for the features involved.

Key attributes & component-specific safety functions

The only repository component partially affected by a Scenario 2 event would be the CRZ. The relevant key attributes pertain to the hydraulic properties with transmissivity of the rupturing fault enhanced, leading to an overall increased permeability after an event. The range of distributed displacements to be expected through components of the repository is handled by Scenarios 3 and 4, respectively.

[18] FEP 2.4.2 – Common FEPs – Radionuclide migration pathways and processes
FEP 11.2.2 – Geologic Setting – Effective hydraulic properties
FEP 11.3.1 – Geologic Setting – Radionuclide migration processes and pathways
FEP 12.3.1 – Containment-providing rock zone – Radionuclide migration processes and pathways

[19] FEP 14.9 – Geological processes and events – Self-sealing

Conclusion

The creation of fluid pathways along reactivated rupture surfaces through the CRZ are of potential relevance with respect to post-closure safety and will therefore be considered by performance assessment. However, ruptures through the OPA host rock would self-seal in a relatively short time frame. This agrees with the lack of indications in the profiles of the natural tracers (Nagra 2024g) that long-lived perturbations of the hydraulic system would leave behind. Instead, the tracer profiles indicate that such processes did not take place or were too short-lived to be resolved. Hence, a lasting impact through temporary increases of transmissivity of geological features seems unlikely. The concomitant stress changes due to displacements in the CRZ or other rock units do not pose a problem to the structures of the repository, since they are small in comparison to the static stresses due to the underground location.

5.3 Scenario 3: Rupture through elements of the L/ILW repository

Scenario 3 is a rupture through parts of the L/ILW repository and its gas sealing system. Besides the L/ILW main and pilot repositories, this also includes the central area, as well as parts of the HLW access tunnels and the HLW observation drift (cf. Fig. 5-2). All these structures provide gas storage volume and ruptures through any of these would have comparable effects. The main hazard from this scenario lies in the potential release of gas that contains ^{14}C. A rupture directly through the L/ILW packages would not be of significantly greater impact than through other parts of the gas sealing system.

The potential impact of a rupture through the L/ILW repository sealing system depends on the time of occurrence during the post-closure phase. During the early post-closure phase gas pressure is slowly rising, starting with atmospheric initial conditions at the time of repository closure. The backfilled repository structures remain partially saturated over long periods, only the shaft seals will saturate quickly due to the ingress of groundwater from the Malm aquifer. Gas pressure stays below hydrostatic pressure until after several thousand years. A rupture caused in that early period would be entailed by an enhanced saturation of repository structures, associated with relatively quick self-sealing of the activated fault (Nagra 2024i).

After several thousand years, gas pressure may increase to levels greater than hydrostatic. If a rupture through the gas sealing system was to occur then, gas could leak out until the gas overpressure in the repository structures have dissipated. A quasi steady-state gas flow develops, which is controlled by the gas generation rate in the repository structures. Self-sealing would occur only once the gas production ceases. After several tens of thousands of years, the ^{14}C has largely decayed, and a hypothetical Scenario 3 event would be of ever diminishing radiologic impact.

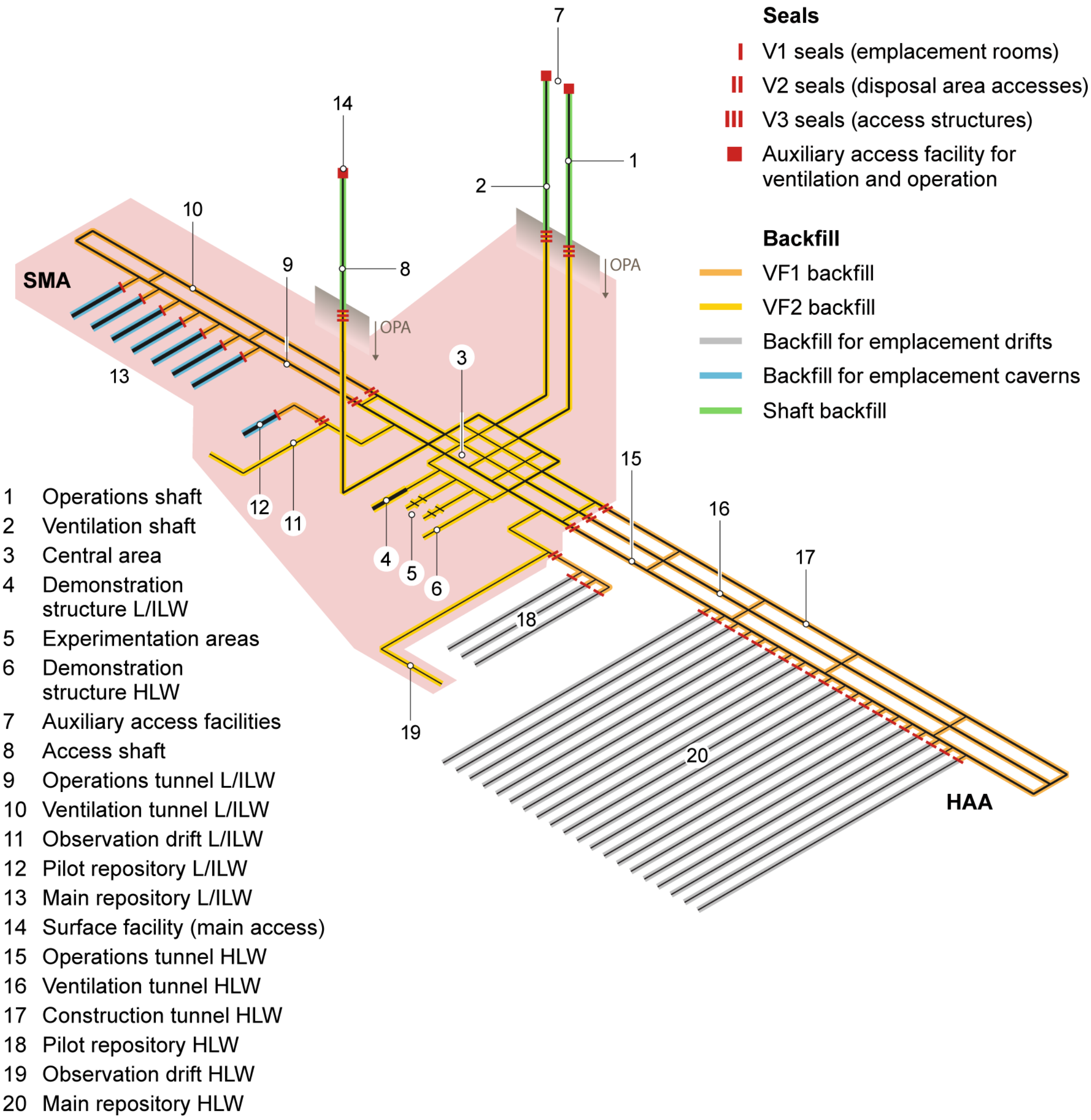

Fig. 5-2: The provisional schematic layout of the designed combined repository with the gas sealing system of the L/ILW repository, for which Scenario 3 would apply, highlighted by red shading

Features, Events, Processes

In addition to FEPs perturbed by a Scenario 2 event, a Scenario 3 event may impact several FEPs relevant to the L/ILW waste and packages, L/ILW cavern backfill and liner as well as access structures.

Earthquakes may lead to the formation of radionuclide pathways in parts of the L/ILW sealing system where a rupture was to occur. This may include the waste packages, cavern backfill and liner as well as the access structures and the sealing section[20]. Depending on the timing of such an event, elevated gas pressure may inhibit self-sealing of fractures in backfill and CRZ if the gas pressure is above the hydrostatic pressure.

Key attributes & component-specific safety functions

The component-specific safety functions of the waste packages, the L/ILW backfill and liner do not concern hydraulic conductivity and are not significantly perturbed by a Scenario 3 event. Therefore, the only components affected by a Scenario 3 event would be the sealing sections and the CRZ. The latter would be similarly affected as due to a Scenario 2 event. However, in a Scenario 3 event, the perturbation of the CRZ continues into the repository structures, potentially providing a direct hydraulic shortcut from the repository system to the CRZ and potentially beyond.

Conclusion

It is unlikely that an earthquake occurs along an existing feature that intersects the host rock and ruptures to the edge of the CRZ. For the highly unlikely case where such a rupture would occur at a time when the ^{14}C inventory is still high, the performance of the barrier integrity and safety of the repository system need to be evaluated in safety assessment.

5.4 Scenario 4: Rupture through elements of the HLW repository

Scenario 4 considers a hypothetical rupture through the HLW repository, including emplacement drifts and waste packages. A rupture through the HLW pilot repository would be of similar impact as one through the HLW main repository. However, the amount of stored waste in the pilot repository is smaller and therefore, this scenario is not treated separately.

With the current status of knowledge from the 3D seismic survey, we have no evidence for features that could produce a displacement in excess of 0.05 m (Section 3.3.1). If an event produces a displacement larger than about 0.05 m (Jonsson et al. 2018) which intersects a HLW canister or an event occurs at a time when extensive corrosion sufficiently reduced the wall thickness, the disposal canister may not perform its safety function, i.e. complete containment. It should be noted that the processes in safety assessment only take credit of this safety function for the first 10,000 years of post-closure phase, although the canisters are expected to last a longer period. However, the retention function of the surrounding granular bentonite material would be largely intact. Given the known absence of seismically mappable faults in the HLW disposal area and the continued effort to characterise the host rock during construction, a scenario where displacements in excess of 0.05 m are generated appears very unlikely. This includes possible distributed displacement from a Scenario 2 event. The following discussion therefore serves to check the robustness of the repository system and provide a complete set of conceivable scenarios.

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[20] FEP 2.4.2 – Common FEPs – Radionuclide migration pathways and processes
FEP 6.2.12 – L/ILW waste and packages – Impact of geological events and processes
FEP 6.3.4 – L/ILW waste and packages – Radionuclide migration and pathways
FEP 9.2.12 – L/ILW cavern backfill and liner – Impact of geological events and processes
FEP 9.3.1 – L/ILW cavern backfill and liner - Radionuclide migration and pathways
FEP 10.2.10 – Access structures and sealing system – Impact of geological events and processes
FEP 10.3.1 – Access structures and sealing system – Radionuclide migration processes and pathways

We can broadly divide the evolution of the HLW repository into three phases with respect to the likely impact of a Scenario 4 event. The thermal phase starts with emplacement and lasts several thousand years (Nagra 2024i). During that period a thermally-induced pore pressure pulse propagates outward from the waste emplacement room into the host rock. The backfill has high suction and resaturates after several hundred years. Corrosion gases are being produced but do not contribute significantly to gas pressure.

After about 1,000 years the thermal effect declines, and the produced corrosion gas begins to dominate the repository-induced pressure perturbation. Safety assessment conservatively assumes that all canisters breach at 10,000 years, leading to a peak in gas pressure (Nagra 2024i). This phase lasts several 10,000 years after repository closure. Gas pressures may reach above hydrostatic where it could inhibit self-sealing initially (Nagra 2024i). During this unsaturated phase the enhanced transmissivity of the rupture could lead to gas release until the gas over-pressures cease. Because the later stage gas generation in the HLW repository is low, there would not be sufficient gas accumulated as a free gas phase to maintain significant gas-induced overpressure. The pressure in the ruptured feature with high transmissivity would decline quickly and allow self-sealing to occur. After the gas-induced overpressure has declined, resaturation and self-sealing will take effect in the activated feature.

In the late post-closure phase gas pressure declines and self-sealing capacity is no longer impacted. Any transmissivity created by a Scenario 4 event would thus self-seal within a short time and limit the release of radionuclides.

Features, Events, Processes

In addition to FEPs perturbed by a Scenario 2 event, a Scenario 4 event may impact several FEPs relevant to the HLW canisters and HLW emplacement drift, buffer, and liner. Earthquakes may lead to the formation of new radionuclide pathways in parts of the HLW emplacement drifts, buffer, and liner[21]. The bentonite backfill does have self-sealing capacity and may act as a compliant mechanical buffer between the host rock and the waste canisters[22]. In case the rupture goes through waste canisters, they may breach early[23] if sufficient displacement is reached.

Key attributes & component-specific safety functions

A Scenario 4 event will have impacts on the CRZ, similar to a Scenario 3 event, i.e., the perturbation of the CRZ continues into the repository structures. In addition, the component-specific safety functions of the HLW buffer material would be affected. In the extreme case of a rupture through a waste canister, their component-specific safety functions, specifically the complete containment, may be impacted, if the accumulated displacement leads to early canister breaching.

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[21] FEP 2.4.2 – Common FEPs – Radionuclide migration pathways and processes
FEP 7.2.13 – HLW canister – Impact of geological events and processes
FEP 7.3.1 – HLW canister – Radionuclide migration and pathways
FEP 8.2.15 – HLW emplacement drift, buffer and liner – Impact of geological events and processes
FEP 8.3.1 – HLW emplacement drift, buffer and liner – Radionuclide migration and pathways

[22] FEP 8.1.3 - HLW emplacement drift, buffer and liner - Bentonite plasticity and self-sealing

[23] FEP 7.2.8 – HLW canister – Canister breaching

Conclusion

Given the measures made to verify the suitability of the host rock and the emplacement position, it is very unlikely that a rupture through the HLW repository occurs that would have significant consequences, such as early canister breaching. Even if such an event were to occur, the impacts would generally be limited through the self-sealing capacity of the backfill and the host rock. The retention capacity of the host rock would not be affected significantly by a rupture. Scenario 4 will be propagated to post-closure safety assessment.

To mitigate a Scenario 4 event, the HLW repository will be placed in a zone without seismically mappable faults. Should it be deemed necessary, a suitable respect distance to known features will be maintained, and thus potential radiologic consequences avoided.

6 Conclusions

In this report, we develop geological scenarios related to the occurrence of seismic events as a basis for evaluation of performance and of possible consequences to post-closure safety.

A robust knowledge base, consisting of an in-depth understanding of the geological history of the site and the host rock has been established (Nagra 2024g). In addition, prior work on the quantification of seismic hazards for nuclear power plants in Switzerland, conducted in the framework of the PEGASOS and PRP projects, as well as complementary work on the national seismic hazard models (Wiemer et al. 2016) are considered state-of-the-art. Still, the recorded history of seismicity does only provide a shot snapshot and cannot be extrapolated towards the time period for assessment. Hence, instead of relying on a probabilistic seismic hazard assessment, we have developed geologic scenarios that are evaluated for possible impacts on key attributes and on component-specific safety functions.

Because earthquakes occur on faults, the most important means towards mitigation of seismic impacts to post-closure safety lies in the site selection and the placement of any relevant repository structures inside the host rock and away from known faults. To that end, 3D seismic images have been acquired and carefully analysed to identify faults (Nagra 2024h). Repository structures will be placed such, that no relevant seismic events can occur in critical locations.

Further, we can rely on the Opalinus Clay host rock as a robust geological barrier. Its geomechanical properties reduce the impact of earthquake processes: i) the mechanical layering between more competent formations attenuates tectonic loading effects in the softer Opalinus Clay, and favours more distributed and segmented deformation; ii) seismic slip is hindered by velocity-strengthening frictional properties; and iii) the high self-sealing potential will reduce any created hydraulic transmissivity of faults such that they have no lasting impact on radionuclide transport through the host rock.

Despite the evidence that the repository will be placed in a zone without seismically mapped faults, a range of geological scenarios were developed and relevant processes that could influence post-closure safety were discussed. The developed scenarios investigate effects of earthquake sources in a range of distances from the repository or through parts of the repository. To ensure completeness in the evaluation of the developed scenarios a FEP audit methodology was followed. In none of the developed scenarios shaking from earthquakes was identified to pose a threat to post-closure safety. However, if a rupture was to occur very close to the repository or even go through repository structures, damage to the CRZ, repository structures or even to the waste packages could occur. Based on the seismic images currently available, we can exclude pre-existing faults that could produce earthquakes larger than about M3.4 or displacements in excess of 0.05 m through repository structures.

The present report supplements the assessment basis by providing the evidence and knowledge relevant to seismic events. The geological scenarios related to the occurrence of seismic events which are potentially relevant for long-term safety are further assessed in the safety assessment workflow (Nagra 2024m).

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App. A Features, events, and processes relevant for earthquake processes

To ensure that possible effects of earthquakes on the repository (and vice versa) and hence post-closure safety are covered by this report, the list of FEPs provided in (Nagra 2024i) was checked based on expert judgement. FEPs that are directly influenced by the occurrence of earthquakes or shaking were copied. In addition, the reverse relationship of FEPs that may potentially lead to earthquakes are considered. FEPs that were judged to not be directly influenced by earthquakes or do not lead to earthquakes are not listed here.

Tab. A-1: Listing of FEPs, that are associated with earthquakes with links to the relevant sections in the main text

Number	Feature, event, or process	Section of this document
	Description	
Common FEPs		
Evolution processes		
2.2.4	Pore pressure	4.3
2.4.2	Radionuclide migration pathways and processes	5.2, 5.3, 5.4
Siting, design and implementation		
Siting		
3.1.1	Repository site	3.1
L/ILW waste and packages		
Evolution processes		
6.2.12	Impact of geological events and processes	5.3
Radionuclide migration		
6.3.4	Radionuclide migration and pathways	5.3
HLW canister		
Evolution processes		
7.2.8	Canister breaching	5.4
7.2.13	Impact of geological events and processes	5.4
Radionuclide migration		
7.3.1	Radionuclide migration and pathways	5.4
HLW emplacement drift, buffer and liner		
Facility, design and operation		
8.1.3	Bentonite plasticity and self-sealing	5.4
8.2.15	Impact of geological events and processes	5.4

Number	Feature, event, or process	Section of this document
Radionuclide migration		
8.3.1	Radionuclide migration and pathways	5.4
L/ILW cavern backfill and liner		
Evolution processes		
9.2.12	Impact of geological events and processes	5.3
Radionuclide migration		
9.3.1	Radionuclide migration and pathways	5.3
Access structures and sealing system		
Evolution processes		
10.2.10	Impact of geological events and processes	5.1, 5.3
Radionuclide migration		
10.3.1	Radionuclide migration processes and pathways	5.3
Geological setting		
Geological features		
11.1.6	Current regional stress regime	4
11.1.7	Local stress regime	4
11.1.8	Regional fault zones	4.1, 4.2
11.1.9	Local faults	4.1
11.1.10	Undetected features	3.3.1
Hydrogeological characteristics		
11.2.2	Effective hydraulic properties	5.1, 5.2
Radionuclide migration		
11.3.1	Radionuclide migration processes and pathways	5.2
Containment-providing rock zone (CRZ)		
Radionuclide migration		
12.3.1	Radionuclide migration processes and pathways	5.2
Repository-induced effects		
Thermal- and gas-related effects		
13.3.3	Thermally-induced pore pressure increase	4.3.1
13.3.5	Gas-induced pore pressure increase	4.3.1
13.3.6	Pore-pressure-induced rock damage and fault reactivation	4.3.1
Geological processes and events		
14.1	Regional vertical movements	4.2
14.2	Regional horizontal movements	4.2
14.7	Neotectonic activity	4.2

Number	Feature, event, or process	Section of this document
14.8	Seismic activity	3.1, 4.2
14.9	Self-sealing	5.2
14.17	Evolution of regional stress regime	4
14.18	Fault re-activation and formation of new faults	4.1
Climatic processes and events		
Environmental processes		
15.2.4	Ice sheet effects (loading, melt water recharge)	4.1
Future human actions		
17.2.2	Geothermal exploitation	4.3.2
17.3.2	Liquid waste and gas injection	4.3.2