Summary record of the topical session of 16th Meeting of the IGSC

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Handling extreme geological events in safety cases during the post-closure phase

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1. Introduction

The sixteenth meeting of the Integration Group for the Safety case (IGSC) was held at the OECD/NEA offices in Paris on 7th-9th October 2014. The meeting included a topical session titled:

Handling extreme geological events in safety cases during the post-closure phase.

The session included nine presentations on the handling of such events by various national programmes, questions and answers on each presentation and ended with a general discussion period. The present document makes summarises the outcome of the meeting. The document is structured as follows:

- Section 2 describes the types of extreme geological events discussed in the session and how these are identified,
- Section 3 discusses the measures that can be taken to avoid such events and to mitigate their impact on repositories,
- Section 4 describes how the likelihood and consequences of events are assessed,
- Section 5 address experiences regarding interactions with regulators and other stakeholders,
- Section 6 covers remaining issues and planned R&D to address these, and
- Section 7 presents a recommendation for possible future collaborative work on this topic.

2. Types of events and their identification

The first observation from the topical session is that no programme has a specific definition of "extreme geological events". Indeed most take a broad view of the topic and included not only "events" of relatively short duration such as earthquakes and magma intrusions, but also more extended "processes", "situations" or "features", such as uplift and erosion or the (unexpectedly) persistent presence of corrosive agents in groundwater at repository depth. Furthermore, not all of the events and processes discussed were "geological" in origin, but included external, climatic phenomena such as periods of ice-sheet or permafrost cover at the site, which could have significant effects on the geological environment around a repository. A list of the main features, events and processes (FEPs) considered in the topical session presentations is given in

Table 1, together with their potential relevance to the safety case, i.e. their possible impacts on the safety functions of a repository.

Some of the features, events and processes (FEPs) discussed could be “extreme” in the sense that:

- their occurrence at all at a given site was judged highly unlikely, or
- their occurrence at all at a given site was judged likely, or even virtually certain, but e.g. their rates, frequencies, magnitudes or spatial extent were at the bounds of, or even beyond, the ranges supported by current scientific understanding.

Examples of the latter are the occurrence of an unexpectedly (or unprecedentedly) thick ice sheet or unexpectedly large earthquake. However, the topical session, as shown in Table 1, also considered a range of geological FEPs that are not extreme in either of these senses, but nevertheless need to be assessed as part of the safety case because of their potential impact on the safety functions.

For implementers, the identification of extreme geological FEPs that need to be included in a safety case is part of normal FEP management and scenario development, as applied to other types of events and processes. However, specific geological analyses aimed, in part, at identifying and characterisation of extreme FEPs, are generally undertaken, and these contribute to an overall, integrated understanding of the site. In Canada, for example, NWMO has undertaken:

Table 1: Main FEPs considered in the topical session and the possible safety impacts identified

FEPs	Possible safety impacts (perturbations) discussed
Volcanism	Magma intrusion into repository structures
Hypothetical (undetected) transmissive structure near to, or intersecting, the repository	Potential fast pathway for nuclide transport through the geosphere
Seismicity, earthquakes, tectonic movements	Loss of integrity of seals
	Creation of new fault zones
	Secondary movements on fractures intersecting the repository
Major climate change (including permafrost, glaciation)	Erosion of ground surface, including formation of glacial channels and, following glacial retreat, breakthrough channels (overflow of lakes from retreating glaciers)
	Effects on surface hydrology and exfiltration
	Effects of mechanical loading on the host rock; compaction and decompaction (relevant to argillaceous media)
	Influx of low ionic strength water to repository depth, causing loss of clay buffer and accelerated canister corrosion (relevant to fractured, hard rocks)
	Effects of increased mechanical loading on engineered barrier system
Uplift and erosion	Loss of repository depth, potential effects on favourable host rock properties and ultimately exposure of repository at the surface

Subrosion	Degradation of geological barrier.
Persistent presence of corrosive agents (e.g. sulphide, oxygen) in groundwater	Accelerated corrosion of metallic components (canisters, overpacks)
Seal-level change	Impact on flow and composition of groundwater.
Geothermal activity.	Temperature perturbations, impact on flow and composition of groundwater.

- a natural analogue study of shale cap rock barrier integrity,
- outcrop fracture mapping,
- a glacial erosion assessment,
- a seismic hazard assessment,
- an assessment of long-term climate change,
- a long-term geomechanical stability analysis (to assess the impact of, for example, glacial loading and crustal flexure), and
- an assessment of neotectonic features and landforms.

In a few cases, national regulations mention specific FEPs that, at a minimum, need to be included in safety case. Examples from French regulations are:

- exceptional seismic activity or rock displacements, and
- the geological impact of climate change with exceptional magnitude.

Finnish regulations also state that rock movements jeopardising the integrity of disposal canisters should be considered. Swiss regulations state that scenarios in which the repository is increasingly exposed to surface influences as a result of geological processes have to be taken into consideration. Such scenarios are of particular relevance to the Swiss programme due to the known past variations in the thickness of the overburden above the Opalinus Clay, which is the favoured host rock for the disposal of high-level waste in that country.

Other regulations specifically exclude certain types of events or scenarios. Swiss regulations, for example, explicitly exclude scenarios involving the impact of a large meteorite (like climate change, not a geological event in itself, but rather an event with potential geological consequences).

Most national regulations, however, do not specify which geological FEPs are to be considered in safety cases. Rather, it is left to the implementer to ensure that the safety case is sufficiently comprehensive, taking into account all relevant geoscientific data. In Canada, for example, the 2009 Guidelines for the Preparation of the Environmental Impact Statement for the Deep Geologic Repository for Low- and Intermediate-Level Radioactive Wastes state that assessment scenarios should be “sufficiently comprehensive to account for all of the potential future states of the site and the environment”.

3 Avoidance and mitigation

All programmes attempt to avoid, as far as possible, extreme geological FEPs by appropriate site-selection criteria and by the choice of host rock. Regulations in some countries also explicitly state that extreme FEPs with negative impacts should be excluded by site selection. Site-selection criteria may, for example, relate to:

- current and past seismic and volcanic activity,
- rates of uplift, and
- geomechanical stability.

Criteria may take the form, for example, of respect distances to fault zones or areas of present or past volcanism.

Fig. 1 illustrates, as a specific example, how regional fault zones and tectonic zones have been identified and avoided in selecting siting regions for high-level waste and low- and intermediate-level waste repositories in Switzerland.

More generally, site selection based on an integration of geoscientific knowledge in a geosyntheses, or site descriptive models, is a key step towards avoiding, or at least minimising the probability of, extreme events. Multiple lines of evidence for site stability are in general sought, including quantitative analyses and natural analogues, as well as site-specific geological information. Examples of the latter are environmental tracers and the presence of abnormal hydraulic heads, both of which can provide evidence for very slow groundwater movement through the geosphere, and hence resilience to perturbations, over geological timescales.

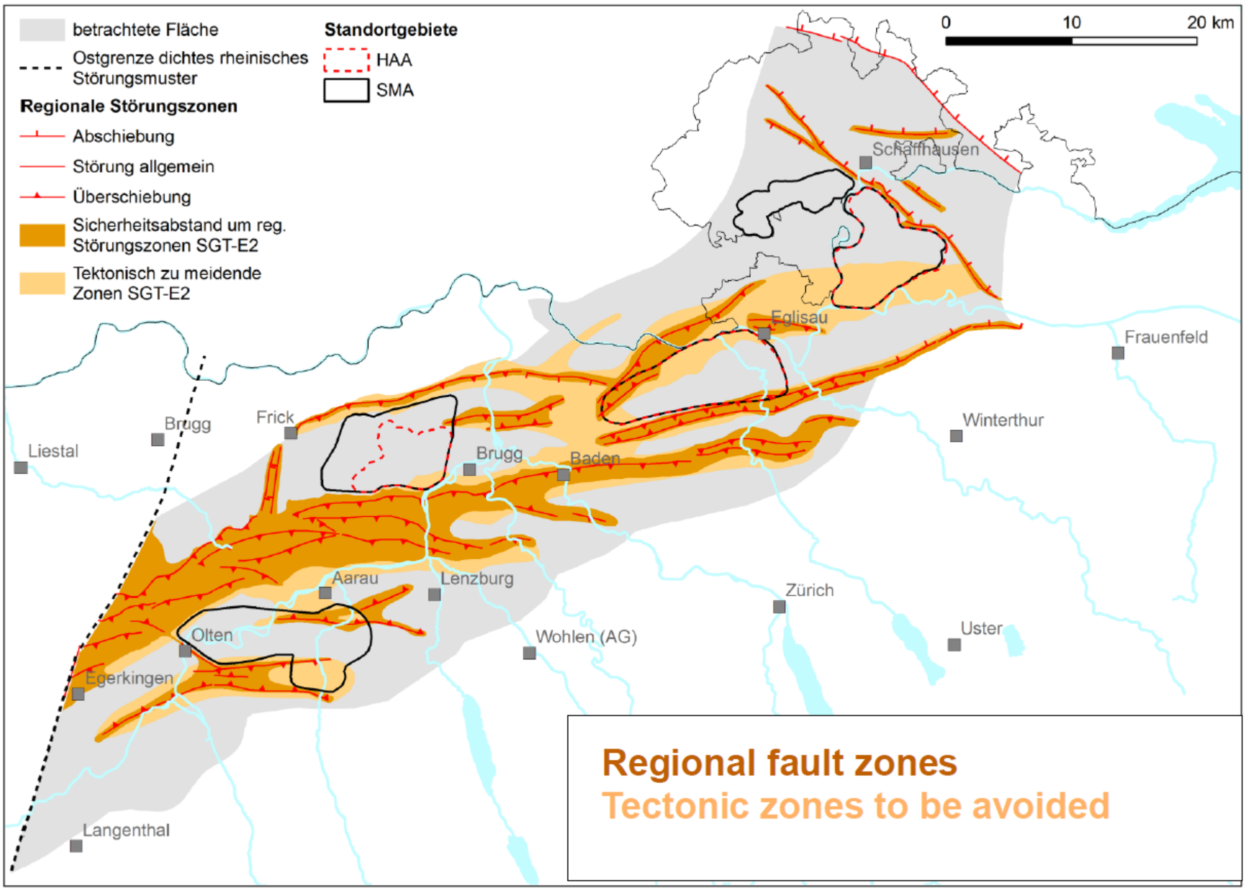

Figure 1: **Identification and avoidance of regional fault zones and tectonic zones in the selection of siting areas in Switzerland**

Nevertheless, all programmes operate under certain constraints, notably the geological environments that are available within national borders. Thus avoidance of extreme geological events can be more challenging for some programmes than for others. For example, the Japanese programme cannot avoid operating within tectonically active regions, and showing that extreme geological events will not compromise repository safety is thus an essential component of the safety case. The Japanese programme has therefore developed advanced methods for the identification of volcanic and tectonic hazards at potential repository sites in Japan in terms of their likelihood and scale, which can provide a basis for site comparison (Figure 2).

As a further example of how extreme geological FEPs can be programme-specific, the Swiss programme has to consider the possibility of glacial break-through channels, which is rather specific to the situation in the siting regions under consideration in northern Switzerland.

Overall, no programme has succeeded in completely avoiding extreme geological events by siting, given the broad definition of such events adopted in the topical session.

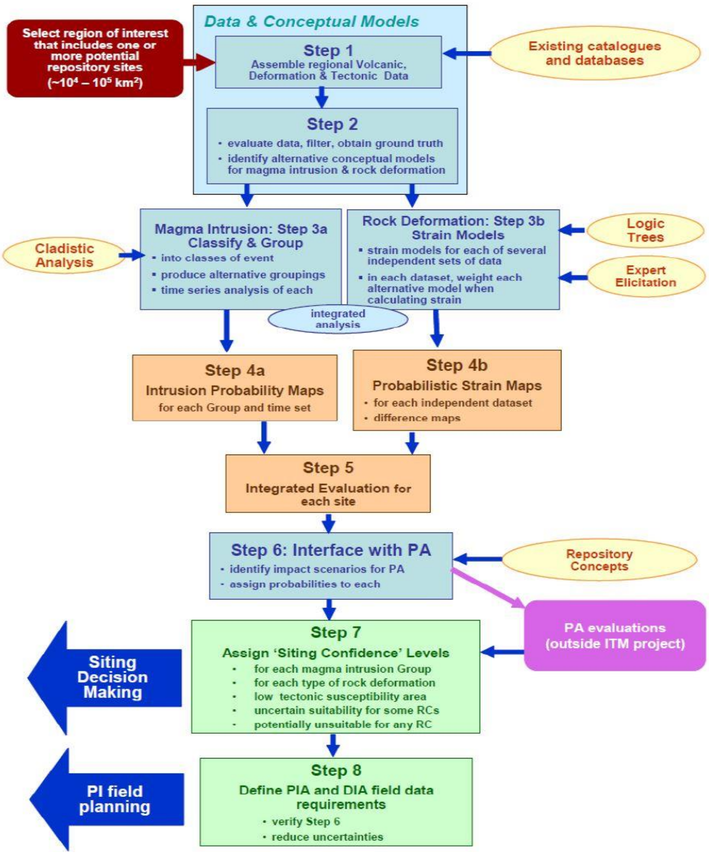

Figure 2: **Steps in the ITM[1] methodology for the identification of volcanic and tectonic hazards**

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[1]. ITM: International Tectonic Meeting. The ITM project has developed tools to assess hazards up to 100,000 years in the future. The possibility and constraints for making forecasts up to one million years is being addressed in the TOPAZ (Tectonics of Potential Assessment Zones) project.

A key positive feature of geological disposal is that it isolates the waste from poorly predictable events and processes operating near or above ground surface, such as climate change, and so inherently mitigates the effects of at least some extreme events. In addition, however, all programmes also aim to further mitigate the impact of extreme geological FEPs by choice of repository depth, host rock, layout and other design measures. For example, choice of a host rock with self-sealing capacity, such as salt or some argillaceous media, will mitigate the effects of some events or processes that could otherwise lead to permanent fracturing of the rock. Requirements on performance of engineered components, e.g. canister strength, are generally set based on conservative assumptions regarding extreme geological FEPs that may occur in the future. An example from the Gorleben programme in Germany is that of "dimensioning earthquakes" that cover the extent of all past earthquakes known to have occurred in the siting region. As another example of a mitigation measure, compartmentalisation of the waste within the repository may mean that an extreme event is likely to affect only a small part of the radionuclide inventory. Further examples of such measures are given in Table 2.

Finally, while most presentations in the topical session focussed on impacts of geological FEPs in the post-closure phase, the presentation by NUMO also discussed resilience to risks in the operational phase, which has been highlighted as an issue especially in Japan following the Tohoku earthquake and tsunami in 2011.

Table 2: Examples of measures that can mitigate the effects of extreme geological events

Measures	Benefits in terms of mitigation
Repository depth	Protection from certain types of geological and other processes, such as uplift and erosion and permafrost. May also favour a desirable attributes such as low hydraulic conductivity and low ambient hydraulic gradient (see below).
Selection of host rock with low hydraulic conductivity	Mitigation of the effects of events or processes that could otherwise lead to high hydraulic gradients
Selection of host rock with ambient hydraulic gradient	Mitigation of the effects of events or processes that could increase the hydraulic conductivity of the rock or generate discrete transmissive features
Selection (where available) of host rock with self-sealing capacity	Mitigation of the effects of events or processes that could otherwise lead to permanent fracturing of the rock
Rock suitability classification criteria (to guide layout)	Avoidance of locally problematic features, such as large fractures that may conduct high water flows or undergo large shear movements in the event of an earthquake
Compartmentalisation and waste solidification	Ensuring that extreme events are most likely to affect only a small part of the radionuclide inventory
Choice of engineered materials, e.g. use of clay-based backfill materials	Protection of the waste containers from high water flows (associated e.g. with glacial retreat), seismic events, corrosive agents in the groundwater etc.
Requirements on performance of engineered components, e.g. canister strength, longevity of seals	Ensuring containment of radionuclides following e.g. seismic events or mechanical loading due to glaciation
Limitation of unfilled void spaces in the engineered barrier system	Minimisation of the effects of earthquakes (shaking hazard)

4 Assessment of likelihood and consequences

In most cases, when assessing extreme geological FEPs, the first issues to be addressed are:

- the likelihood or plausibility of the FEP (or combination of FEPs), and
- the effects of the FEP or FEPs on the repository barriers and their safety functions.

The Japanese ITM methodology shown in Figure 2 is an example of an approach to evaluate the likelihood and scale of future tectonic processes and events. As another example, in the U.S. Yucca Mountain Programme, probabilities of events such as igneous intrusion were estimated using a formal expert elicitation process.

Some national regulations explicitly state that the consequences of scenarios (FEPs or combinations of FEPs) of very low probability do not need to be assessed. This lower limit to probability is in some cases specified in laws or regulations. For example, the scenarios with a probability of 10^{-7} per year can be disregarded according to regulations of the Czech Republic. The corresponding figure in U.S. regulations is 10^{-8} per year.

The value of evidence for the past and present stability of the site, sometimes referred to as the natural analogue of the site itself, is recognised by all programmes in arguing, at least qualitatively, the low probability of extreme FEPs, or the likely minor effects such FEPs have on the geological environment. Regarding the effects of such FEPs on the engineered barriers, the topical session provided examples of numerical modelling aimed at quantifying these effects, including an analysis presented by NWMO of the effects of seismic ground motions on a shaft.

While measures, such as those listed in Table 2, can mitigate the effects of extreme geological FEPs or reduce the severity or likelihood of significant detrimental impacts on the safety functions, they may not completely eliminate the possibility of some detrimental impact. For example, rock suitability classification criteria are used in Swedish and Finnish programmes to avoid emplacing spent fuel canisters in deposition holes that are intersected by large fractures that could undergo damaging secondary shear movements in the event of an earthquake. However, because fracture size can only be indirectly inferred by the trace the fracture makes along the walls of the holes and overlying tunnels, some large fractures can escape identification, and there is thus the possibility of a small number of canisters failing due to rock shear. The number of failed canisters can be estimated using multiple realisations of a discrete fracture network model of the site, which can be combined with estimates of earthquake frequency to obtain the residual risk of canister failure.

If an event cannot be disregarded on account of its low likelihood or implausibility, and if the effects on the repository barriers and their safety functions are potentially both significant and detrimental, the final issue is to be assessed in that of radiological consequences. National regulations in many cases allow higher calculated release or dose rates for low probability scenarios. Thus, regulatory guidelines for such scenarios may be framed in terms of:

- risk limits,
- limits to the expectation value of dose or activity release rates, and
- higher dose or activity release rate limits than for more likely scenarios.

An example from the Korean programme, where a risk limit applies for “uncontrolled” natural or man-made events while a dose limit applies to normal evolution, is given in Figure 3.

Classification		Performance Objectives	Applicable Regulation
During Operation	Normal	• Workers: 20 mSv/year • Public : 1.0 mSv/year	Korean Atomic Energy Act and its Enforcement decree
	Accident	• Workers: 50 mSv • Public : 5.0 mSv	Suggested by KORAD
Post Closure	Normal	• Performance Objective caused by natural phenomena • 0.1 mSv/year	NSSC Notice No. 2012-55
	Accident	• Risk induced by un-controlled natural or man-made events • 10^{-6}/year	
	Human Intrusion	• After Institutional Control Period • 1.0 m Sv/year	

Figure 3: **Korean radiological protection criteria for long-term safety of low- and intermediate-level radioactive waste disposal**

Some regulations are framed in quantitative terms over, say, a million year time frame, but provide more qualitative safety criteria for still more distant times. In Finland, for example, regulations state that safety evaluations beyond one million years can be mainly based on "complementary considerations", which can be used for scenarios that cannot reasonably be assessed by quantitative means. Similarly in Switzerland, beyond a million years, it has to be shown that the range of variations of possible radiological impacts are not "higher than natural radiological exposure". It is thus recognised in at least some regulations that the quantitative evaluation of safety indicators, such as dose, becomes increasingly difficult to justify at very distant times, mainly because geological evolution becomes increasingly uncertain.

It should be noted that phenomena such as seismicity and glaciation are not necessary unexpected at some sites. They may thus form part of the reference, or normal evolution scenario. In France and the U.S., this is required by regulations, which state that likely natural events, even if extreme, are to be included in the "reference situation" or "nominal scenario" that describes evolution in the absence of unlikely events. In all programmes, low-probability scenarios may, however, include more still more extreme versions of these same phenomena.

An alternative to modelling the impact of extreme events explicitly is to take a conservative approach that bounds their maximum impact. For example, in the German programme, no credit is taken for the sedimentary overburden above the repository as a transport barrier, because of the possibility that this will be severely perturbed in the future by glacial channels (the repository is deep enough that such channels do not affect the other geological and engineered barriers).

In addition to low probability scenarios, some programmes choose to analyse "what if" scenarios or cases for which there are good arguments (supported e.g. by multiple lines of reasoning) that the geological event in question will not happen. An example is the severe shaft failure scenario analysed in the Canadian programme, which is not linked to any specific cause, and is considered in spite of evidence, e.g. from process modelling, for the resilience of the shaft to sources of mechanical loading such as glaciations. Similarly, a scenario in which seals malfunction because of an extreme earthquake event, with a magnitude high that in considered possible in the siting region, is considered in the French programme. A further example from the Swedish programme is a scenario in which canisters are assumed to fail due to isostatic load, even though current understanding is that the canisters will withstand even the worst-case loading that could occur in the future. Such analyses are intended to demonstrate the robustness of a disposal system, and to illustrate the functioning of specific barriers (by disregarding others). They may thus demonstrate a degree of redundancy in the system: even if a barrier or safety function were to be severely perturbed or lost by some hypothetical event or process, adequate levels of safety are nevertheless provided. The results of these analyses may provide a counter-argument to the possible assertion that there may by events or processes detrimental to the repository barrier system that the programme has failed to identify specifically in the safety case.

5 Interactions with regulators and other stakeholders

Interactions between developers (or implementers) and regulators occur continuously in most national programmes, so as to keep each party informed of developments and plans by the other. Such interactions are clearly at their most intense during the regulatory review of safety cases, when the regulators may request additional information, including new analyses of extreme geological FEPs. Some national programmes (Sweden and Finland) are currently in this situation; an example was given at the topical session where the Finnish regulator, STUK, had requested information on Posiva´s handling of large earthquakes at relatively early times (a few hundred years post-closure), and this has led Posiva to perform additional, supplementary calculations after the publication of the safety case. A further example was given from the French programme, in which interactions with the regulator had led to the inclusion of additional "what-if?" scenarios in ANDRA´s safety calculations.
A significant challenge facing all programmes is how to communicate safety in the face of extreme geological FEPs in an understandable way. This challenge can be particularly acute if the repository is sited in a geologically active region, or where extreme geological FEPs are well known to have occurred in the past. In the (now cancelled) Yucca Mountain Programme in the U.S., for example, the treatment of disruptive events was a focal point for regulator and stakeholder interactions from the beginning.

A particular issue is that, for some types of extreme geological FEPs that are postulated to occur, the consequences in terms of safety indicators such as dose rates may exceed the regulatory guidelines applicable to more likely scenarios. As noted above, national regulations in many cases allow higher calculated releases or doses for low probability scenarios, but it is not always easy to convince the public that this is a well justified approach. The importance of openness about such events, as well as their likelihood and consequences, was stressed in the topical session.

A more general challenge is how to communicate to a sometimes sceptical public that meaningful statements on such events can be made over timescales of a million years or more. Several programmes have found that knowledge of the past and present stability of the site (the natural analogue of the site itself referred to above), as well as natural analogues elsewhere, can be especially valuable for communicating the fact that predictions made about the future evolution of the site are well founded on scientific evidence. In addition, the safety case philosophy of seeking and presenting multiple lines of evidence has been found to contribute positively to confidence on the part of stakeholders. It can also be helpful to stress in communicating with the public that geological disposal is an effective strategy to at least minimise the impact of some types of extreme geological events (or the impact of external, climatic events such as glaciation on the disposal system). Finally, it can be stressed that, extreme events, if they occur, may only affect part of the repository, and the value of compartmentalisation of disposed materials to ensure this is the case.

As well as openness, the need for attentiveness and respect for the concerns of stakeholders was pointed out during the session.

6 Remaining issues and planned R&D

A key conclusion of the topical session was that none of the extreme geological events that have been identified pose are seen as having the potential to undermine safety cases, given the possibilities available to all programmes to avoid such events, mitigate their effects and assess their residual likelihood and consequences, as explained in the previous sections. Some types of events are inevitably difficult or impossible to model in detail, given that they generally have significant associated uncertainties, some of which are difficult or impossible to reduce with further R&D. Nevertheless, the conservative modelling approaches that are used to deal with such uncertainties have proved broadly adequate for the safety cases prepared to date.

Where programmes are at an early, generic stage, as in the case of the disposal of the civilian high-level waste is in the U.S., R&D tends to focus on building confidence in the viability of multiple generic disposal concepts, rather than on extreme disruptive events. In Japan, on the other hand, where the programme is also at a generic stage, there has been intensive research in the characterisation of such events, since the Japanese programme cannot avoid operating within tectonically active regions. Other programmes that are actively engaged in site selection and characterisation also carry out R&D aimed at characterising and further mitigating the effects of extreme geological events, as well as refining parameters and reducing conservatism in the assessment of their likelihood and consequences. Some examples of ongoing R&D are given in Table 3.

Table 3: **Examples of R&D activities to address issues associated with extreme geological events**

(i) Basic understanding and characterisation of extreme geological events
Characterisation of past and current neotectonic activity.
Assessment of likelihood and/or rate of occurrence of large earthquakes and volcanism, including the current and recent situation (based on historical records), as well as potential future variations (e.g. large, post-glacial earthquakes).
Assessment of the attenuation of the magnitude of seismic disturbances with depth.
Enhanced understanding of the creation mechanisms for over-deepened valleys, including numerical modelling of these.
(ii) Mitigation of the effects of extreme geological events
Definition and identification of layout-determining features, e.g. large fractures that may conduct high water flows or undergo large shear movements in the event of an earthquake. Stability of such features under different (glacial) load conditions.
(iii) Assessment of the consequences of extreme geological events
Improvement of geo-prospective models, to allow better evaluation of the evolution e.g. of surface morphology in response to climate change.
Assessment of the response of host rocks to large earthquakes, including secondary movement on minor fractures that may intersect waste emplacement positions, as well as potentially irreversible changes in the properties of fractures and rock matrix.
Assessment of the response of the engineered barriers to seismic events causing rock shear movements, including effects on waste containers and the capacity of e.g. clay buffers to protect these.

For the Waste Isolation Pilot Plant in the U.S, which is a unique example of an operating geological repository, no extreme geological events (defined in the U.S. as those with a probability greater than 10^{-8} per year) have been identified; human intrusion scenario dominate radionuclide releases in safety assessments.

7 Recommendation

It was clear from the topical session that, while some extreme geological events can be site-specific, such as the possibility of glacial break-through channels mentioned above in the context of the Swiss programme, many are common to most, if not all, programmes. It could potentially undermine safety cases if programmes that consider essentially the same or similar events handle these in different ways, e.g. using different assumptions regarding the advance and thickness of future ice sheets across a given continent. Thus, there is a potential benefit to harmonising the treatment of scenarios involving extreme geological events between programmes, including the main assumptions made and the generic data used.