Monitoring for the deep geological disposal of radioactive waste in Switzerland

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Abstract

Site selection for a deep geological repository for radioactive waste in Switzerland is in its final stage. The resulting general licence application will include a concept that foresees diverse monitoring campaigns at the surface and underground.

We present a selection of ongoing surface-based monitoring projects aimed at providing data to

- support site characterisation;
- demonstrate that the repository complies with legal and regulatory requirements during construction and operation;
- increase confidence of different stakeholders in repository design and safety.

Geodynamic baseline monitoring, for example, started decades ago with the extension of national geodetic and seismic station networks that focus on the areas in and around the potential siting regions. This included significantly extending the seismic network to improve the seismotectonic characterisation of the areas. Three additional short-period borehole seismometers were installed at depths of 120-150 m below the surface, and seven broad band seismometers were installed between 2012 and 2013, providing a network with a magnitude of completeness below Mc=1.3 in and around the siting regions. Seismicity in the siting regions is very low, with few locatable events every year. Temporary seismic stations were added to the network to improve the seismotectonic understanding of the few seismogenic zones in the surrounding of the seismically inactive siting areas.

In addition, eleven high-precision geodetic global positioning (GNSS) antennae were carefully attached to the ground to establish a geodetic network with an average station spacing of 25 km. This network was completed in 2012 and a decade of monitoring data is now available. Consistent with the seismotectonic measurements, the GNSS-inferred crustal deformations are in the submillimetre range and close to or below the network's level of significance.

Another key project is monitoring the groundwater in deep exploratory boreholes. Multi-packer systems measure fluid pressures in the foreseen host rock (Opalinus Clay) and in over- and underlying formations down to a depth of approximately 1000 m. The recorded time series will be analysed in terms of the undisturbed fluid pressures.

In conclusion, high-resolution measurement technology and long-term time series are required to derive relevant parameters for demonstrating the safety of radioactive waste disposal in Switzerland.

Keywords: Radioactive waste disposal, GNSS, Microseismicity

1. Introduction

The Swiss National Cooperative for the Disposal of Radioactive Waste (Nagra) is responsible for the safe disposal of all radioactive waste in Switzerland in a deep geological repository (DGR). The Opalinus Clay, a Mesozoic claystone approx. 175 million years old, has been identified as a suitable host rock for a DGR in Switzerland (Nagra 2008). Guided by the Swiss Sectoral Plan (SFOE 2008), which is currently in its third and final stage, the site selection process is mainly governed by safety-relevant criteria. Based on detailed investigations, sites for the surface and underground structures of the DGR concept were identified, as illustrated schematically in Fig. 1. The combined repository for low- and intermediate-level waste (L/ILW) and high-level waste (HLW) provides a solution for efficient repository construction and operation using centralised surface and access facilities (1-4 in Fig. 1).

The long-term safety of the repository is ensured by the multi-barrier design, which essentially encapsulates the waste using (1) low-solubility waste forms, (2) disposal canisters and containers, (3) bentonite backfill (for HLW) and mortar backfill (for L/ILW), and (4) low-permeability host rock.

Swiss legal and regulatory requirements call for baseline monitoring before construction of the DGR as well as a monitoring phase following waste emplacement before the decision is made on final closure of the repository (Nagra 2021 foresees a 50-year monitoring period). Monitoring activities may not negatively influence the passive safety of the repository but are required to demonstrate that time-dependent processes remain within given ranges and that repository evolution meets expectations. Long-term safety, however, does not depend on monitoring or the ability to monitor.

We introduce a variety of available surface-based monitoring techniques capable of identifying potential changes in the near-surface and geological environment. Examples of such changes could be drawdown of formation pressures and settlement close to shaft sinking. The monitoring programme must provide a comprehensive database to allow a distinction to be made between natural variations in the environment and the geological surroundings and potential changes induced by the construction and operation of the DGR. The current stage of Nagra's monitoring programme is focused on geological monitoring of a wider area surrounding the siting regions and on developing a concept for later stages. Aside from the concept for future surface-based monitoring activities, we present previously realised monitoring projects dedicated to characterising the natural baseline.

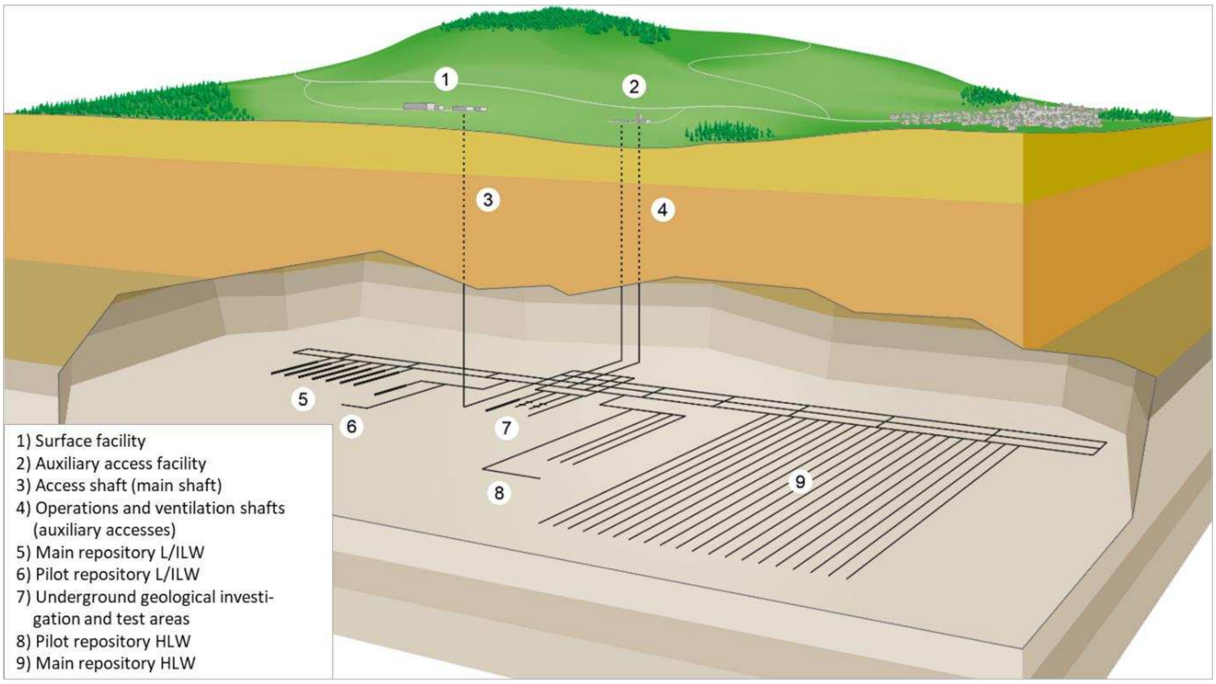

Figure 1: Schematic illustration of a combined DGR for HLW and L/ILW

2. Concept for surface-based monitoring of the environment and the geological surroundings

The concept for surface-based monitoring is based on Swiss regulations and comprises radiological and non-radiological measurements. The objectives of the surface-based monitoring data are to:

- determine the baseline of natural variations in the environment and the geological surroundings of the DGR,
- assess the levels of radionuclides or other contaminants in the environment before construction and operation of the DGR, and
- provide a basis for selecting post-baseline monitoring parameters.

The conceptual timeline in Fig. 2 visualises the start and varying intensity of different monitoring activities over the evolution of the DGR. The start of baseline monitoring is planned for the late 2020s once the technical assessment of the general licence applications by the authorities has been completed. The range of hydrogeological, meteorological and radiological measurements will be intensified before and during shaft construction, when the largest impact on the environment and geological surroundings is expected. The intensity of the sampling and measurement programme is planned to return to a normal level during the construction and operation of the main repository areas (see Fig. 1). Excavation of the main repository areas may require denser sampling of selected parameters, e.g. around waste emplacement zones. The current concept for baseline measurements for surface-based monitoring of the environment and the geological surroundings will be further refined and concretised for the general licence application. The design optimisation, specification, installation and sampling plans will be finalised after the general licence application has been submitted.

In anticipation of the low deformation rates in Northern Switzerland, microseismic monitoring was initiated as early as 1983 (Mayer-Rosa et al. 1984) and has since seen multiple upgrades and extensions. Geodynamic monitoring was further enhanced in 2010 when the GNSS station network was established. Both the seismological and the GNSS networks provide essential information for assessing the baseline in the low-deformation areas under consideration.

Monitoring of undisturbed formation pressure (hydraulic head) in deep aquifers and low-permeability formations such as the Opalinus Clay also requires a period of several years of baseline observation. Nagra can already benefit from a decade of monitoring data from one deep exploratory borehole. An extension with the installation of additional monitoring systems in three new deep boreholes, one in each siting region, is underway. The system at the definitive DGR site will be maintained during repository construction, and additional systems will be installed before excavation of shafts and disposal areas begins (Fig. 2).

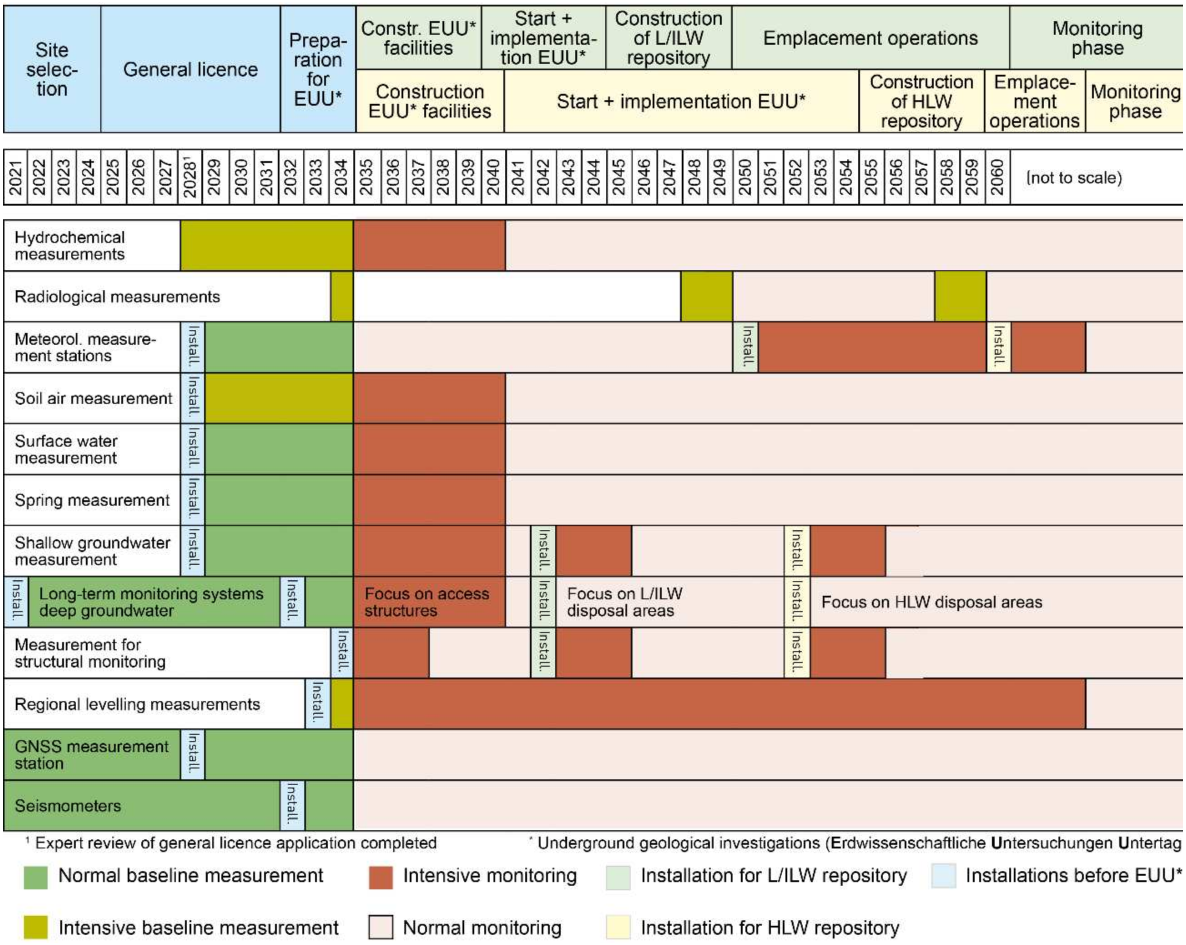

Figure 2: Concept for the surface-based monitoring of the environment and the geological surroundings of the Swiss DGR

3. Realised baseline monitoring networks

3.1 GNSS

The potential DGR siting regions are located in the northern foreland of the Swiss Alps. This area is characterised by deformation rates significantly below 1 mm/y (e.g. Villiger 2014; Houlié et al. 2018). Horizontal displacements of > 0.2 to 0.3 mm/y can now be captured reliably by analysing long time series of more than 10 years with well-placed permanently recording GNSS stations.

Swisstopo operates a network of continuously recording GNSS stations, providing the national geodetic reference system. This Automated GNSS Network for Switzerland (AGNES) consists of 31 stations evenly distributed throughout Switzerland (Brockmann et al. 2006) with an average station spacing of approx. 70 km. As part of the site selection process for a DGR, Nagra decided in 2009 to densify the AGNES network with eleven additional stations optimally placed from a geodynamic viewpoint. The criteria for selecting the station locations were station distribution within the tectonic framework and optimum coupling with the underground (Fig. 3). Each station is erected on a concrete pedestal and equipped with a 2.5-m-high steel mast and a geodetic choke-ring antenna and recorder. Automatic operating procedures ensure compliance with QC requirements and data flow to the processing centre that provides daily and monthly station coordinate solutions. Linearly averaged horizontal velocities with corresponding uncertainty estimates in Fig. 3 demonstrate that the displacement signal significantly exceeds the noise level after around one decade of recording time.

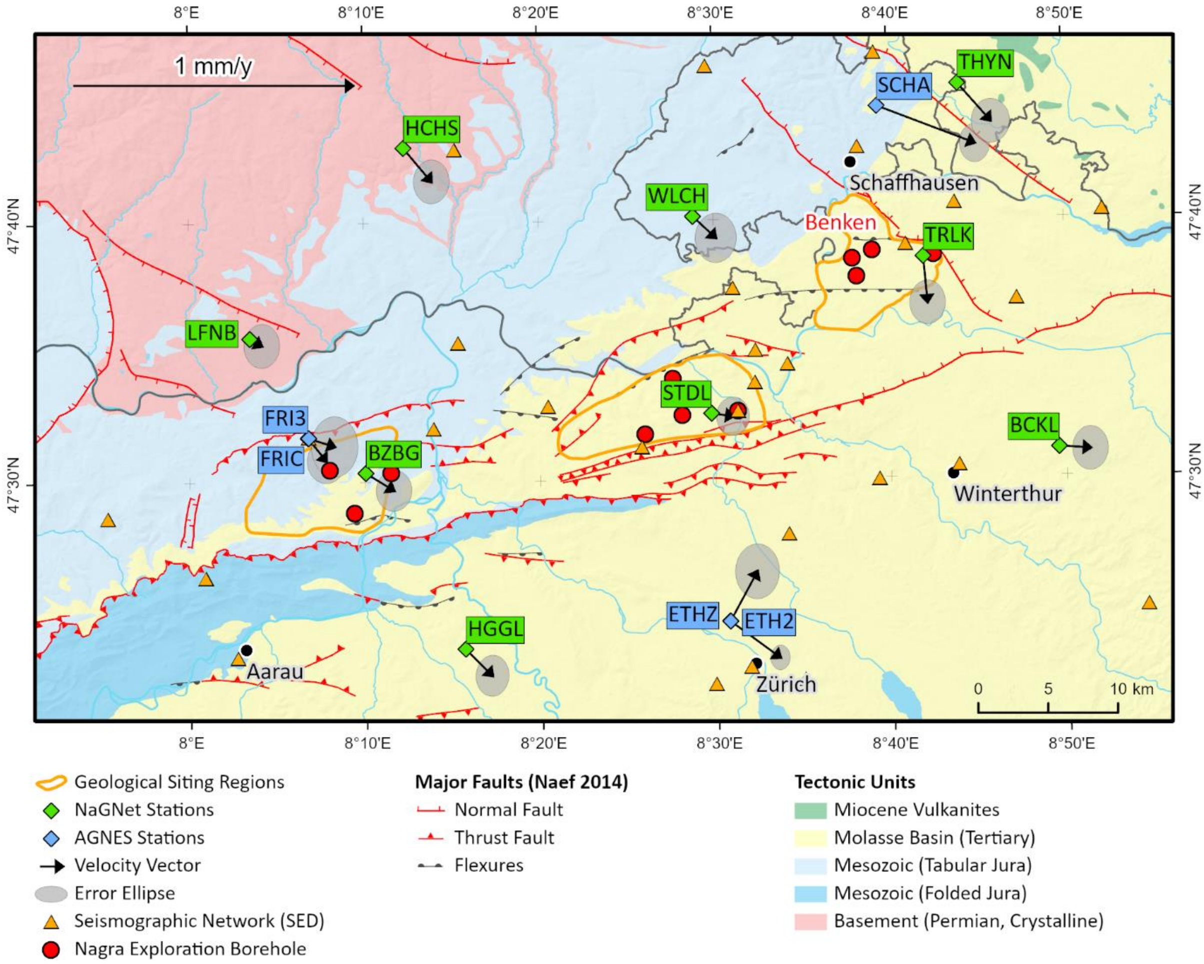

Figure 3: Simplified tectonic map after Nagra (2014) showing the distribution of permanent seismological and GNSS stations with horizontal displacement rates

3.2 Microseismicity

Observation of seismicity has a range of applications in DGR-related monitoring: (1) seismotectonic characterisation, (2) seismic hazard assessment, and (3) observation of potentially induced seismicity. The first two are routinely assessed by the Swiss Seismological Service (SED) which operates a dense seismometer network for this purpose. Characterisation of seismicity in the DGR siting regions is a task entrusted by Nagra to the SED since the mid-1980s. Beginning in 1984 with mainly vertical-component, short-period seismometers, initial network improvements in 2002 and 2003 included the installation of mostly three-component seismometers and continuous digital transmission (Deichmann et al. 2000). Real-time data exchange with neighbouring seismic networks further improved earthquake detection in border regions. By 2013, additional weak-motion stations had been installed to achieve a magnitude of completeness of $M_C \leq 1.0$ in and around the three siting regions (Kraft et al. 2013; Diehl et al. 2021). This network extension includes three underground short-period borehole stations at depths of 120-150 m and seven broadband surface stations (Plenkers et al. 2015; Diehl et al. 2014). Since 2018, the network has been further densified locally with six temporary surface stations for monitoring local earthquake clusters and Nagra's first deep borehole seismometer.

Plotting the magnitudes of digitally recorded earthquakes as a function of origin time (Fig. 4) located within the area shown in Fig. 3 demonstrates the enhancement of the seismic detection capabilities. The detection threshold of M_L~0.0 – 0.5 reached after the network densification in 2013 is clearly visible, and increasing slopes of the cumulative sum of earthquakes illustrate the well-known abundance of smaller earthquakes.

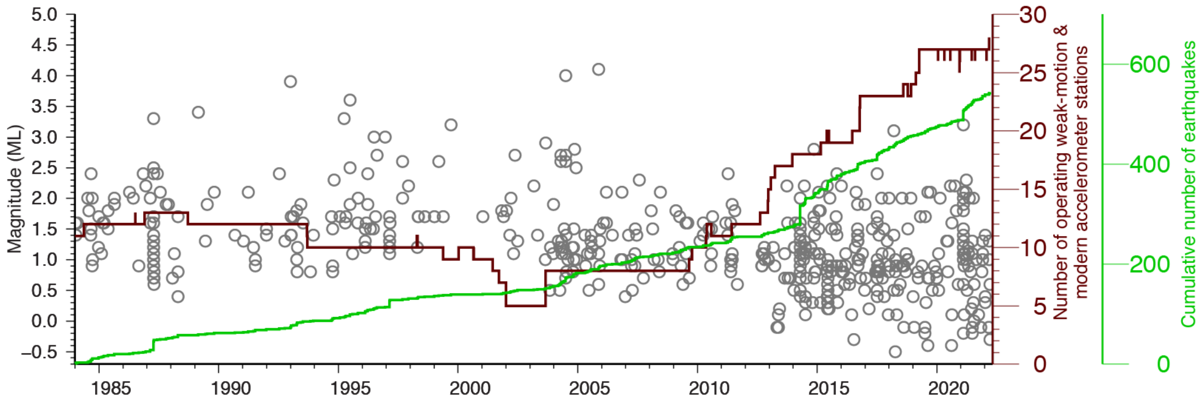

Figure 4: Temporal evolution of earthquakes located in the area of Fig. 3

3.3 Long-term hydraulic head monitoring of deep aquifers and low-permeability formations

The in-situ hydrogeological characterisation of low-permeability rock formations such as the Opalinus Clay is challenging. Open-hole hydraulic packer testing during the drilling period is the preferred approach to determining hydraulic conductivity. Use of drilling fluids that minimise the borehole history by inhibiting clay swelling is essential to obtain reliable measurements of hydraulic conductivity. Long-term monitoring is required to obtain undisturbed formation pressure. Nagra is using multi-packer systems in deep exploratory boreholes for long-term monitoring of the hydraulic heads (Fig. 5). The boreholes are generally cased, and the hydraulic connection between a packer interval inside the casing to the geological formation is established through perforation. The monitoring zones focus on the deep aquifers (Malm, Keuper, Muschelkalk), the Opalinus Clay host rock and its low-permeability surrounding formations in the Dogger and Lias (Fig. 5). The multi-packer systems have standpipes in the upper 100-200 m that facilitate measurements of artesian and sub-artesian conditions. Furthermore, this setup enables individual adjustment and replacement of the high-resolution pressure transducers without removal of the packer system.

The multi-packer system shown in Fig. 5 was installed in 2009 in the Benken borehole (Fig. 3). The installation of three similar systems, one in each siting region, will be completed by summer 2022. The newly recorded time series will help to derive large-scale, undisturbed hydraulic properties of the formations. In addition, the multi-packer systems enable groundwater sampling in the deep aquifers for hydrochemical analyses. Fibre-optic cables for distributed temperature sensing that are installed along the multi-packer systems provide information for temperature corrections. The resulting hydrogeological properties will complement the current regional and local hydrogeological models.

4. Conclusions

Rigorous planning and licensing procedures for the Swiss DGR project ensure inherently safe containment of the disposed waste. Surface-based monitoring will provide the basis for detecting and reliably separating natural changes in the repository environment from impacts of repository construction and operation. The monitoring programmes are therefore also intended to promote public confidence with regard to repository safety.

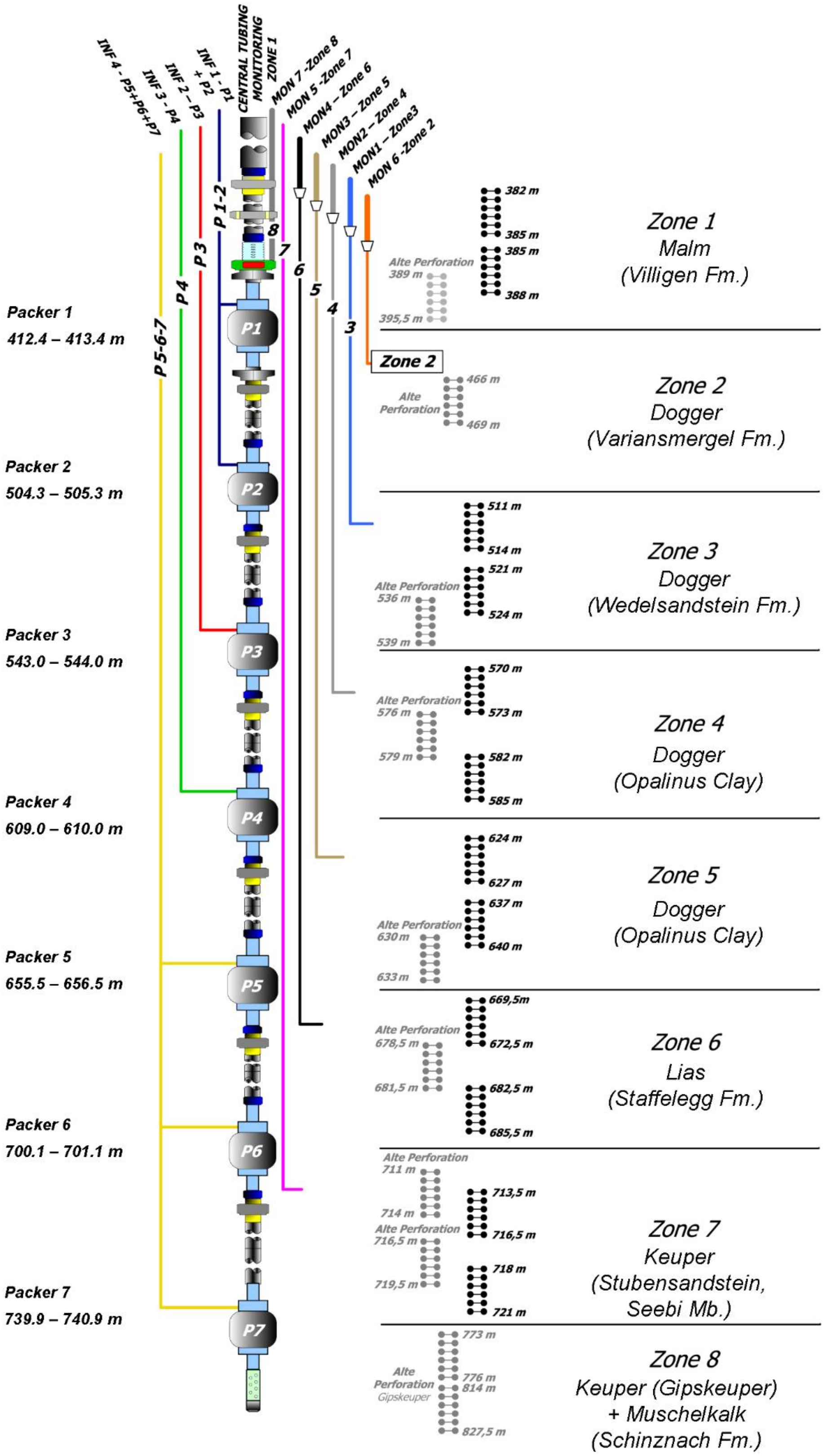

Figure 5: Schematic drawing of the multi-packer system in Benken with monitoring zones and perforation intervals

We outlined the concept for surface-based monitoring of the environment and the geological surroundings that will form the basis for further optimised assessment of baseline conditions before repository construction starts. Monitoring includes meteorological stations, soil and hydrogeological measurement and sampling campaigns and geodynamic and geotechnical processes.

In the low-deformation Alpine foreland of Switzerland, geodynamic processes can only be detected by means of long-term monitoring. We present snapshots of microseismic and GNSS station networks, which allow resolution of horizontal displacements of 0.2-0.3 mm/y (GNSS) and complete detection of $M_L \geq 1.0$ microseismic events in the area of interest. Multi-packer systems are used to monitor hydraulic pressure evolution in the low-permeability host rock and other formations of interest, thereby reducing the uncertainties of the undisturbed hydraulic heads in the monitored formation. Such baseline monitoring will be extended to capture possible effects of the construction and operational activities until a decision on final closure of the DGR is taken.

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