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Nagra's permanent GNSS network for geodynamic monitoring in the sub-millimeter range: site selection, installation and first measurement results

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Abstract
The geological evolution of a deep geological repository (DGR) for the safe disposal of radioactive waste is an important issue many developed countries are facing. The National Cooperative for the Disposal of Radioactive Waste (Nagra) in Switzerland uses various methods to assess the geodynamic situation of Northern Switzerland with regard to the long-term stability of a DGR planned in this region. One such method is the trend analysis of long-term time series of position coordinates measured by permanent Global Navigation Satellite System (GNSS) stations.

Swisstopo (Swiss Federal Office of Topography) operates the Automated GNSS Network of Switzerland (AGNES), consisting of about 30 permanent GNSS stations evenly distributed throughout Switzerland. In order to densify this existing network in the potential siting regions for a DGR and to allow the placement from a geological point of view, Nagra began operating its own permanent GNSS stations (NaGNet).

Identification of geologically suitable sites for these stations was achieved by overlaying relevant information in a Geographic Information System (GIS), followed by a verification in the field. All stations were located in areas with minimum slope gradients and maximum satellite visibility. They were either placed directly on bedrock or their foundations were reinforced with grout-injected piles. In total, 11 new stations were installed over an area of ca. 3'000 km^2.

Measuring very slow geodynamic deformation rates is a challenging task. This paper presents site selection, construction and first measurement results after more than a decade of successful GNSS station monitoring.

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1 Motivation & Background

Nagra is responsible for the safe disposal of all radioactive wastes in Switzerland. International consensus is that the safest option is deep geological disposal. The Swiss Sectoral Plan (SFOE, 2008) defines the procedure for selecting deep geological repository (DGR) sites. Opalinus Clay, an over-consolidated, approx. 175-million-year-old Mesozoic shale has been identified as a suitable host rock for a DGR in Northern Switzerland (Nagra, 2008). A DGR for high-level waste, consisting of spent fuel rods from the nuclear power plants, is designed to retain the wastes for more than 1 million years. In this context and given timeframe, geodynamic processes need to remain below certain threshold values.

Repeated high-precision levelling gives a good indication of vertical deformations. The first measurements in Switzerland started in the late 19th century. Long time series allow for the identification of vertical uplift rates as low as 0.1 mm per year (Schlatter, 2013 and Fuhrmann & Zippel, 2013). Resulting uplifts of ~100 m after 1 Ma demonstrates that a DGR several hundred meters below ground will be protected against potential erosion. Such short-term measurements are important for quantifying recent processes and extrapolations are verified by methods such as river terrace dating and basin modelling (Nagra, 2008).

Horizontal displacements as low as 0.1 mm per year can also be captured reliably with

ID	NaGNet station	Located in	Type of foundation	Electricity supply	Internet connection	Monitoring since
BCKL	Buchs	Switzerland	With piles	Grid	LAN cable	June 2011
BZBG	Bözberg	Switzerland	With piles	Grid	LAN cable	Febr. 2011
HCHS	Höchenschwand	Germany	On rock	Solar panels	GSM	May 2011
HGGL	Hägglingen	Switzerland	With piles	Grid	LAN cable	Oct. 2010
LFNB	Laufenburg	Germany	With piles	Grid	GSM	May 2011
MRGT	Murgenthal	Switzerland	With piles	Grid	LAN cable	Oct. 2010
SLTB	Seltisberg	Switzerland	On rock	Grid	LAN cable	Febr. 2011
STDL	Stadel	Switzerland	With piles	Grid	LAN cable	Nov. 2010
THYN	Thayngen	Switzerland	On rock	Solar panels	GSM	June 2012
TRLK	Trüllikon	Switzerland	With piles	Grid	LAN cable	May 2011
WLCH	Wilchingen	Switzerland	With piles	Grid	LAN cable	March 2012

Tab. 1: Nagra's 11 permanent GNSS stations and the details of their installation

well-placed permanent GNSS stations by analyzing their data continuously over a long time period (years to decades). By collecting GNSS signals with an antenna sensitive to the carrier frequency, the receiver can calculate the distance from the antenna to the transmitting satellite and by doing this for at least four satellites the three-dimensional position can be triangulated (Zogg, 2014). For accurate centimetric positioning, at least 5 satellites are required in addition to a geodetic datum as reference. The main satellite systems providing this information are the Global Positioning System (GPS), developed by the United States military and supplying a non-artificially disturbed signal since the 1990ies with 31 satellites and the Russian's Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS) with 24 satellites currently in orbit. Today, the system of the European Union (GALILEO) also has 24 active satellites as well as China's BeiDou, not counting the newest Chinese satellite generation.

Swisstopo has operated a network of permanently installed GNSS stations as reference points for local surveyors since the 1990ies. This Automated GNSS Network for Switzerland (AGNES) consists of stations at about 30 locations evenly distributed throughout Switzerland (Brockmann et al. 2006) with an average station spacing of approx. 70 km. As part of the siting process for a DGR, Nagra decided in 2009 to densify the AGNES network with an additional eleven stations optimally placed from a geodynamic viewpoint. Station distribution in the tectonic framework and best connection to the bedrock were criteria for site selection.

2 Siting process

The process developed for identifying suitable station locations is outlined in Figure 1. Ideally, geodetic GNSS stations are evenly distributed within the monitored region, forming a regular network of equilateral triangles. Furthermore, the stations were planned to sample all relevant tectonic units, thereby respecting sufficient distance from regional tectonic faults. For the region between Basel in the west, Lake Constance in the east, the Black Forest in the north and Lake Lucerne in the south, eleven new GNSS stations with average station spacing of approx. 25 km was found ideal, also from an

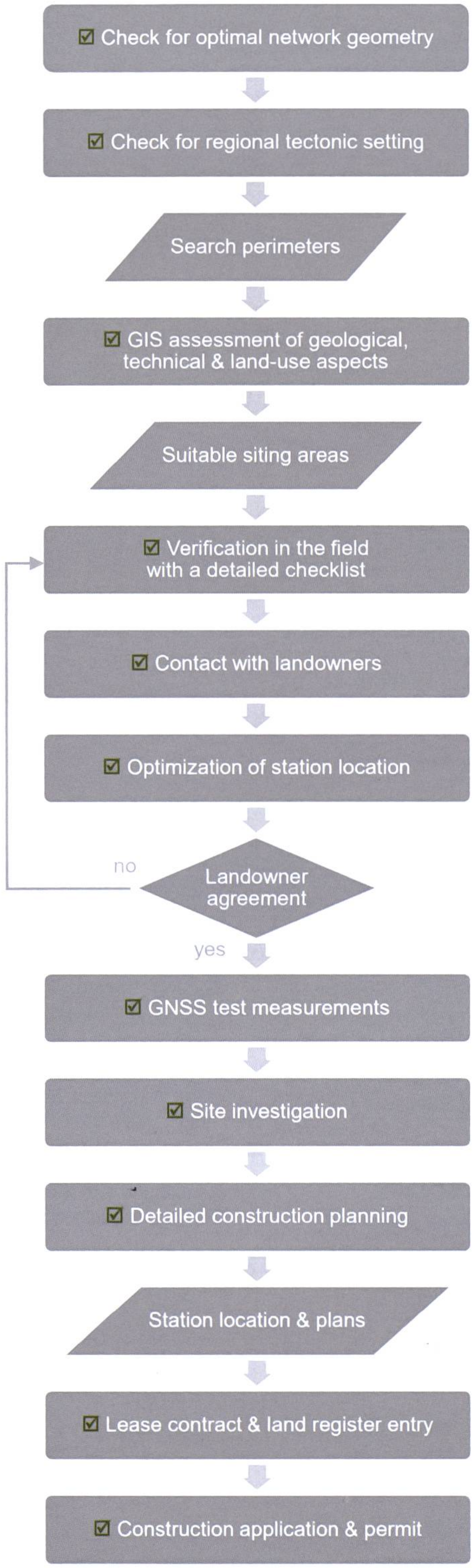

Fig. 1: Siting workflow for Nagra's permanent GNSS stations tracking geodynamic deformations in Northern Switzerland.

economical viewpoint. At least one station was also to be placed in each of the potential repository siting regions.

Optimization between an ideal network design and the tectonic setting was an iterative process, which was guided by geological experience. After the definition of station specific search perimeters, all information relevant for identifying ideal sites for permanent GNSS stations was collected and stacked with a GIS software. The relevant criteria were refined with the help of experts. Simplified, the criteria can be grouped into geological, technical and land-use aspects.

In order to allow for the transferability of the station velocity to the underlying geological unit, the permanent GNSS stations needed to be embedded to outcropping bedrock where possible. Otherwise, minimal thickness of the topsoil and unconsolidated sediments was targeted. Areas of local subsidence (e.g. due to underground construction) or mass movements (e.g. landslides) were excluded. Plain topography with an inclination below 2° were targeted.

Satellite visibility was judged with the help of digital terrain models (DTM). Locations with a free, undisturbed view of the sky and a horizon below 3° from horizontal were favored. Although the placement of GNSS antennas on multistory buildings can help to address this issue, such installations were eliminated due to the potential for differential movements (e.g. settlement). Potential disturbances of the GNSS signal were anticipated by avoiding planar surfaces (e.g. lakes), which may lead to so-called multipath errors, and other sources of electromagnetic signals (e.g. mobile phone antennas and power poles). Selection of the choke-ring antennae design to suppress multipath further mitigated this issue.

Finally, aspects of land-use planning (e.g. protected areas), possibly conflicting with

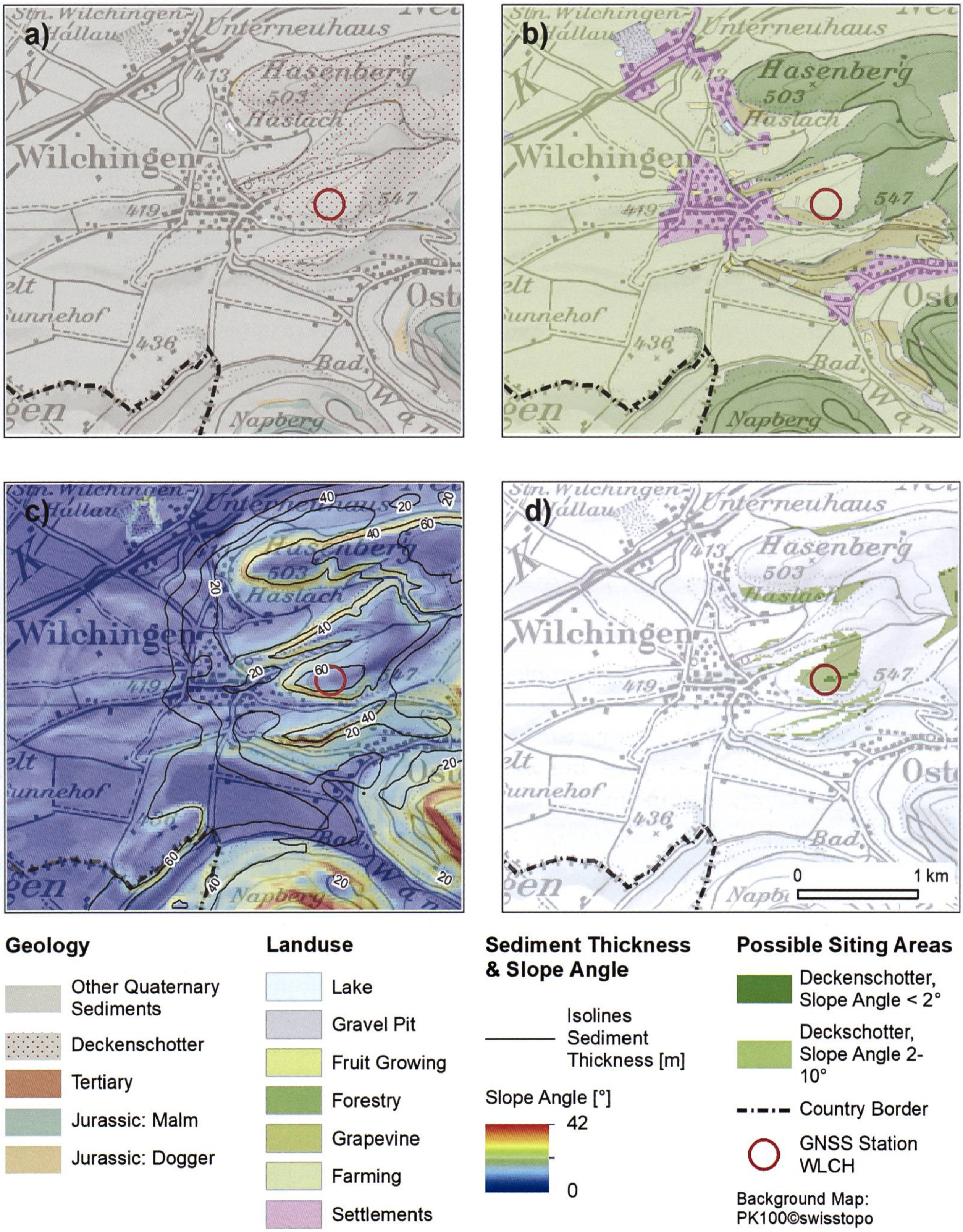

Fig. 2: Exemplary sketch of the evaluation process for identifying suitable siting areas with the help of a geographic information system; maps representing a) geological units, b) land-use zones, c) unconsolidated sediment thickness and slope inclination, d) possible siting areas for GNSS stations. In this case the GNSS station Wilchingen was constructed on a conglomerate («Deckenschotter»).

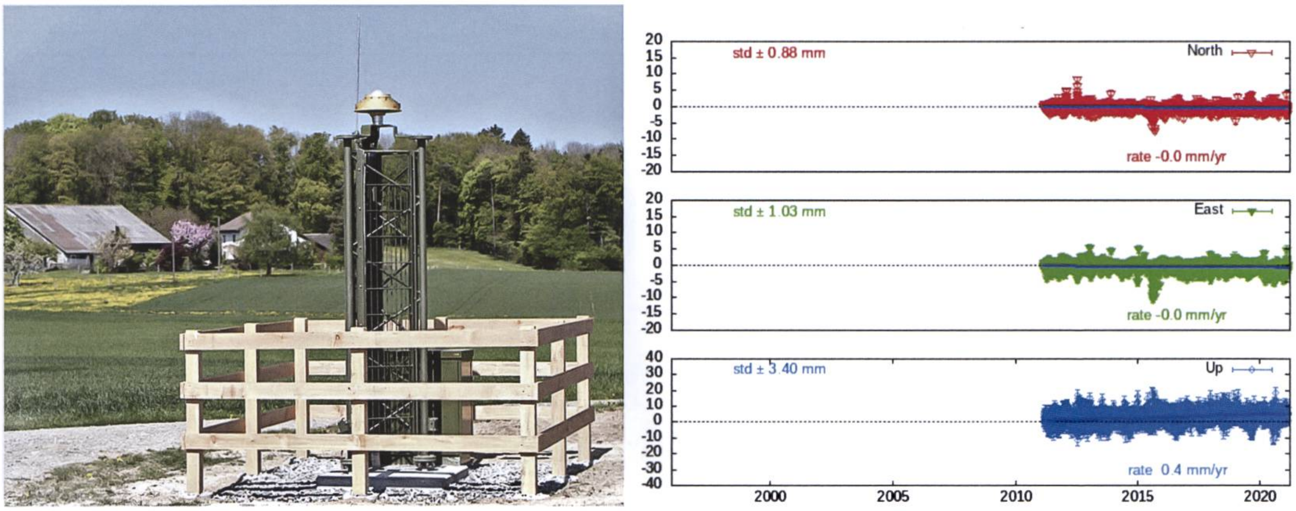

Fig. 3: Exemplary photograph of Nagra's permanent GNSS station Trüllikon (left) and exemplary time series from the north/east/up coordinates of Nagra's permanent GNSS station Seltisberg (right).

the required construction permits, were considered. An example of the GIS supported desktop evaluation process is illustrated in Figure 2. Early in the assessment it became apparent that there are not many suitable locations for permanent GNSS aimed at capturing slow geodynamic processes in Northern Switzerland. Desktop studies were followed by a verification in the field. A checklist was developed covering the aspects used for the GIS assessment, but was extended by additional parameters such as local obstacles not visible on a DTM (e.g. trees).

When the most suitable areas had been identified, the landowners were contacted and lease agreements set up. Test measurements were performed at each site by recording GNSS signals for 72 hours. The signals were analyzed with the LEICA Spider software for quality parameters (e.g. signal/noise ratios, cycle slips, code multipath). The shallow underground was then investigated with the help of dynamic probing. For all locations a stiffness modulus of more than 30'000 kN/m^2, suitable for the foundation of permanent GNSS stations, was found roughly 1 – 8 m below ground level. Once the permits had been granted by the authorities, construction started in 2010.

3 Construction, Installation and operations

3 out of 11 stations were built directly on sound rock by excavating pits with a depth of ca. 2 – 4 m below ground level. For each of the remaining stations, 3 piles were drilled ca. 7 – 15 m into the ground and each injected with several hundred liters of a cement-based grout. On top of the rock or piles a rigid concrete base was poured holding a steel grid mast with a height of ca. 2.6 m. Steel grid masts were chosen because of their low weight (leading to a reduced potential for settlement), minimal visual impact, wind insensitivity, durability and replaceability.

At every station a cabinet was installed housing all electrical components (e.g. GNSS receiver, modem, power surge protection, batteries, ventilation, heating). Whenever economically feasible, the stations were connected to a permanent electricity supply and internet connection; connecting distances were ca. 100 – 500 m. A few remote stations are operated via mobile phone internet connection and solar power supply (Table 1). All equipment was procured via public submission. After performing a sound calibration, the high quality GNSS equipment (choke-ring anten-

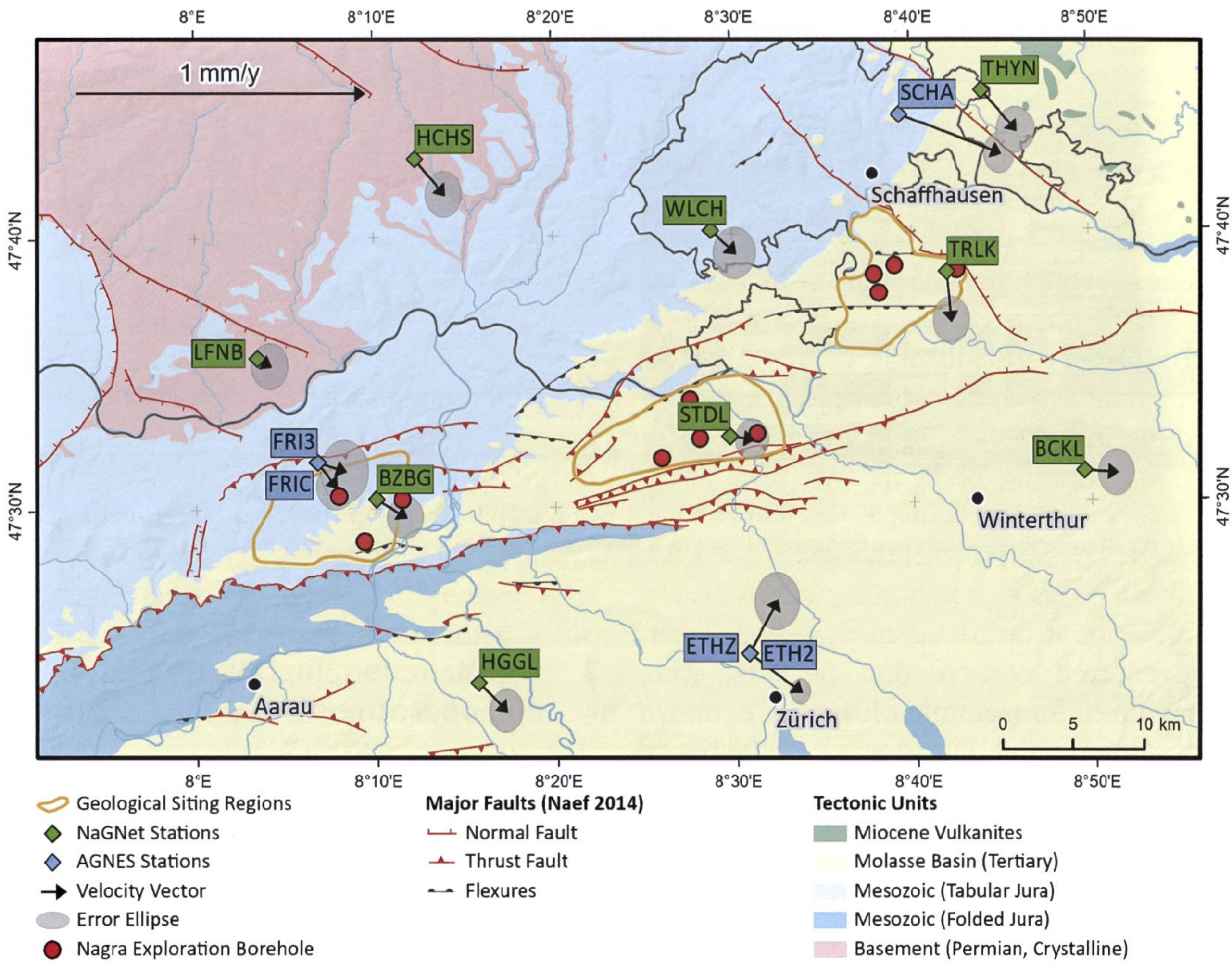

Fig. 4: Distribution of NaGNet and AGNES permanent GNSS stations in Northern Switzerland. Horizonal displacement rates (mm/y) with respect to the Swiss reference station Zimmerwald (ZIMM) are shown. Ellipses indicate uncertainties.

na AR25 & receiver GRX1200+) from LEICA Geosystems were installed on the masts (see Figure 3) and permanent recording was started.

The LEICA Spider software is used for continuously and automatically checking all relevant operating and quality parameters for each permanent GNSS station. Recording out-of-bound parameters triggers a field inspection according to a well-defined maintenance protocol.

The Receiver Independent Exchange Format (RINEX) files produced on an hourly and daily basis at each station are automatically retrieved by swisstopo's servers. The data with 30 s sampling interval are transferred to swisstopo's Permanent Network Analysis Centre (PNAC) (Brockmann, 2006) for processing with the scientific Bernese GNSS software (Dach, 2015). Results are made available and updated every hour on a dedicated open-access web platform (http://pnac.swisstopo.admin.ch).

With a delay of several days until the precise satellite orbits of the CODE analysis center (Dach, 2020) are available, the precise 3D-coordinates for each permanent GNSS station are updated. The original 30 s time series of these coordinates are then averaged to receive hourly, daily, and weekly data series. Using a statistical trend analysis, the long-term horizontal (and vertical) deformation rates of each permanent GNSS station can be derived.

An example of such a time series including the trend estimation is shown in Figure 3. Station velocities are expressed in relation to the Swiss reference station Zimmerwald. A first indicator of the quality of the stations from a measurement viewpoint is the high coordinate repeatability based on weekly GNSS solutions, which for most NaGNet stations is (as initially targeted) ca. 1 mm horizontally and ca. 3 mm vertically or less. In comparison to the analysis of other European and Swiss stations, the repeatability performance of the Nagra stations is excellent.

A detailed description of the installation and setup of Nagra's permanent GNSS Network (NaGNet) can be found in Studer & Zanini (2013). The data processing and analysis are described in Brockmann (2006 and 2010).

4 First measurements, interpretation and outlook

Average horizontal velocities derived from more than one decade of monitoring permanent GNSS stations in Northern Switzerland (see Tab. 1 for monitoring start times) are shown in Figure 4.

The horizontal movements in the region of interest are small and usually less than 0.2 mm/year (relative to Zimmerwald). The confidence ellipses of the velocity estimates shown in Figure 4 indicate that the inferred movements become statistically significant after one decade of monitoring. We draw two important conclusions: (1) permanent GNSS monitoring has shown no tectonic movements larger than 0.2 mm/y in an area surrounding the siting regions for a DGR, and (2) no substantial deformation (e.g. strain) is observed in the area. For identifying a suitable site for a DGR differential deformation patterns in the region prove relevant for indicating potentially active tectonic fault zones. Consequently, the relatively inactive northern Switzerland (e.g. Houlie et al., 2018) provide the necessary tectonical stability to host a DGR.

Beside the displacement information shown in Figure 4, resulting from a combined analysis of AGNES and Nagra permanent stations, there are two additional information sources:

1. Passive GNSS stations: swisstopo maintains a LV95-network of 200 passive GNSS markers (with an average spacing of approximately 25 to 35 km) which are selected based on geological criteria. Also this network was densified with stations of special interest for Nagra. All points are re-observed approximately every 6 years, allowing for a very reliable velocity information[2] (Online results: http://pnac.swisstopo.admin.ch/pages/en/chtrf.html) on an even more densified scale (Brockmann, 2018).

2. European site velocities: The stability of points outside the Swiss border is shown in the project "EU Dense Velocities" (Brockmann, 2019) under the umbrella of the European Reference Frame (EUREF). More than 30 contributions from many European countries result in about 7'000 site velocities in Europe in January 2021. Interestingly, a combined data set derived from INSAR, GNSS and leveling in the areas South-west Germany, France and North Switzerland is included in this European data set.

Geodetic monitoring of permanent GNSS stations in Northern Switzerland provides valuable insight into tectonic movements in the region. Such information is important for the siting and emplacement of a DGR and monitoring will continue during the later monitoring phase.

Challenges during this long time period could prove to be the replacement of aging equipment (such as GNSS antennas and receivers) or due to major technology developments (e.g. newly available satellite systems) without disturbing the long-term trend measurements. Another challenge will be the data storage and, consequently, the reprocessing of the data. Together with the involved experts from universities and organizations such as swisstopo, Nagra is very confident that these challenges can be tackled, as proven by the last 30 years of successful GNSS monitoring in Switzerland.

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