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Autor: Schnellmann, Michael / Zuidema, Piet / Gautschi, Andreas

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Deep geological disposal of radioactive waste in Switzerland – overview and outlook

Michael Schnellmann[1], Piet Zuidema[1], Andreas Gautschi[1]

1 Introduction

Roughly 40% of the electrical energy consumed in Switzerland is currently supplied from the 5 operating nuclear power plants (NPP). All of the Swiss high-level radioactive waste (HLW) and ~ 70% of the low- and intermediate level-waste (L/ILW) results from nuclear power production and power plant decommissioning. A significant amount of the L/ILW (~ 30%) results from medical, industrial and research applications.

The responsibility for safe and sustainable management of all categories of waste lies with the producers. Hence, the electricity supply utilities involved in nuclear power generation and the Swiss Confederation (directly responsible for the waste from medicine, industry and research) founded the «National Cooperative for the Disposal of Radioactive Waste» (Nagra) in 1972. Nagra is responsible for deep geological disposal and for providing advice to the producers on conditioning of all types of waste.

The Swiss concept of ‹monitored long-term geological disposal› (EKRA 2000) combines passive safety with a monitoring period and retrievability ‹without undue effort› during this period. Due to the different radionuclide inventories and requirements on the barrier system, HLW and L/ILW will be disposed in two separate repositories, either in two different regions or in a combined repository with common surface facilities. The periods of concern for long-term safety of HLW and L/ILW repositories are 1 million years and 100 ka, respectively.

[1] Nagra, Hardstrasse 73, 5430 Wettingen, Switzerland

The waste is enclosed in a multi barrier system consisting of (1) the waste matrix and the spent fuel pellets within their cladding, (2) disposal canisters/containers (corrosion-resistant canisters with a lifetime of at least 1,000 years for HLW, concrete containers for L/ILW and ILW), (3) backfill of the disposal tunnels (pre-compacted granulated bentonite for HLW, cement-based mortars for L/ILW and ILW), (4) the geological barrier (host rock and adjacent low-permeability confining units), and (5) the geosphere and the general geological situation (mainly relevant with regard to long-term stability).

The site selection process for a radioactive waste repository in Switzerland is defined in the «Sectoral Plan for Deep Geological Repositories» (SFOE 2008, referred to as the «Sectoral Plan» below). Its preparation and the corresponding broad consultation was the responsibility of the federal authorities under the lead of the Swiss Federal Office of Energy (SFOE). The Sectoral Plan defines the roles and responsibilities of the main stakeholders, the site selection criteria and the three stages of the site selection process. Throughout the site selection process, highest priority is given to safety.

Stage 1 of the site selection process started with a «white map of Switzerland» and the full spectrum of potential host rocks and led to the identification of several geological siting regions for each repository type through the systematic application of the predefined site selection criteria (Tab. 1). In **Stage 2**, based on further investigations, the number of siting regions is narrowed down to at least two potential siting regions for each repository type (L/ILW and SF/HLW), each of them including the location for the surface facilities, which were determined in a participatory process with the siting regions and cantons. In **Stage 3**, the remaining geological siting regions are further investigated by means of intensive field work, leading to a further safety-oriented narrowing-down to one site for each repository type and the corresponding general license applications.

Besides the site investigations, the national geological disposal programme benefits strongly from experiments in two operating underground research laboratories (URLs) located in Switzerland in two different host rocks – the Mont Terri Project (FMT) and the Grimsel Test Site (GTS). The GTS, owned and operated by Nagra, is situated in crystalline rocks in the Swiss Alps and has been in operation since 1984 (www.grimsel.com); the Mont Terri underground rock laboratory, owned by the Republic and Canton of Jura and operated by the Swiss Geological Survey of the Swiss Federal Office of Topography (swisstopo), is situated in the Opalinus Clay in the Jura Fold and Thrust Belt. It has been in operation since 1996 (www.mont-terri.ch). In addition to the direct contribution to the national disposal programme, both URLs offer a platform for cooperation with international partners, for training and for interaction with interested stakeholders. A detailed overview of the type of experiments carried out at the FMT and their contribution to the disposal programme is given in Bossart (2015, this volume).

In the following, this paper summarises the Swiss geological disposal programme, with the focus on the site selection process, the relevant geological aspects and the most important datasets. For an overview of the geological setting in Northern Switzerland and a presentation of the results of Nagra's most recent 2D seismic campaign, the reader is referred to Madritsch (2015, this volume) and Meier (2015, this volume), respectively. An overview of the nuclear waste disposal programmes in other countries is given by Gautschi (2015, this volume).

2 Site selection Stage 1 (completed): Proposal of geological siting regions looking at the full spectrum of potential host rocks in the entire country

The focus of Stage 1, which started in 2008, was a scientific screening process leading to the identification of geological siting regions. The site selection process was conducted in five steps using mainly pre-existing geological data (e. g. reflection seismics, existing boreholes, underground research laboratories, geological maps, tunnel mapping) (Nagra 2008a, b). In a **first step**, the **waste inventory** was defined and the vari-

Group of criteria	Criteria
1. Properties of host rock	1.1 Spatial extent 1.2 Hydraulic conductivity 1.3 Geochemical conditions 1.4 Migration paths
2. Long-term stability	2.1 Durability of properties 2.2 Erosion 2.3 Repository induced effects 2.4 Resource conflicts
3. Reliability of geological information	3.1 Characterisation of host rock 3.2 Spatial explorability 3.3 Temporal predictability
4. Suitability for construction	4.1 Rock mechanical properties 4.2 Underground access

Tab. 1: Site selection criteria defined in the «Sectoral Plan» (SFOE 2008).

ous waste types were allocated to either the HLW or the L/ILW repository.

In a **second step**, the **barrier and safety concepts** for the two repositories were defined and quantitative and qualitative requirements on geology were derived. These related to the site selection criteria defined in the Sectoral Plan and considered host rock properties (e. g. spatial extent of intact rock blocks, hydraulic properties), long-term stability (e. g. uplift/erosion and differential movements for the timescales of concern), the reliability of geological findings (e. g. spatial explorability) and the suitability for construction (e. g. mechanical properties of the host rock) (Tab. 1).

In **step three**, the country was subdivided into **large-scale geotectonic areas** for a first rough screening from the viewpoints of long-term stability and explorability of spatial conditions. For the HLW repository, the Alps, the Jura Fold and Thrust Belt, the western Tabular Jura and a small part of the Molasse Basin (western Subjurassic Zone) were already excluded in this step. In contrast, for the L/ILW repository all large-scale geotectonic areas were further evaluated in steps four and five, mainly due to the lower requirements on host rock dimensions, host rock hydraulic properties and the shorter period of consideration.

Step four involved selecting the preferred **host rock formations** within the large-scale areas still under consideration. This was done in several sub-steps and led to the following results: For the HLW repository, only the Opalinus Clay with its confining units was proposed as the preferred host formation. For the L/ILW repository, the Opalinus Clay with its confining units, the claystone-dominated unit «Brauner Dogger» with its confining units, the marly-calcareous Effingen Member and the ‹marl formations of the Helveticum› (local tectonic accumulations of low-permeability marly rocks in the alpine Helvetic nappe stack) were proposed.

In **step five**, the **configurations of the preferred host rocks** within the large-scale areas under consideration were evaluated. Taking into account the presence of regional geological features (regional fault zones, overdeepened valleys resulting from glacial erosion, zones with indications of small-scale tectonic dissection, other zones to be avoided for reasons of neotectonics), preferred areas were identified within which the preferred host rocks could be found at suitable depth and with sufficient thickness and lateral extent. The preferred areas were used as the basis for delimiting the geological siting regions.

In October 2008, Nagra proposed three geological siting regions for the HLW repository and six for the L/ILW repository (Fig. 2, Nagra 2008a, b). Three of the siting regions for the latter are almost identical with the ones for the HLW repository. After an extensive review by the authorities and a public consultation process, Nagra's proposals for the geological siting regions were approved by the Federal Government in November 2011. This completed Stage 1 of the Sectoral Plan process.

3 Site selection Stage 2 (ongoing): Reduction to at least two siting regions per repository type

Stage 2 of the Sectoral Plan process has two main goals: firstly to select at least one site for the surface facilities in each of the geological siting regions and, secondly, to narrow down the number of siting regions to at least two for each repository type. This paper focuses on the narrowing-down of the siting regions, which – in contrast to the search for locations for surface facilities – depends strongly on the local geological conditions.

3.1 New key datasets

As a basis for Stage 2, existing datasets were reprocessed and reinterpreted and new data were acquired. In the following, some of the resulting new key datasets are briefly described. A total of 68 2D reflection seismic profiles from various campaigns of Nagra and the hydrocarbon industry with a total length of > 1,300 km were reprocessed (Fig. 2). Thanks to the consistent processing scheme (including a detailed revision of the static corrections and the mute function, CRS-stacking, pre-stack time and pre-stack depth migrations), the comparability between the different surveys could be clearly enhanced. The quality of the seismic imaging substantially improved in many cases, particularly for the surveys dating back to the 1980s. In contrast to the data from Northern Switzerland, reprocessing efforts for existing seismic data from the Wellenberg siting region did not substantially improve the seismic image. In the years 2011 and 2012, approximately 300 km of new 2D seismic lines were acquired in four of the five siting regions in Northern Switzerland (Fig. 1) to increase the comparability with the siting region Zürich Nordost, which had already been covered by a high quality 2D seismic survey from 1991 and 1992 (Naef et al. 1995, Naef & Birkhäuser 1996) and a 3D seismic survey from 1997 (Birkhäuser et al. 2001). The resolution of the newly acquired data is clearly higher compared with the lines of the eighties. The new seismic data were processed in a similar way to the reprocessed datasets, facilitating an integrated seismic interpretation (Madritsch et al. 2013, Meier 2015). With respect to Stage 2 of the site selection process, the new interpretation allowed a better delineation of the regional fault zones and the detection of additional tectonic zones to be avoided (e. g. border zones of the Permo-Carboniferous Trough of Northern Switzerland and anticlines in the surroundings of the Jura Fold

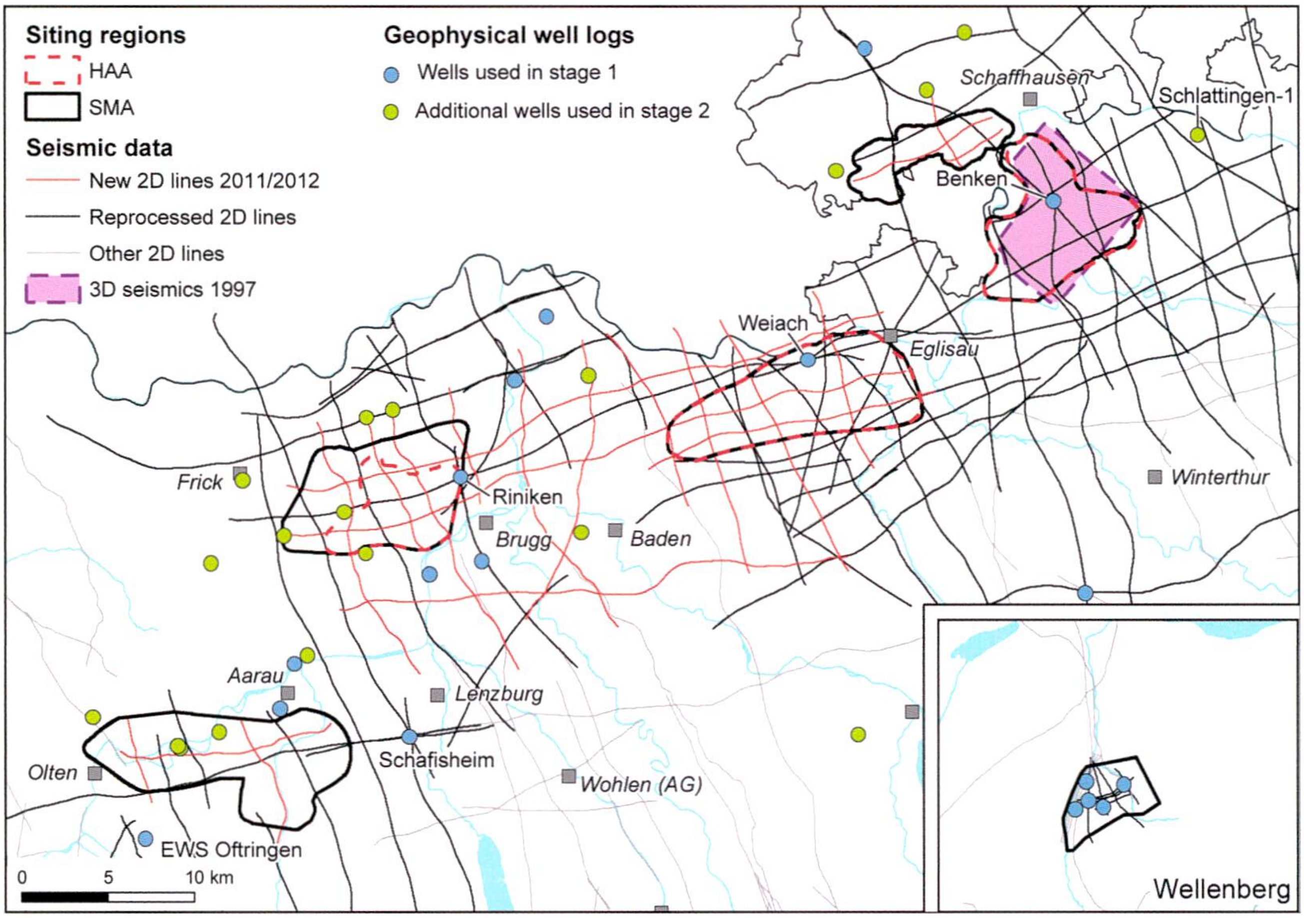

Fig. 1: Map of Northern Switzerland with siting regions investigated in Stage 2 of the Sectoral Plan and available seismic data and geophysical well logs. Note that the database was substantially expanded compared to Stage 1.

and Thrust Belt) for a deep geological repository (Nagra 2014b).

A new Bouguer gravity map and corresponding residual and filtered gravity maps of Northern Switzerland and Southern Germany were compiled by Green et al. (2013). In combination with the seismic and the borehole data, these products proved useful for delineating deep Permo-Carboniferous Troughs and glacially overdeepened valleys. New information concerning the lithofacies of the potential host rocks and the surrounding low-permeability rocks (‹confining units›) was acquired by means of geophysical well logging in third party boreholes (e. g. shallow geothermal wells, Fig. 1). These logs, together with new sedimentological and stratigraphic analyses of existing/new boreholes and outcrops, revealed a much clearer picture of the lithofacies conditions of the potential host rocks and the related confining units in Northern Switzerland (Bläsi et al. 2013, Deplazes et al. 2013, Kiefer et al. 2015). For example, the lithofacies of the Effingen Member (proposed as a potential host rock in Stage 1 of the Sectoral Plan) could be better characterised by correlation of geophysical logs. It was shown that calcareous marl and limestone sequences are laterally very continuous and a number of 5–10 m thick limestone sequences and one sequence locally up to 30 m thick could be correlated from the lower Aare valley to the Pfaffnau-1 borehole (Deplazes et al. 2013).

Geotechnical tests were carried out on cores from the Schlattingen-1 deep geothermal

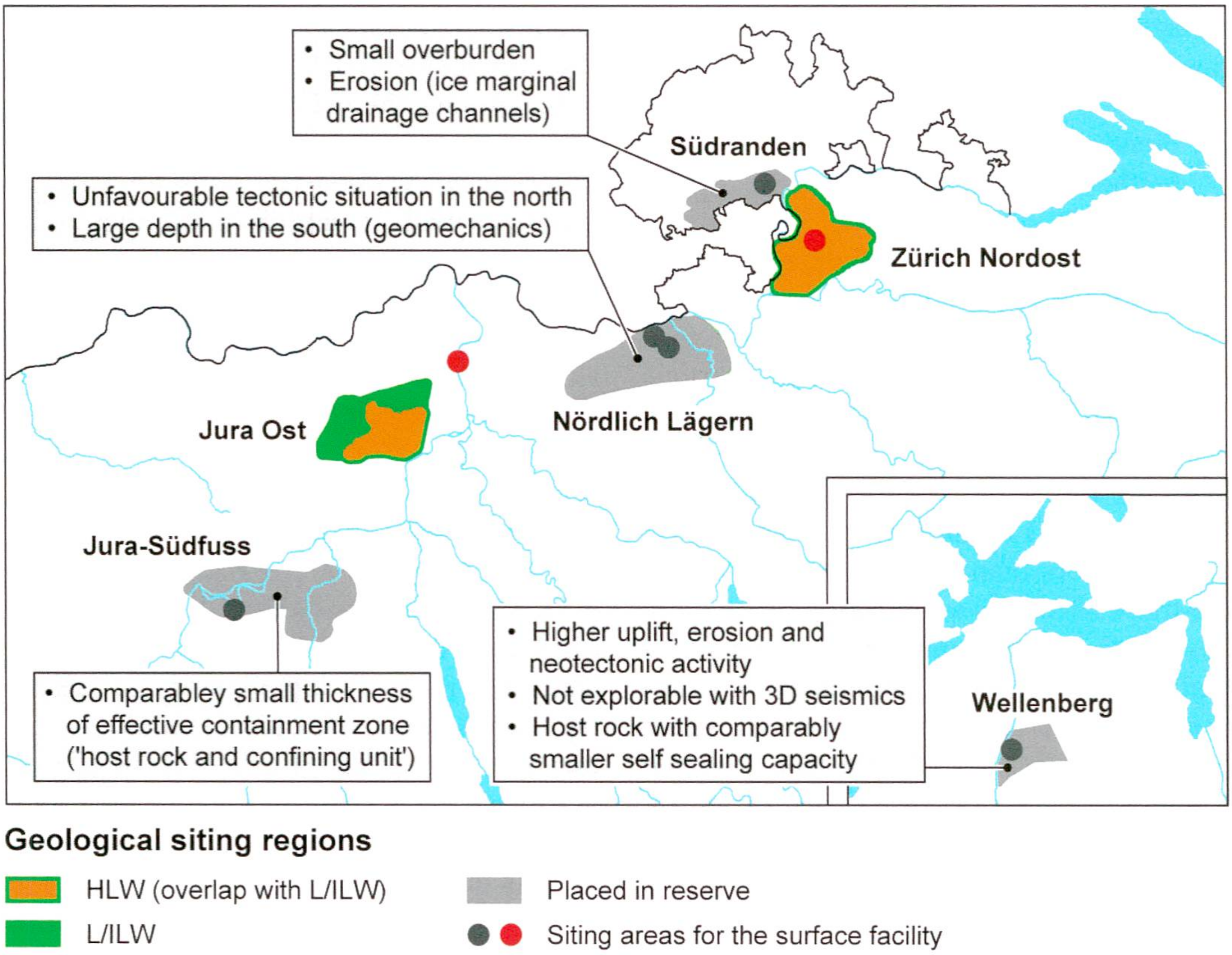

Fig. 2: Geological siting regions in Switzerland investigated in Stage 2 of the Sectoral Plan. In January 2015, Nagra proposed the two sites «Jura Ost» and «Zürich Nordost» (marked in green and orange colours) for further investigation in Stage 3 and to place the other siting regions (marked in grey) in reserve. For the latter, characteristics rated as ‹clear disadvantages› are indicated in grey boxes.

well, delivering new information on geomechanical properties (Ferrari et al. 2012, Jahns Gesteinslabor 2013). Natural tracer profiles from the Schlattingen-1 and the Oftringen boreholes delivered new information concerning the hydraulic properties of the host rocks (Mazurek et al. 2012, Wersin et al. 2013).
Concerning the investigation of the region's long-term geological evolution, a map series describing the drainage evolution over the last 5-10 million years was compiled based on an extensive literature review (Heuberger et al. 2014). A GIS-based compilation of the Early Pleistocene Deckenschotter deposits (Heuberger & Naef 2014) and a new top bedrock map (Pietsch & Jordan 2014) helped to reconstruct the fluvial incision and glacial overdeepening over the last 2 million years. This information was used as a basis for developing future erosion scenarios (Nagra 2014b).

3.2 Results: Proposals for the regions to be further investigated

In the **first step** of Stage 2, the methodology used in Stage 1 was adapted to address the changes in boundary conditions and to take into account requirements and suggestions put forward by the authorities and the various stakeholders.
Some of the siting regions identified for L/ILW in Stage 1 of the Sectoral Plan process included more than one potential host rock. For these sites, in a **second step** the priority host rock was determined, based on a systematic safety-based comparison. When comparing the Opalinus Clay with the other host rocks of Northern Switzerland (Effingen Member, «Brauner Dogger»), clear disadvantages of the latter emerged, such as (1) intercalations of potentially water-conducting sandy-calcareous or calcareous beds, (2) reduced self-sealing capacity due to a lower clay content and (3) limitations with respect to explorability and ease of characterisation of safety-relevant properties.

In a **third step** of Stage 2, the optimised spatial configuration of the priority host rock within each siting region was identified and outlined. The most important factors for identifying this configuration were host rock overburden with regard to future erosion (minimum depth), host rock overburden with regard to construction feasibility (maximum depth) and the tectonic situation (avoiding regional fault zones, anticlines and border zones of the deep Permo-Carboniferous Trough of Northern Switzerland due to an enhanced potential for neotectonic reactivation).
The suitability of the optimised spatial configurations was evaluated in **step four**, on the one hand using dose calculations and, on the other hand, through a qualitative assessment using the criteria relating to safety and technical feasibility set out in the Sectoral Plan (Tab. 1). This step resulted in the conclusion that all investigated siting regions meet the safety requirements, but the qualitative assessment revealed clear differences between the sites for various aspects. Finally, in **step five**, the most relevant of these aspects (specified by ENSI) were compared between the geological siting regions, resulting in the identification of siting regions with ‹clear disadvantages› in comparison with other siting regions (Fig. 2, Nagra 2014b).
Nagra's proposals were published in January 2015 (Nagra 2014a, b). Of the six L/ILW and the three HLW siting regions identified in Stage 1, the regions «Jura Ost» and «Zürich Nordost» were proposed for further investigations in Stage 3. Nagra stated that all six regions would meet the safety requirements, but that the regions proposed to be placed in reserve show clear disadvantages from a safety viewpoint compared to the two regions mentioned above. Both regions are suitable for the disposal of L/ILW and HLW, as well as for constructing a so-called combined repository for both waste categories. Nagra's proposals are currently being reviewed by the safety authorities and com-

missions and will be submitted to a broad public consultation before the Swiss Federal Council decides on the result of Stage 2.

4 Site selection Stage 3 (to come): Selection of one site per repository type and submission of a general license application

In the upcoming Stage 3 of the Sectoral Plan, the siting regions designated by the Federal Government at the end of Stage 2 will be investigated in depth. 3D seismic data are being acquired in the siting regions «Jura Ost» and «Zürich Nordost» in autumn and winter 2015/2016. In addition, a series of deep boreholes with extensive testing programmes are planned. The investigations will be accompanied by regional geoscientific studies addressing sedimentary facies distribution of the host rock and confining units, long-term geological evolution (neotectonics, erosion) and hydrogeology. Based on these investigations, sites will be selected and general license applications will be submitted. The decision of the Federal Council on a general license is not expected before 2027. It will be followed by a debate in Parliament and an optional referendum at a national level.

Following the construction and operation of an in situ rock laboratory, applications for a construction license and ultimately for an operating license for each repository will be submitted to the Federal Government for approval. According to the current schedule, the L/ILW repository should be operational around 2050 and the HLW repository around 2060.

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