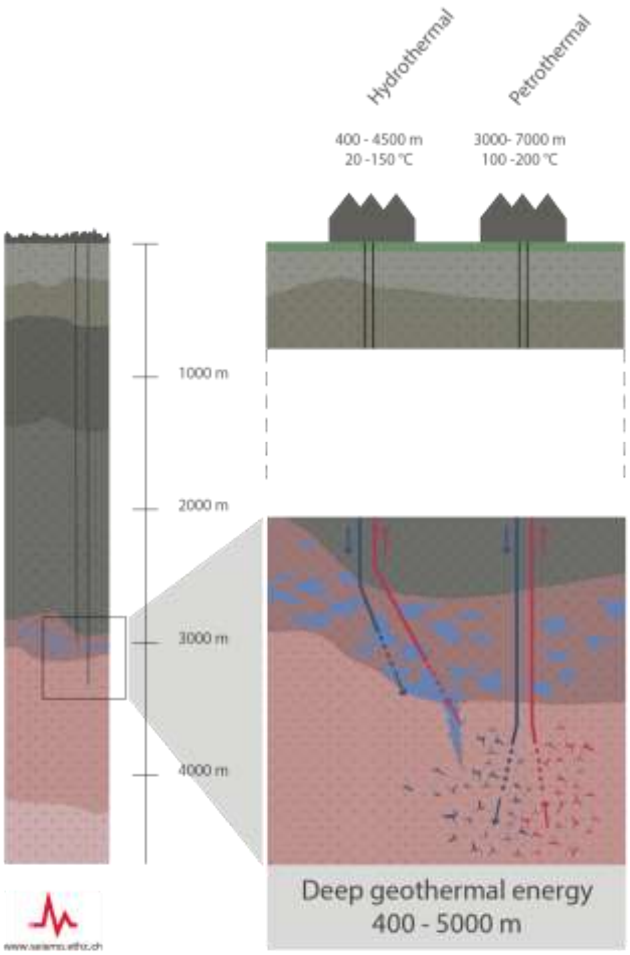
Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

"Good Practice" Guide for Managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland



induSED seismicity

swiss energy
Our commitment: our future.

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Cover picture

Schematic representation of the two types of systems for energy recovery from great depths: petrothermal and hydrothermal.

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Content

1. Introduction

1.1 Motivation, background and context

Switzerland is facing a challenging turn in its energy policy. Nuclear power plants, which cover 39% to 45% (in winter) of the national electricity consumption, will be phased out over the next decades. Strategies for future energy supply[1] include deep geothermal energy as a potential resource of both heat and electricity generation that is extremely large, nearly CO_2 free, domestically sourced and probably reliable (e.g. Hirschberg et al. 2015).

Both high-profile, deep geothermal energy projects initiated in Switzerland in the last 10 years have been stopped – with financial losses exceeding 100 Mio. Swiss Francs – partly because of felt induced earthquakes and the concerns they caused. Other types of geo-energy projects using the deep underground have been experiencing similar challenges around the globe, such as fracking-related waste-water disposal in the eastern United States, fracking-induced earthquakes in United Kingdom and western Canada, ground-water-extraction-related induced earthquakes in Spain or gas-reservoir depletion-related earthquakes in the Netherlands. Managing induced seismicity has thus increasingly become one of the most pressing challenges for geothermal and other geo-energy applications that alter the stress and pore-pressure conditions in the underground (Kraft et al., 2009; Giardini, 2009; Zoback et al., 2012; Ellsworth, 2013; Grigoli et al., 2017).

As a consequence, the topic of induced earthquakes is now high on the agenda of many research institutions worldwide, leading to a strong increase in the number of scientific, peer-reviewed publications (Figure 1). The knowledge and understanding of induced seismicity is evolving rapidly.

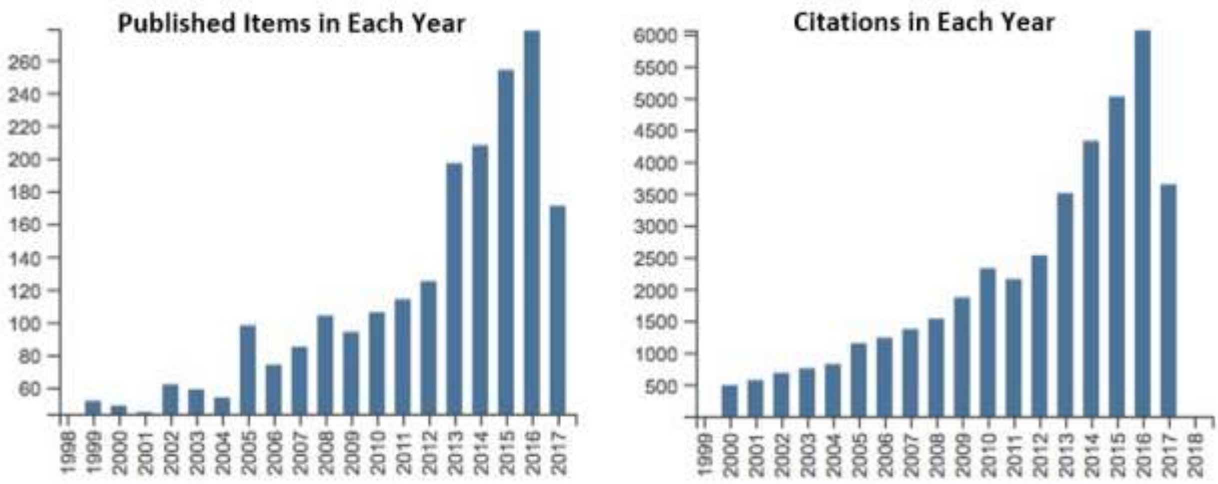

Figure 1: Left: Number of publications in the last 20 years that list 'induced earthquakes' as a topic. Right: Number of times these publications have been cited (from *Web of Science*, status: August 2017).

1.2 The goals and limitations of this good practice guide

The Swiss Seismological Service at ETH Zurich (SED, www.seismo.ethz.ch) wants to contribute to a sustainable and safe use of deep geothermal energy with this report on good practice on monitoring, assessment and management of induced seismicity related to the exploitation of deep geothermal energy. The report is aimed at a range of audiences: field opera-

[1] http://www.bfe.admin.ch/energiestrategie2050/06445/index.html?lang=en [Accessed: 17 Oct. 2017].

tors, regulators at local, cantonal or federal level, insurance companies looking to assess the financial risk, as well as media and the general public that wish to be informed on the topic.

The report builds on the wide range of knowledge and experience that the SED has collected in the past years through participation in the monitoring as well as in the hazard and risk assessment for a number of deep geothermal projects in Switzerland (e.g., (e.g., Basel (2006-today), Zurich (2010-2011), St. Gallen (2013-today, Figure 2), Schlattingen (2013-2015), Geneva (2016-today)). In this context, the GEOBEST[2] project, funded by the Swiss Federal Office of Energy (SFOE) and *SwissEnergy*[3], are instrumental in gaining experience in seismic monitoring and induced-seismic hazard and risk assessment. The report also builds on the ongoing research at the SED and at the *Swiss Competence Center for Energy Research – Supply of Electricity* (SCCER-SoE). It benefits from the research and discussions with colleagues from other countries, for example, during the Schatzalp workshops on induced seismicity in Davos in March of 2015[4] and March 2017[5]. We also profit in many parts from the TA Swiss study 'Energy from the Earth' (Hirschberg et al., 2015), where the SED was a major contributor.

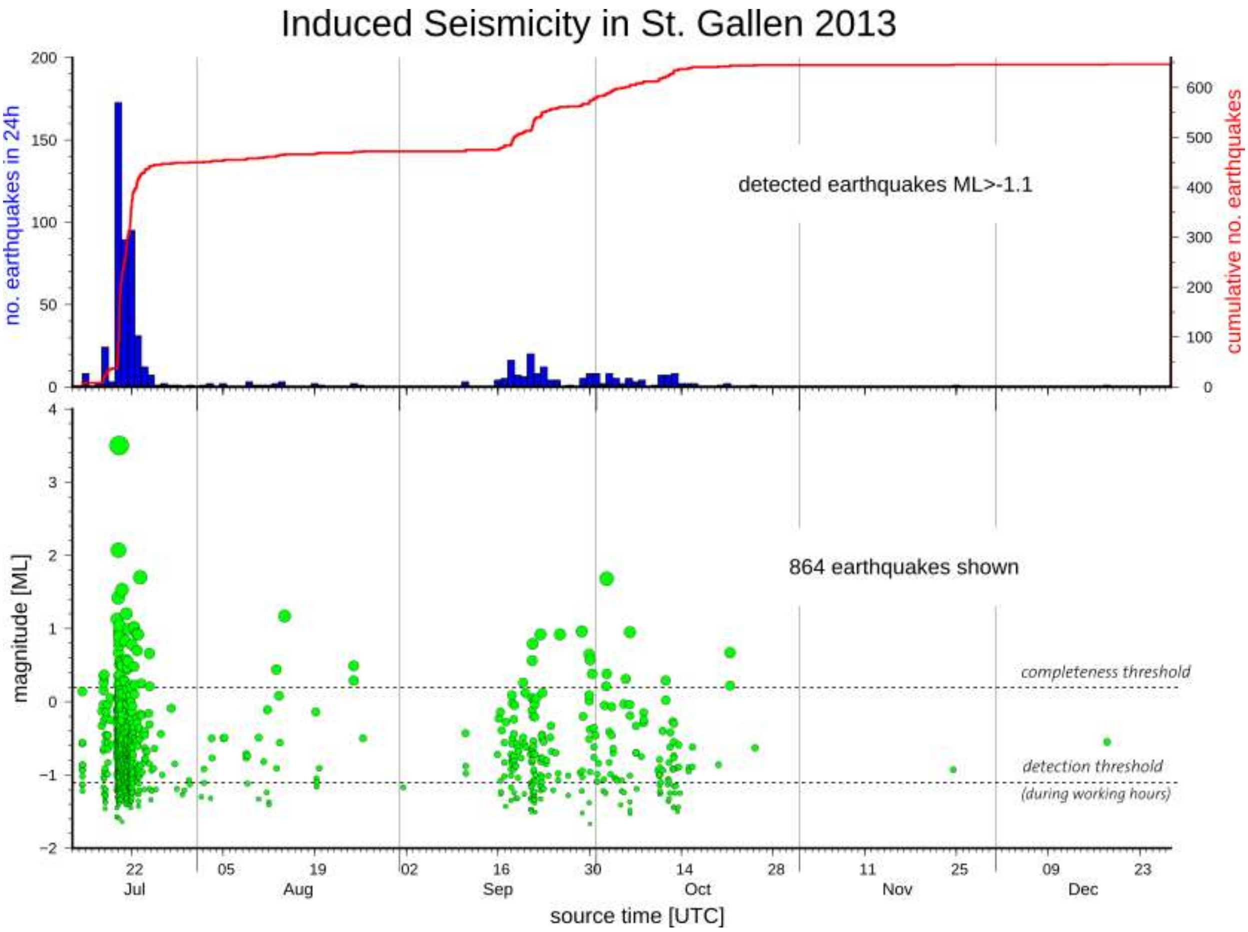

Figure 2: Induced earthquakes detected by the SED during the deep geothermal project in St. Gallen between July and December 2013 by careful visual seismogram inspection.

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[2] http://www.seismo.ethz.ch/en/research-and-teaching/ongoing-projects/#pr_00008.xml [Accessed: 28 Aug. 2017].
[3] https://www.energieschweiz.ch [Accessed: 17 Oct. 2017].
[4] http://www.seismo.ethz.ch/research-and-teaching/schatzalp-workshop/archive-first-schatzalp-workshop/index.html [Accessed: 28 Aug. 2017].
[5] http://www.seismo.ethz.ch/research-and-teaching/schatzalp-workshop [Accessed: 28 Aug. 2017].

Induced seismicity hazard and risk assessment, as well as risk management are without doubt difficult tasks. Considerable uncertainties remain in the understanding of the underground, for example we do not know with certainty where faults are, nor do we know the state of stress acting on the faults. It is generally not possible to achieve zero risk even if the good practice guide outlined in this report is followed and the SED cannot guarantee that damaging earthquakes will not occur.

We are well aware that the measures we propose here will result in additional costs to the projects. However, these costs are typically below 1% of the total project budget and in our view justified given the benefits in terms of risk reduction and acceptance by regulators and the public. In the GEOBEST-CH project, the SED is able to assist regulators and operators in monitoring and assessing hazard and risk needs during the period 2017 – 2019 with financial support from the Swiss Federal Office of Energy's (SFOE) program *SwissEnergy*.

The report is a publicly available document. It is also a living document in the sense that we strive to update it regularly as new knowledge emerges. We chose to write this good practice guide in English because we welcome and actively solicit feedback from the international community faced with similar problems. We hope that other organizations may be interested to adopt parts of the good practice guide outlined here.

1.3 The chosen concept: Induced Seismicity Risk Governance

In the good practice recommendations outlined in this report, we follow the concept of risk governance that considers "the totality of actors, rules, conventions, processes, and mechanisms concerned with how relevant risk information is collected, analysed, and communicated and how management decisions are taken" (IRGC, 2005, p. 80). This concept assumes that risk is dealt with and influenced by multiple actors, including project operators, licensing authorities/regulators, experts (including those in academia), stakeholders, media, and the wider public. The risk governance concept acknowledges two dimensions: (i) the factual risk dimension addressed in technical risk assessments and (ii) the value-laden risk dimension, when the perspectives and actions of the decision makers, stakeholders, and the wider public also shape which risks are addressed and whether they are acceptable (Stern and Fineberg, 1996; Renn, 1999, 2008; IRGC, 2005). Risk governance is neither a complementary nor a competing concept to risk assessment, risk management, prescriptive and performance-based risk regulation, or legal and compliance procedures of licensing. Risk governance, in fact, includes all these elements and adds wider consideration of social concern assessment, information (outreach), and public and stakeholder.

Successful risk governance is an analytical-deliberative process in which field operators, independent risk analysts, regulators and stakeholders collaborate in managing risks risks (Trutnevyte & Wiemer, 2017). Key elements of this process are a clear separation of roles, the transparency of the process, and the quality of the two-way exchanges and communication. In such situations, it is the role of science and engineering to produce the factual baseline for discussion and decision-making. Ideally, risk-cost-benefit analyses offer a transparent pathway to assemble and integrate relevant evidence to support such complex decision-making processes under deep uncertainties and with knowledge gaps. In a recent review article, Fischhoff (2015) outlined and discussed this kind of approach, based on selected case studies from the past. Ultimately, the acceptance of the risk assessment and risk management transpires largely from the trust in the models and in their authors.

1.4 The role of the SED in Induced Seismicity Risk Governance

The SED is one of several actors and has several specific roles in induced seismicity risk governance. First of all, the SED is an independent actor. The SED is the official specialist unit in Switzerland for earthquakes and, on behalf of the federal government, is responsible for monitoring earthquakes, assessing seismic hazard, and issuing warnings in the context of

OWARNA[6] and Single Official Voice[7]. Therefore, the SED has an official role to play in the case of felt induced earthquakes. Yet, the SED has currently no general mandate to be involved in the seismicity monitoring, hazard and risk assessment of deep geothermal projects. Operators as well as communal and cantonal authorities involve the SED on a voluntary basis. In each individual case, it is therefore important to define the roles and responsibilities of each involved party at the beginning of the process. Appendix A lists the official SED statement on independence and transparency.

The SED generally does not conduct hazard and risk assessment for deep geothermal projects, because qualified private companies exist that can provide this service. What's more, the SED sees its role primarily in the support of authorities and regulators, for example by accompanying such studies as part of a participatory review process on their side. The SED does, however, often accept the responsibility for the seismic monitoring and seismological analysis of the data, because substantial synergies with the existing seismic network and duties of the SED exist. Note that also earthquake insurances often list the SED as the agency responsible for issuing a verdict whether an earthquake was of natural or induced origin, although this role has yet to be formalized.

1.5 Where and when this good practice guide applies

This good practice guide applies to essentially all current and future deep geothermal energy projects in Switzerland that inject or extract fluids from the deep underground (hereafter referred to as "open systems"). This excludes closed systems used for heat pumps, where no risk of inducing earthquakes exists.

An important element of risk governance is that risks are considered consistently and transparently throughout all phases of the project. In this spirit, this good practice covers the initial phase of the project planning all the way through to the post-operation phase.

The potential of inducing seismicity and its associated risks are highly variable across the different open systems, depending on different geological, technical and built environment as well as societal parameters (e.g. depth of operation, injected or extracted fluid volume, exposed population). A primary objective of this report is to provide, in a transparent and reproducible way, suggestions for operators and regulators on adequate workflows for their specific project. In order to identify suitable workflows or risk governance processes, we recommend an initial evaluation of each project following the Geothermal Risk of Induced seismicity Diagnosis (GRID) approach, proposed by Trutnevyte & Wiemer (2017) for open or partly open geothermal systems. The GRID approach is based on a series of indicators that describe concern about induced seismicity hazard, risk, and social context. These indicators are generally available before the project is initiated, before the risk study is commissioned and before the first well is drilled. The GRID scores should be jointly evaluated by at least three parties: the project operator, the regulator (e.g. municipal authority that issues the license), and an independent expert. This joint evaluation and discussion is helpful not only for defining the geothermal project category in terms of induced seismicity concern, but also for thinking through in detail the various relevant elements for risk governance.

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[6] Optimization of Warning and Alarming for Natural Hazards (OWARNA), ABCN-Einsatzverordnung, AS 2010 5395.

[7] Verordnung über die Warnung und Alarmierung, AS 2010 5179.

2. Background on natural earthquake and seismic monitoring

One might not consider Switzerland an earthquake-prone country. Yet, unknown to many, among the top natural hazard types in Switzerland, earthquakes have the greatest potential of causing damage (BABS, 2015). This chapter summarizes a few of the key facts on the broader tectonic context, the existing monitoring networks, the distribution of seismicity, and the knowledge on seismic hazard and risk in Switzerland.

The earthquake activity in and around Switzerland has been documented in an uninterrupted series of annual reports from 1879 until 1963 (*Jahresberichte des Schweizerischen Erdbebendienstes*). Three additional annual reports have been published for the years 1972-1974. All these reports, together with historical records of earthquakes dating back to the 13th cent

ury, have been summarized by Pavoni (1977). With the advent of routine data processing by computers, the wealth of data acquired by the nationwide seismograph network has been regularly documented in bulletins with detailed lists of all recorded events (Monthly Bulletin of the Swiss Seismological Service). Since 1996, annual reports summarizing the seismic activity in Switzerland and surrounding regions have been published in the Swiss Journal of Geosciences (Baer et al., 1997; 1999; 2001; 2003; 2005; 2007; Deichmann et al., 1998; 2000; 2002; 2004; 2006; 2008; 2009; 2010; 2011; 2012; Diehl et al., 2013; 2014a; 2015; 2017a). For detailed information, please refer to the website of the SED or to the mentioned publications.[8]

2.1 Earthquake Monitoring in Switzerland

The Swiss Seismological Service celebrated its 100th birthday in 2014. In 1914 the seismic surveillance of Switzerland was anchored in a federal act and the SED officially became the responsible federal agency for earthquake monitoring. Already in 1878, the Swiss Earthquake Commission (SEC) had been established as the first permanent agency for earthquake monitoring in the world. The SEC installed the first seismographic station in Zurich in 1911. Seismograms were recorded mechanically on smoked paper by a so-called Universal Seismograph designed by the famous Swiss physicists Auguste Piccard and Alfred de Quervain. Until 1926, three more of these instruments were installed in Neuchâtel, Binningen, and Chur. In 1936, an auxiliary seismograph station was installed in Sion.

Modern seismology in Switzerland starts in 1975 with the installation of the first electromechanic high-gain-seismometer network. These stations used frequency-modulated telemetry and analog continuous data recorded on microfilm until 1983. Between 1984 and 1996 the analogue recording was replaced by first 10bit, and later 12bit, digital recording. Starting in 1996, the Swiss seismic network entered the fully digital era, that continued with the installation of a broad-band seismological network starting in 2002. In 2017, the SED is operating about 60 high-gain seismometer stations with broad-band and short-period sensors in Switzerland, and records data of nearly the same number of equivalent stations from neighboring countries in real-time (see Figure 3).

Besides the high-gain sensor network (SDSNet) outlined above, which aims to record weak ground motions from small local and large global earthquakes, the SED operates a low-gain accelerometer network (SSMNet), which aims to record strong ground motions from strong Swiss earthquakes. Such recordings help to improve the understanding of ground-motion site effects which can amplify the local seismic hazard considerably. The latest generation of these instruments is sensitive enough to also record small local earthquakes and can additionally contribute to the improvement of monitoring everyday seismicity in Switzerland.

[8] http://www.seismo.ethz.ch/en/research-and-teaching/publications/annual-reports/ [Accessed: 28 Aug. 2017].

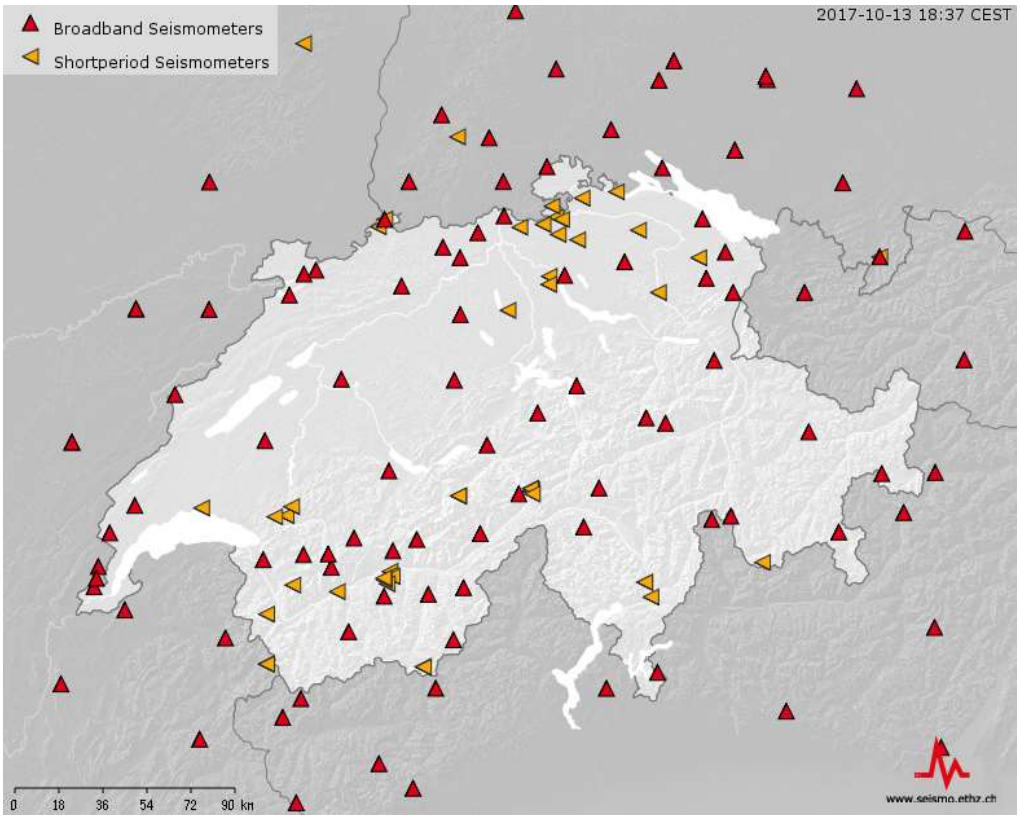

Figure 3: Map of the Swiss Digital Seismic Network (SDSNet) as of October 2017. All seismological broad-band (red triangles) and short-period seismometers (yellow left arrows) that are recorded in real-time at the SED data centre in Zurich are indicated. An updated version of this map can be found on the SED web page[9].

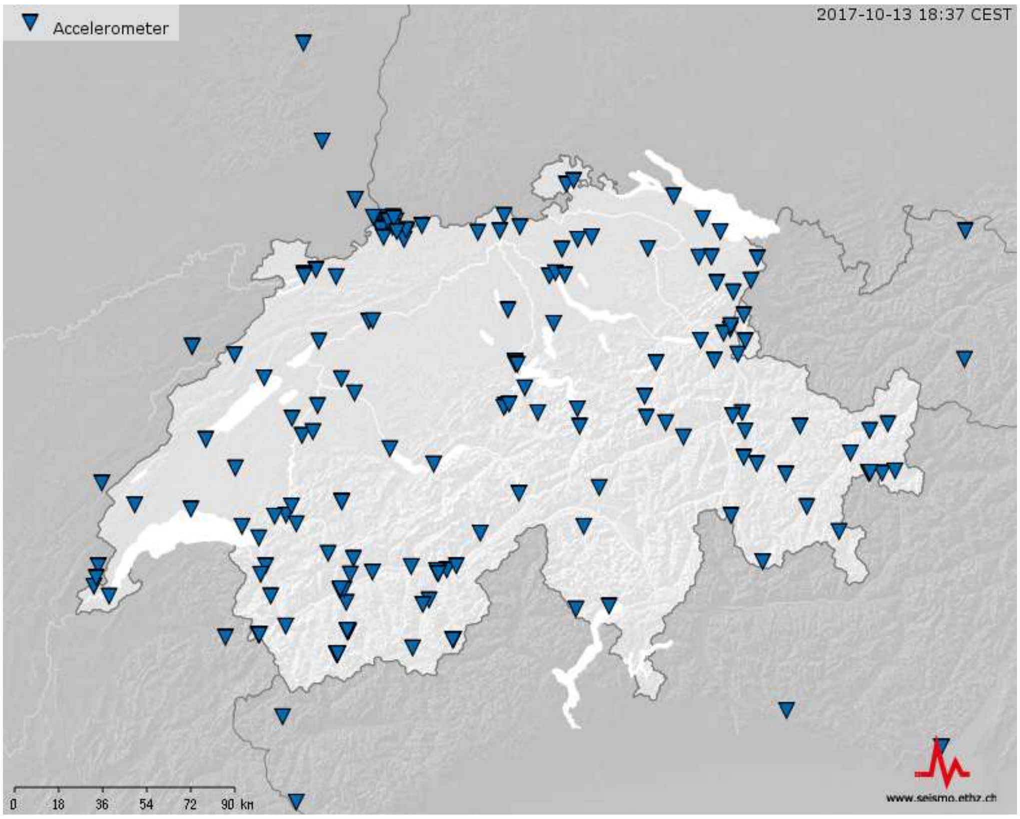

Figure 4: Map of the Swiss Strong Motion Network (SSMNet) as of October 2017. All accelerometer station (blue inverted triangles) that are recorded in real-time at the SED data centre in Zurich are indicated. An updated version of this map can be found on the SED web page[10].

[9] http://www.seismo.ethz.ch/en/earthquakes/monitoring/#cc_00031.xml [Accessed: 17 Oct. 2017].
[10] http://www.seismo.ethz.ch/en/earthquakes/monitoring/#cc_00075.xml [Accessed: 17 Oct. 2017].

The first low-dynamic-range accelerometers (12-16 bit) were installed in Switzerland starting in 1991 at about 50 free-field sites and as part of five mini-arrays in the dams of some of the largest hydro-power reservoirs (Emosson, Mauvoisin, Grande-Dixence, Mattmark and Punt dal Gall). The data was accessed by dial-up for significant events. From 2003 on, high-dynamic-range instruments (24 bit) with continuous real-time data transmission to the SED were installed. Since 2009, the SSMnet-renewal project has been aiming to install up to 100 new high-dynamic range, free-field accelerometers at neuralgic locations in Switzerland. The current status of the SSMNet is illustrated in Figure 4.

Additional to the permanent Swiss National network (CHNet) that consists of the SDSNwt and SSMnet outlined above, the SED operates temporal networks to monitor natural earthquake sequences of interest. For this purpose, a dedicated aftershock instrumentation pool was established in 2016 that consists of six mobile stations that operate totally independent of any infrastructure with solar power and mobile communication. Each station is equipped with a broad-band seismometer and a high-dynamic-range accelerometer. These activities are documented in Deichmann and Sellami (2009) and in the SED Annual Reports mentioned above.

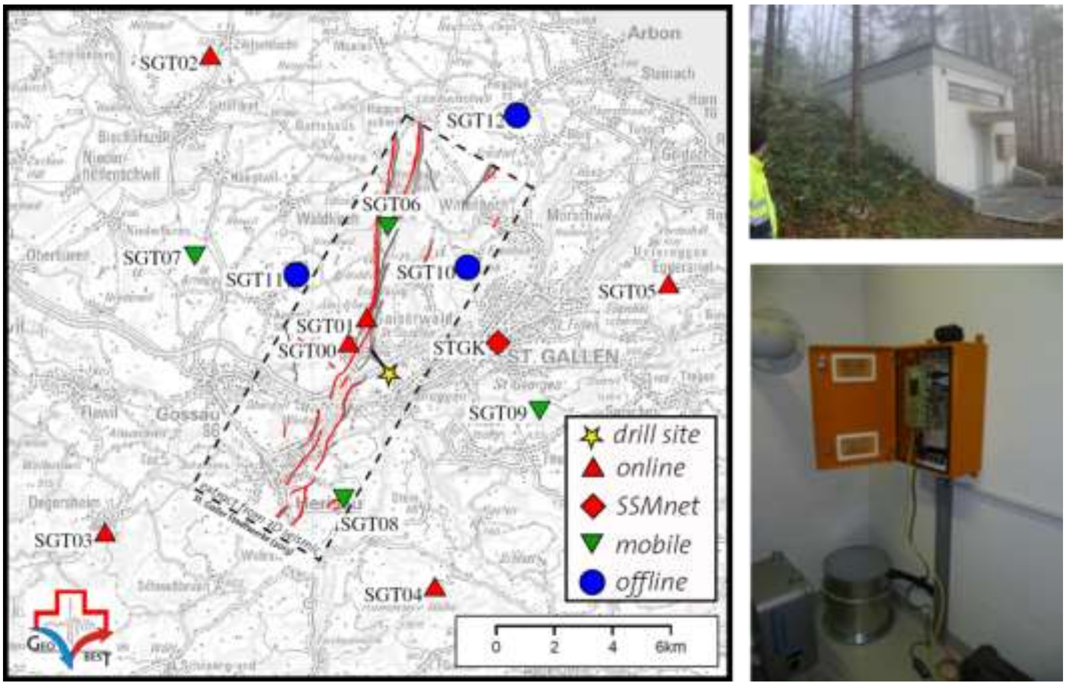

Figure 5: Left: Map of the St. Gallen region where symbols show the locations of sensors installed by the SED to monitor the St. Gallen hydrothermal project. Right: Example of a seismic station installation.

On request by cantonal authorities and project operators, and even if it is not part of its official mandate, the SED has been involved in the monitoring of geotechnical projects that have the potential to induce felt earthquakes. In recent years, deep geothermal projects have been the primary focus of these activities, but also tunneling and hydro-power projects have been monitored in the past. For geothermal energy projects these activities were partly funded by the Swiss Federal Office of Energy (GEOBEST[11] 2010 – 2015) and *SwissEnergy* (GEOBEST-CH[12] 2015-2019). The SED has also assembled a pool of 15 seismic instruments to specifically monitor seismicity related to deep geothermal projects in Switzerland. These stations are typically installed in a semi-permanent way (two years or more) in locations with low seismic background noise. To assist private service providers in finding low-noise installation sites, the SED has recently published a model of man-made seismic noise (Kraft et al., 2016) and made it available online via the GIS portal of swisstopo[13].

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[11] http://www.seismo.ethz.ch/en/research-and-teaching/ongoing-projects/#pr_00008.xml [Accessed: 30 Aug. 2017].
[12] https://www.energieschweiz.ch [Accessed: 17 Oct. 2017].
[13] http://www.map.geo.admin.ch -> search for "Antropogenic Seismic Noise" [Accessed: 10 Oct. 2017].

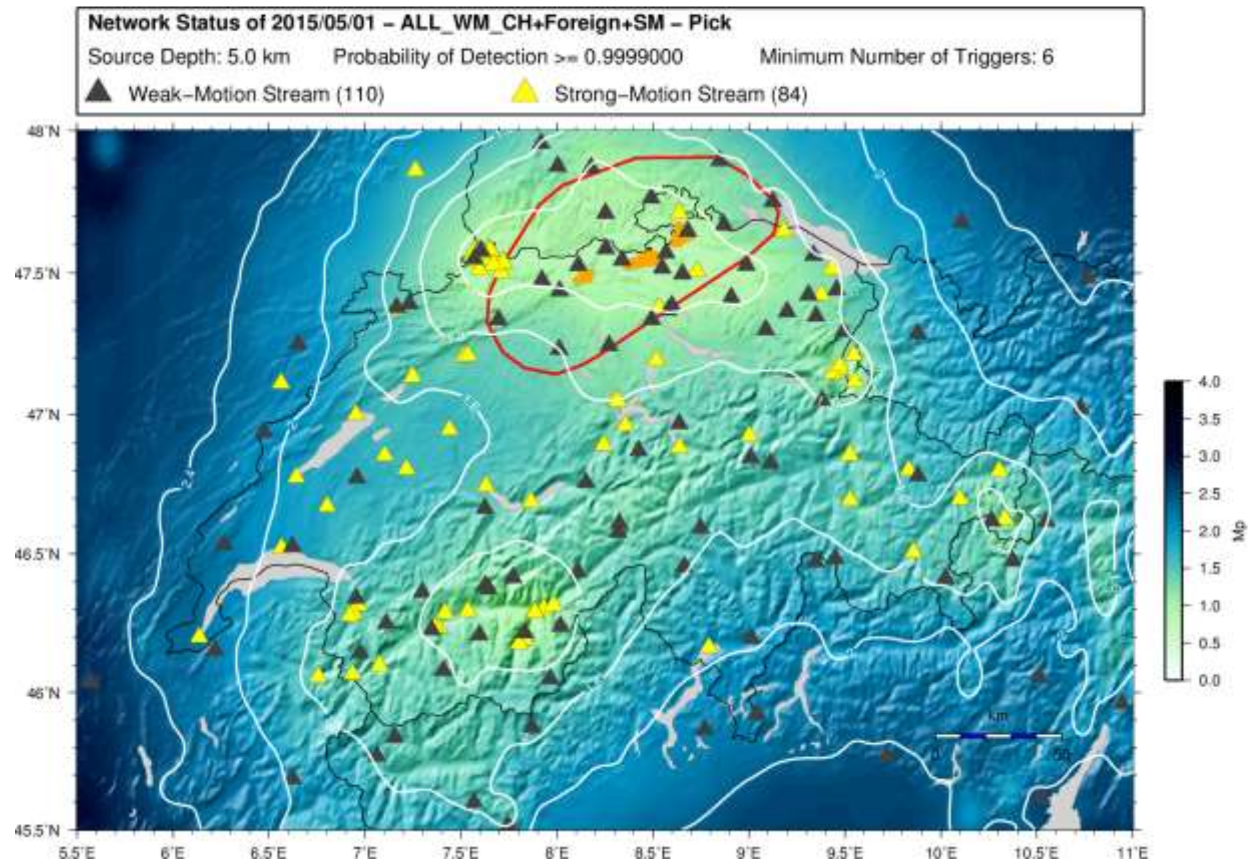

Figure 6: Map of the estimated probabilistic magnitude of completeness PMC (Schorlemmer and Woessner, 2008) using data from 2005/01/01 to 2015/05/01. All weak-motion (black) and strong-motion (yellow) stations used by SED for real-time detection (as of 2015/05/01) were considered. (After Diehl et al., 2015)

The performance of seismic monitoring in Switzerland is illustrated in Figure 6, which shows a map of the estimated completeness of the Swiss earthquake catalogue for the ECOS region (Fäh et al., 2011). Assuming an earthquake size distribution that follows the well-established Gutenberg-Richter law, the map indicates the smallest magnitude for which the catalogue can be assumed complete at a specific location. This magnitude threshold is called the magnitude of completeness and was estimated using the PMC-method of Schorlemmer and Woessner (2008) in Figure 6. At the end of 2015, a Mc of M_L 1.3 and lower was achieved for large parts of northeastern Switzerland. In regions with low noise and high close-by seismicity, the SSMNet stations improve completeness (e.g. Valais, Graubünden, Basel, Sargans). In regions with noisy strong-motion stations, Mc does not improve significantly (e.g. western Molasse Basin, Lake Geneva, etc.). For most of Switzerland Mc reaches values of at least M_L 1.6. Only the Ticino and the Geneva area have Mc values above M_L 2.0. The SED is constantly improving its network to homogenize the completeness of its catalogue in all parts of the country.

In summary, completeness of the knowledge about seismicity of Switzerland is strongly varying with time. Reliable information on small earthquakes starts to emerge in 1975, when the first sensitive seismometers are installed, and reaches a level that ensures the detection and the reliable location of potentially felt earthquakes ($M_L \geq 2.0$) in most parts of the county in 2002. As a consequence, our knowledge on the distribution of potentially active faults is still very limited.

2.2 Seismicity in Switzerland

The SED website publishes all detected earthquakes within Switzerland and its neighbouring territories (i.e. ECOS region; Fäh et al. 2011) within less than a minute of their occurrence (Figure 7). On average, the SED records 500 to 800 earthquakes with magnitudes above M_L

1.0 per year. Of those, however, the public notices only a few, mainly those above magnitude M_L 2.5.

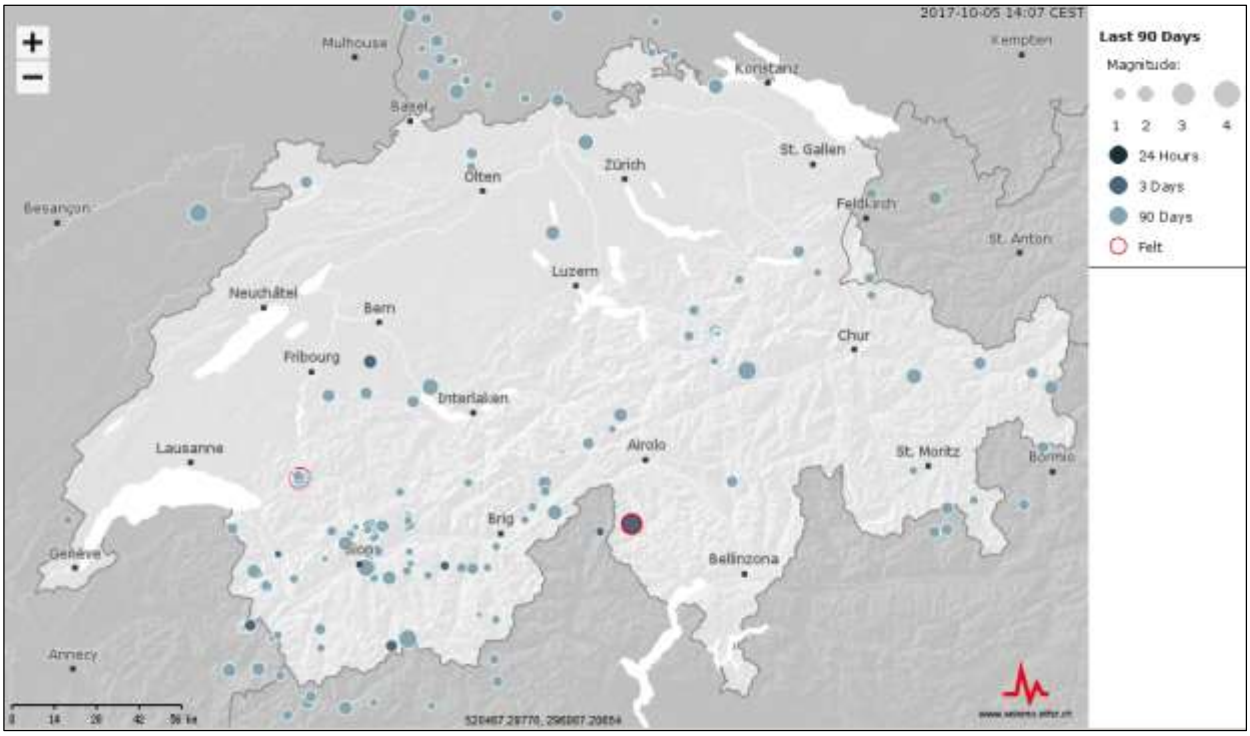

Figure 7: Map of Switzerland as published on the SED website[14]. October 5th, 2017, with the latest earthquakes.

The majority of the recorded earthquakes take place in the Swiss Alps, especially in the Valais and Graubünden (Figure 8). Seismic activity is also comparatively high in the northern foothills of the Alps, in Central Switzerland, and in the Jura and Basel regions. Earthquakes occur at markedly different depths within the Alps and north of the Alps (Figure 8). In the northern Alpine Foreland and the Jura mountains, earthquakes occur over the entire crust, down to the Moho (the boundary between the crust and the mantle, which, outside the Alps, is located at a depth of about 30 km). On the other hand, seismic activity underneath the Alps is limited to the upper part of the crust; here, quakes occur at maximal depths of 20 km only while the Moho reaches a depth of more than 50 kilometers.

Figure 9 shows the distribution of the historic seismicity in Switzerland as documented in the ECOS-09 catalogue (Fäh et al., 2011). Nine earthquakes with a magnitude M_w of 5.5 or more hit Switzerland in the past thousand years. Table 1 lists the 10 strongest earthquakes. With the exception of the largest one, the 1356 Basel earthquake, all occurred in the Alps. The Basel earthquake hit the city on 18 October 1356, at around 10.00 p.m. With a magnitude of M_w 6.6, it is until today the largest earthquake that has occurred in Europe, north of the Alps. Numerous houses collapsed, causing several fires. Considering the strength of the earthquake and the destruction it caused, relatively few people were killed because most had fled their houses after a felt foreshock and remained outside. Would the Basel earthquake occur today, an estimated number of 1'000 to 6'000 fatalities and property damage totaling between CHF 50 billion and 100 billion could be expected.

The last major earthquake in Switzerland took place in 1945 in Sierre, in central Valais (M_w 5.8). The Sierre earthquake claimed three lives and caused severe damage to 3'500 buildings. The total damage caused sums to a present-day value of around CHF 26 million. The Aigle earthquake of 1584 (M_w 5.9) is significant inasmuch as it shows that the secondary effects of an earthquake can be stronger that its primary effects, i.e. the ground shaking. The Aigle earthquake triggered a tsunami on Lake Geneva and caused a large rock fall that killed about 230 people (Fritsche et al., 2012).

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[14] http://www.seismo.ethz.ch/en/earthquakes/switzerland/last-90-days/ [Accessed: 5 Oct. 2017].

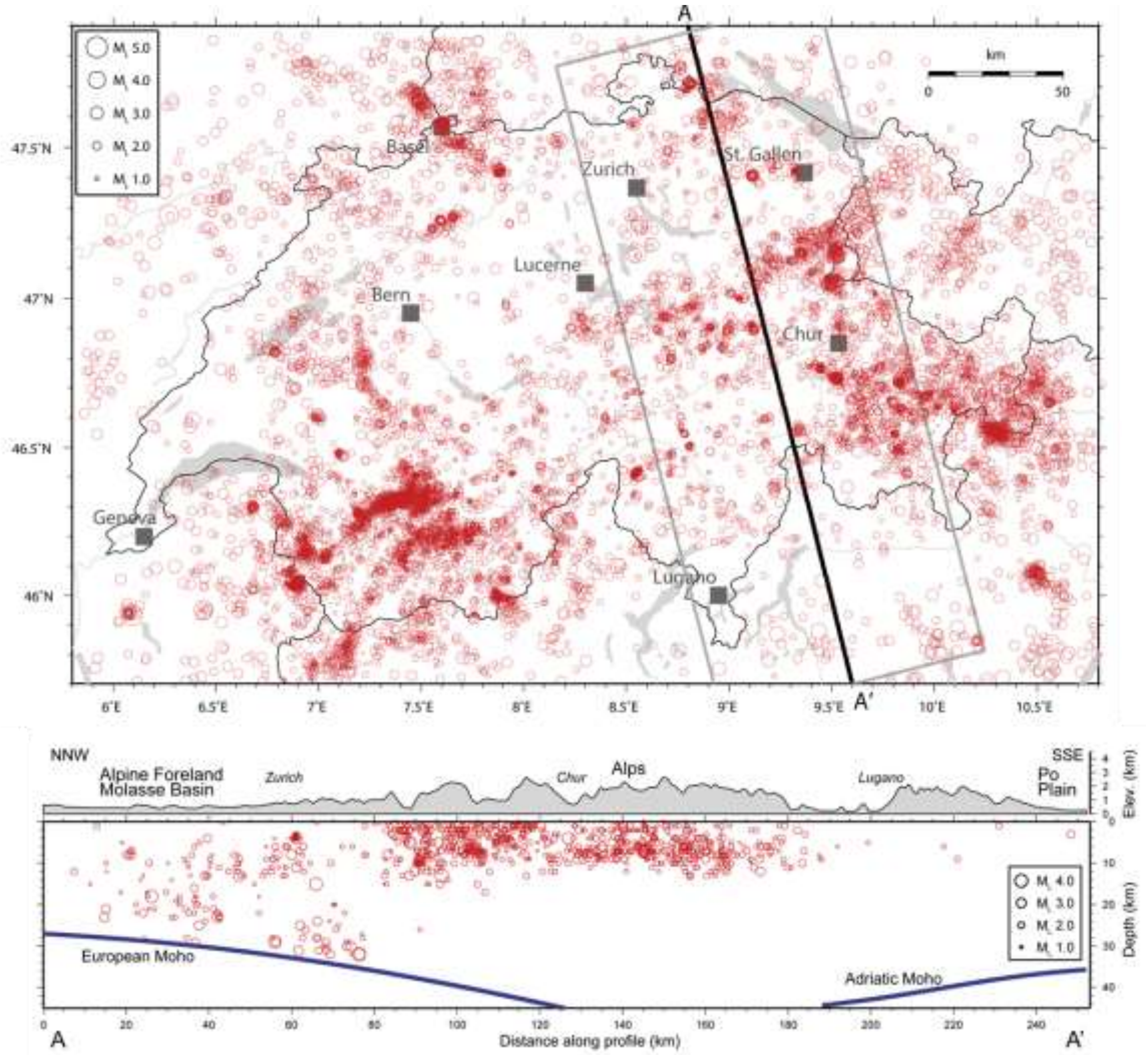

Figure 8: Top: Map of all earthquakes (red circles) with a magnitude of 1 or more in Switzerland between January 1975 and January 2014. Valais and Graubünden are regions in the Swiss Alps that show increased seismicity. The size of the circles indicates the local magnitude (M_L) of the earthquakes. The thick black line shows the location of the deep cross section through Eastern Switzerland shown below. Only quakes within the grey rectangle are used for the profile. Bottom: Vertical cross section through Switzerland documenting the distribution of earthquake depths. In the Alps, the occurrence of earthquakes is restricted to the upper crust while below the northern foothills and the Swiss plateau, earthquakes take place throughout the entire crust. The crust/mantle boundary is marked by Moho (see text). The size of the circles indicates the local magnitude (M_L) of the earthquakes. (Modified and updated from Deichmann et al., 2000).

Table 1: Date, location, moment magnitude and epicentral intensity of the 10 largest earthquakes in Switzerland

Date	Location	Magnitude	Intensity
18.10.1356	Basel (BS) with strong aftershocks	6.6	IX
03.09.1295	Churwalden (GR)	6.2	VIII
25.07.1855	Stalden-Visp (VS) with strong aftershocks	6.2	VIII
11.03.1584	Aigle (VD) with strong aftershocks	5.9	VIII
18.09.1601	Unterwalden (NW)	5.9	VIII
??.04.1524	Ardon (VS)	5.8	VII
25.01.1946	Sierre (VS) with strong aftershocks	5.8	VIII
09.12.1755	Brig-Naters (VS)	5.7	VIII
10.09.1774	Altdorf (UR)	5.7	VII
03.08.1622	Ftan (GR)	5.4	VII

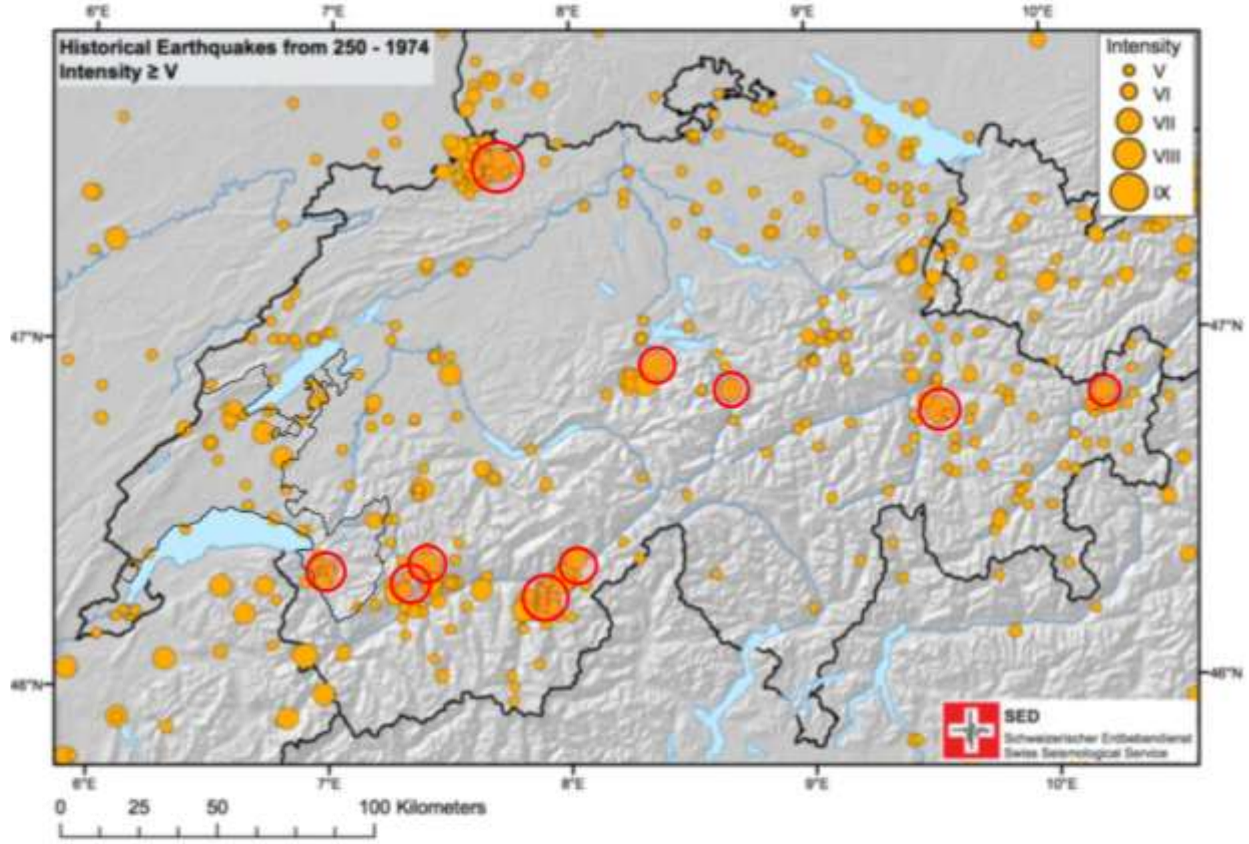

Figure 9: Historic seismicity in Switzerland between 250 and 1975. Earthquakes with an epicentral intensity larger or equal V on the EMS-98 scale (Grünthal, 1998) are shown. The 10 largest earthquakes are highlighted with red, disproportionally large circles.

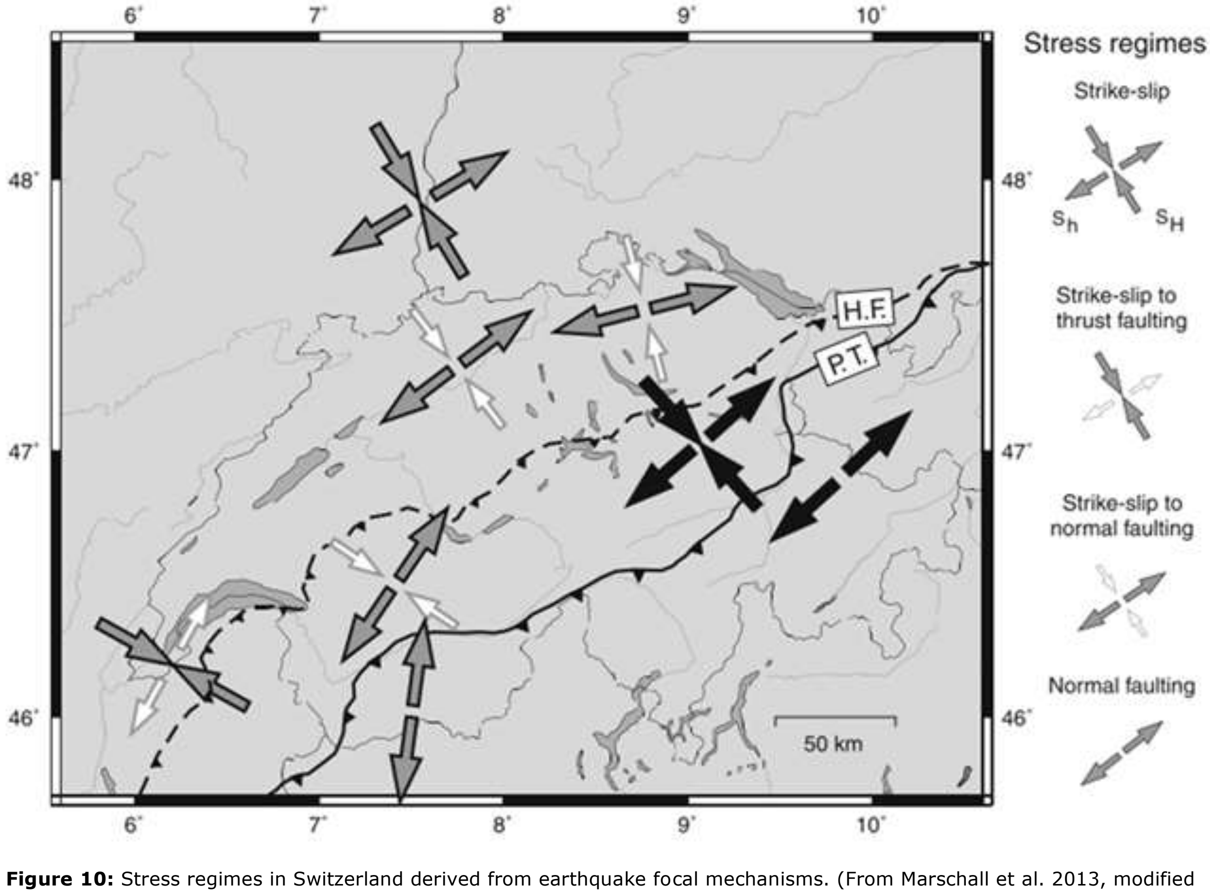

Figure 10: Stress regimes in Switzerland derived from earthquake focal mechanisms. (From Marschall et al. 2013, modified after Kastrup et al. 2004).

The regional tectonic stress field in Switzerland and the associated stress regimes can be obtained through inversions of earthquake focal mechanisms (Kastrup et al. 2004, Marschall et al. 2013, see Figure 10). The resulting picture was corroborated by including borehole and geologic indicators (Heidbach and Reinecker, 2013; Figure 11). The stress field in Switzerland is characterized by a NW–SE orientation of the maximum horizontal stress, SH (155°N in average) and a ENE–WSW orientation of the minimum horizontal stress, Sh. The large-scale contrasts in density of the lithosphere and the collision of the Adriatic and African plates with the European plate (see next section) are the primary elements that shape the stress field in Switzerland. A gradual cumulative rotation of 40° in the orientation of the mean SH from East to West can be observed, SH remaining perpendicular to the strike of the Alpine chain and parallel to the dip of the European Moho.

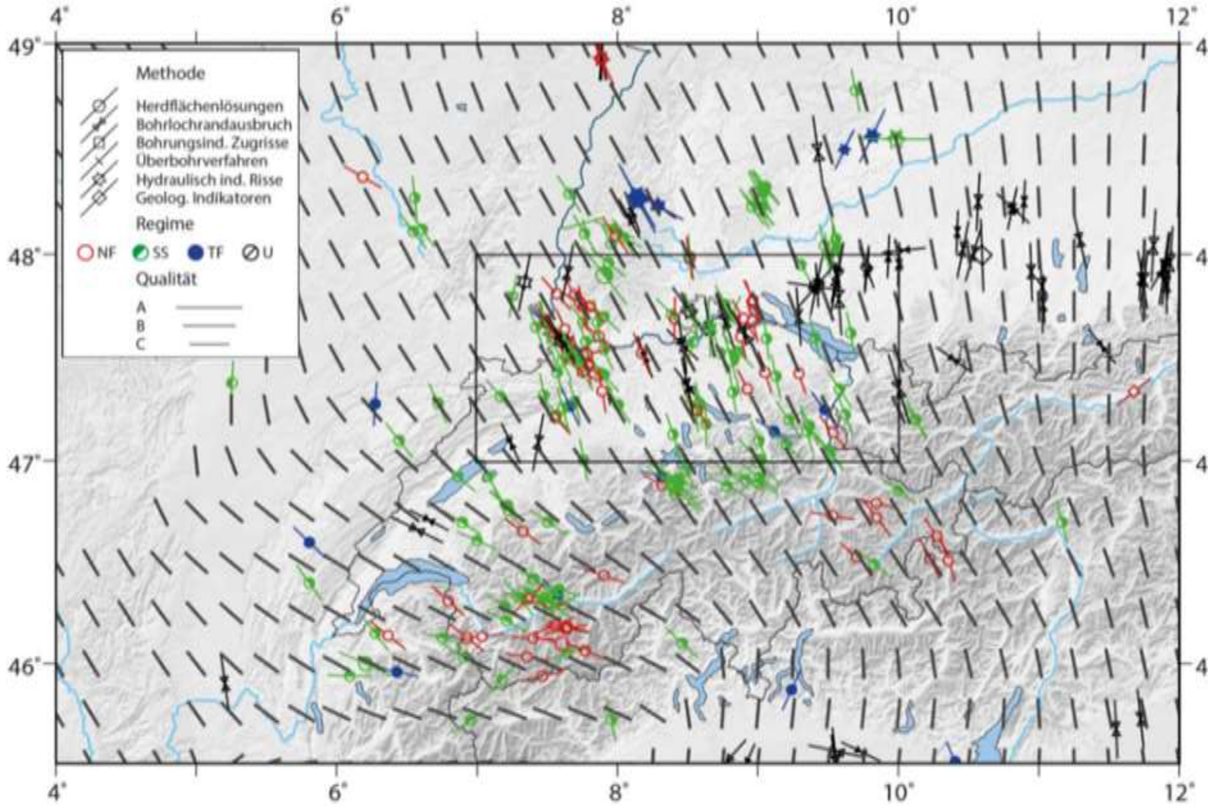

Figure 11: Smoothed regional crustal stress field (SH_{max} orientation) derived from earthquake focal mechanisms, borehole indicators (breakouts, drilling-induced tensile fractures, hydraulic fracturing or over-corring) and geologic indicators. (Modified from Heidbach and Reinecker, 2013).

Based on current knowledge, this is also essentially valid if a separation is made between the basement and the sedimentary cover in northern Switzerland (Heidbach and Reinecker, 2013). This observation can be interpreted as an indication against a large-scale mechanical decoupling of the stresses along Triassic evaporite horizons. Also, the fact that the SH orientation in the post-Triassic sediment sequence of the crust follows the SH orientation in the crystalline basement with little spatial variability seems to supports this interpretation. In the case of a mechanical decoupling of shallow and deep crust, a much higher variability of the stress field in the shallow part would be expected due to topographic effects (Heidbach et al., 2007; Roth & Fleckenstein, 2001). Locally, a decoupling might well be observed but regionally the stress regime seems to be governed in both layers by far-field tectonic forces.

The question of crustal decoupling is tightly linked to a partly controversial debate on the style of tectonic deformation that has been affecting the Jura mountains and the Swiss Molasse Basin for the past 12 Ma. It is now widely accepted that the Jura fold-and-thrust belt formed by thin-skinned tectonics in late Miocene times as a result of detachment in intra-Triassic evaporates. [e.g. Sommaruga et al., 2012 and references therein]. Recently however, evidence of a post-Miocene change from thin-skinned to thick-skinned tectonics has been reported, with basement-involved tectonic activity in the North Alpine Foreland Basin and the Jura (e.g. Becker, 2008; Madritsch et al., 2008). According to the model of Mock and Herwegh (2017), the main deformation in the Jura belt ceased ~4 Ma ago and an incipient thick-skinned tectonic regime started in the central Swiss Molasse Basin and the adjacent Jura Mountains. Mock and Herwegh see evidence of this in reflection-seismic data where the identify major NNE–SSW trending strike-slip fault zones and basement thrusts which cut the intra-Triassic detachment horizon and extend into the crystalline basement. Additionally, a mild, transpressional inversion of inherited Permo-Carboniferous trough structures seems to have occurred. Present earthquake data are in agreement with this thick-skinned strike-slip regime and indicate deformation across the intra-Triassic detachment horizon as well as NNW–SSE compression and WSW–ENE extension.

Even though it is often argued that earthquakes rarely initiate at shallow depths due to rheological reasons, several examples for such earthquakes exist in Switzerland and neighbouring countries (Table 2). For example, the Fribourg fault zone in the central Swiss Molasse Basin is associated with little basement seismicity. The vast majority of the earthquakes along this active fault zone, that reached magnitude M_L 4.3, are located at shallow depths, above 2 km and within the sedimentary cover (Deichmann et al., 2000; Kastrup et al., 2007; Vouillamoz et al., 2017). The Annecy-Épargny (M_L 5.1) earthquake (Thouvenot et al., 1998) is another emblematic illustration of a strong earthquake that has occurred – close to Switzerland – in the sediment cover, on a fault that extends into the basement. Even an example of induced seismicity is present in the list of Table 2. The M_L 3.8 earthquake that occurred in 1997 as the largest event of a small earthquake sequence at only about 1 km depth below the quarry of Quinten at Lake Walensee, was most probably triggered by the gravitational unloading of a thrust fault due to the mined-away rock mass (Deichmann et al., 1998).

Table 2: List of very shallow earthquakes in Switzerland and France between 1975 and 2012 from the ECOS catalog (Fäh et al., 2011)

Year	Depth	M_L	Location
1996	2 km	M_L 5.1	Annecy (F)
1997	1 km	M_L 3.8	Walensee (SG)
1999	2 km	M_L 4.3	Fribourg (FR)
1999	2 km	M_L 3.2	Eglisau (ZH)
2000	1 km	M_L 3.2	Saint Ursanne (JU)
2003	2 km	M_L 2.9	Neuchâtel (NE)
2006	2 km	M_L 3.2	Cortaillod (NE)

The combination of the possible reactivation of Paleozoic structure and the potential occurrence of moderate to strong earthquakes at shallow depths in the sediment package is a very important aspect to consider when assessing the potential hazard and risk associated with geothermal projects in Switzerland. The former aspect highlights the potential existence of critically pre-stressed basement faults that are hydraulically connected to geothermal target horizons. The latter illustrates that earthquakes with magnitudes larger than M 5 can also initiate in shallow (< 5 km depth) sedimentary layers of the crust. Both scenarios should be discussed in the framework of the detailed induced seismicity hazard and risk assessment required for certain deep geothermal projects (see Section 6).

2.3 Plate tectonic context

To put the Swiss seismicity into a wider plate-tectonic context, we discuss in this section a recently postulated geodynamic model. The dominant geodynamic process affecting Switzerland is the formation of the Alps. The so-called orogeny of the Alps is the result of a complex geological history involving two large lithospheric plates, Europe and Africa, and smaller micro plates, among which the Adriatic micro plate plays an important role. The convergence of these plates led to the subduction of the European oceanic lithosphere, causing the closure of the former Tethys ocean and the subsequent collision of continental lithospheres.

A recent model of how the Swiss seismicity relates to these complex processes was published by Singer et al. (2014): They postulate that after the oceanic lithosphere of the former ocean between Europe and Africa had completely subducted into the mantle and the continental plates started to collide, a piece of the original mantle lithosphere remained attached to the European plate and formed a mantle slab. Teleseismic tomography has suggested that this is valid for the central Alps of central and eastern Switzerland while to the West, the oceanic European slab is detached (Lippitsch et al., 2003; Kissling, 2008). Interestingly, the lateral extent of deep earthquakes beneath the northern Alpine foreland is confined to the part of the European crust that is still connected with the mantle slab (Singer et al., 2014). Singer et al. (2014) propose that the mantle slab controls the large-scale, post-collisional, lithospheric dynamics by slab rollback. In this model, the subducted European slab is pulled down by the negative buoyancy force of the dense mantle lithosphere. This forces the positively buoyant, less dense, European crustal lithosphere to delaminate near the Moho, and to form a thick crustal root below the Alps (Figure 12). The authors argue that the positive buoyancy force of this thick crustal root and the negative buoyancy force of the topographic load of the mountain chain would be transferred from the Alpine crest to the foreland, and transformed from a nearly vertical to a nearly horizontal compressional stress, orientated perpendicular to the Alpine arc. Such a tectonic stress transfer would lead to a locally enhanced regional stress field in the lower and upper crust beneath the Alpine foreland with a compressional component perpendicular and an extensional component parallel to the strike of the Alps, and agrees well with the observed stress field in Switzerland (Figure 10 and Figure 11).

Since plate tectonic processes take place over geological time scales, it can be assumed that the current seismicity in the region of the Alps will remain the same for millions of years to come.

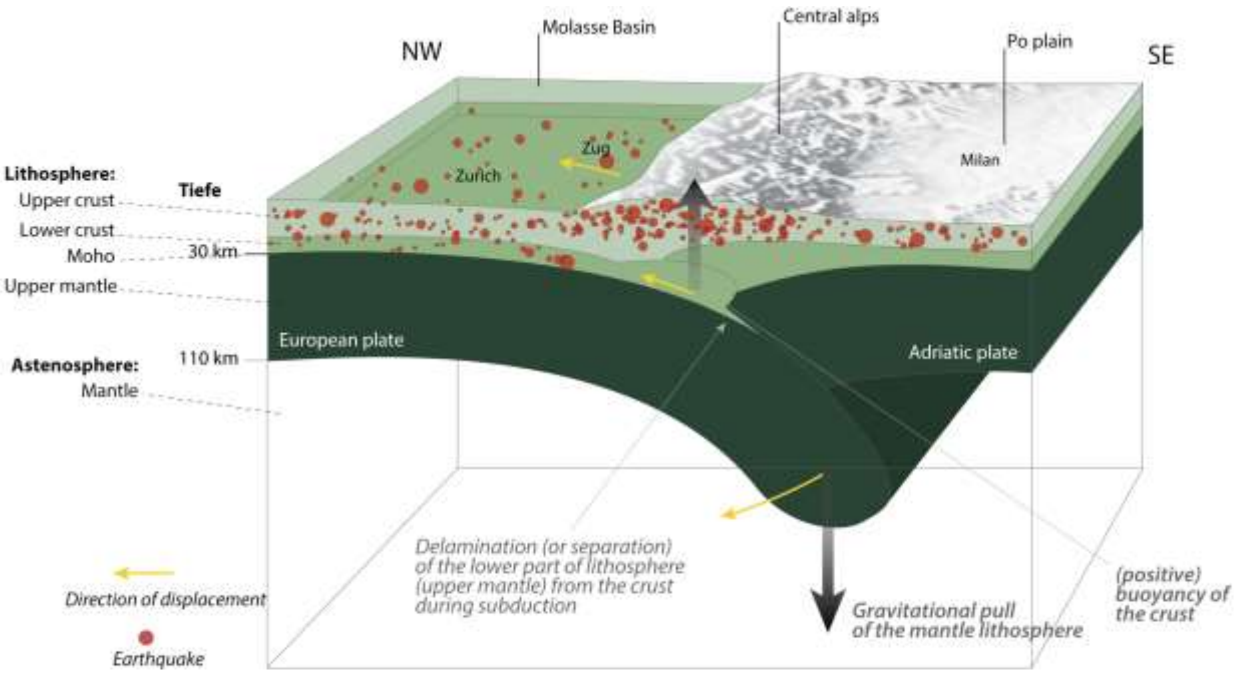

Figure 12: Cross section through the lithosphere schematically showing the various forces acting at depth on the Alps. The hanging European slab (mantle lithosphere) causes a downward force, while the lower crust detaches from the slab and the large crustal root generates buoyancy to compensate for loads by topography (mountains) and by the slab (Singer et al., 2014, EPSL).

2.4 Seismic hazard of Switzerland

In the fall of 2015, the SED published the new seismic hazard model of Switzerland (Wiemer et al., 2016). As mentioned above, earthquakes are the natural hazard with the greatest potential for causing damage in Switzerland. Even if earthquakes cannot currently be prevented or reliably predicted, thanks to extensive research and development, a lot is now known about how often and how intensely the ground could shake at a given location in the future.

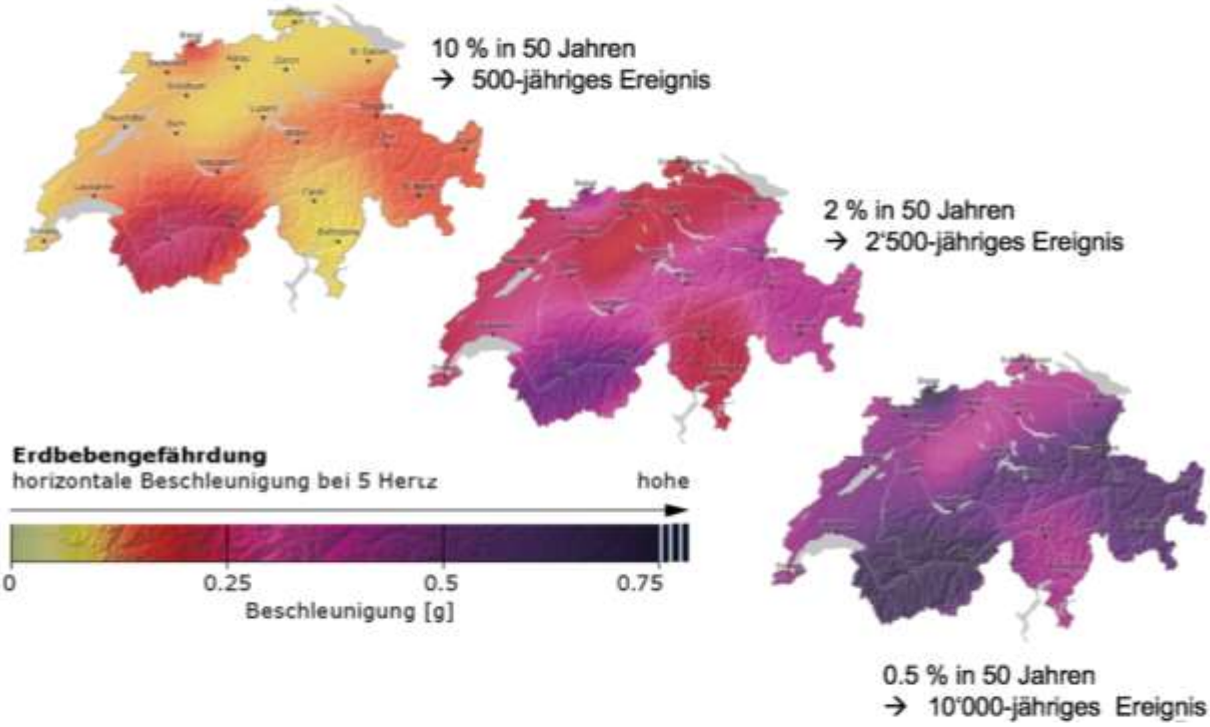

Figure 13: Seismic hazard maps of Switzerland for three different return periods as the median horizontal ground motions to be expected with 10%, 2%, and 0.5% probability in the next 50 years.

Switzerland's seismic hazard model[15] is a comprehensive representation of this knowledge. It makes a probabilistic forecast of potential earthquakes and the resulting ground motions over the next 50 years. The model is based on knowledge of tectonics and geology, information about the history of earthquakes, damage reports, and wave propagation models. Experts and authorities use it as a starting point when making decisions regarding earthquake mitigation and risk management. The Swiss seismic building codes are based on the earlier version of this seismic hazard model.

The 2015 model shown in Figure 13 is an updated version of the previous model from 2004 (Giardini et al., 2004) that reflects the latest technological and scientific findings. The seismic hazard model 2015 is based on new data, revised estimates of historical sources, a homogeneous reference rock, and improved predictive models. The ground motion's uncertainty has been significantly reduced, relative to the 2004 model, thus providing a more solid estimate of seismic hazard and an improved basis for a nationwide risk model.

On its website[16], the SED provides full access to the seismic hazard model and relevant background information for both the public and professional users, interested to download the data and model parameters. Often, users are not interested in acceleration values at certain return periods, but would rather like to know when the next earthquake will happen that can be felt or can damage their house. In order to address these questions, the 2015 hazard model includes two new products: maps of effects and maps of magnitudes (Figure 14).

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[15] http://www.seismo.ethz.ch/en/knowledge/seismic-hazard-switzerland/ [Accessed: 30 Aug. 2017]

[16] http://www.seismo.ethz.ch/eq_swiss/Erdbebengefaehrdung/index_EN

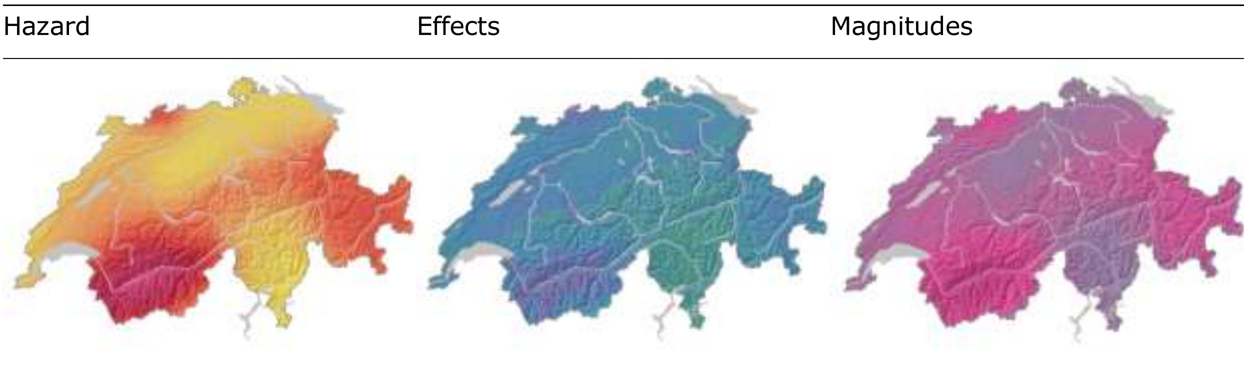

Figure 14: Left: Seismic hazard map. Middle: Seismic effects maps. Right: magnitudes map.

The effects map focuses on the likely consequences of an earthquake, depicting earthquake intensity values. The magnitudes map shows how often earthquakes of a particular strength occur, depicting magnitude values. To distinguish one from the other and from the hazard map, different colour scales are used. Within an interactive web tool, users can choose between different intensities, magnitudes and time frames. Periods in the conceivable future of the users are chosen: 1, 50 and 100 years. In total, 45 different maps are accessible via the web tool. For induced seismicity risk governance, the maps on magnitudes are especially relevant, because they allow to answer the question "*How often could one expect a natural earthquake in the vicinity of a geothermal project*" – an important numeric value to define the likelihood of an earthquake being of either natural or induced origin.

2.5 The importance of local site amplification

Earthquake ground motion on soft soils is amplified as compared to hard rock sites at similar distances from the source. This is known both from theory and from observations (Fäh et al., 2011). As a consequence of amplified ground motion, the earthquake impact is higher and includes increased damage to structures. Accounting for local site amplification is important for site-specific hazard and risk assessment for both natural and induced earthquakes.

Local soil conditions and geology in Switzerland are highly variable in space (the spectrum covers everything from hard rock over moraines to flood plains). Figure 15 shows an indicative site amplification map for Switzerland as published by Fäh et al. (2011). In the past century, cities with their suburbs and industrial areas grew into former flood plains. These big alluvial plains experience very high amplifications of earthquake ground motion. Buildings on such sites are especially endangered of suffering increased damage. Risk studies should therefore include site amplification effects.

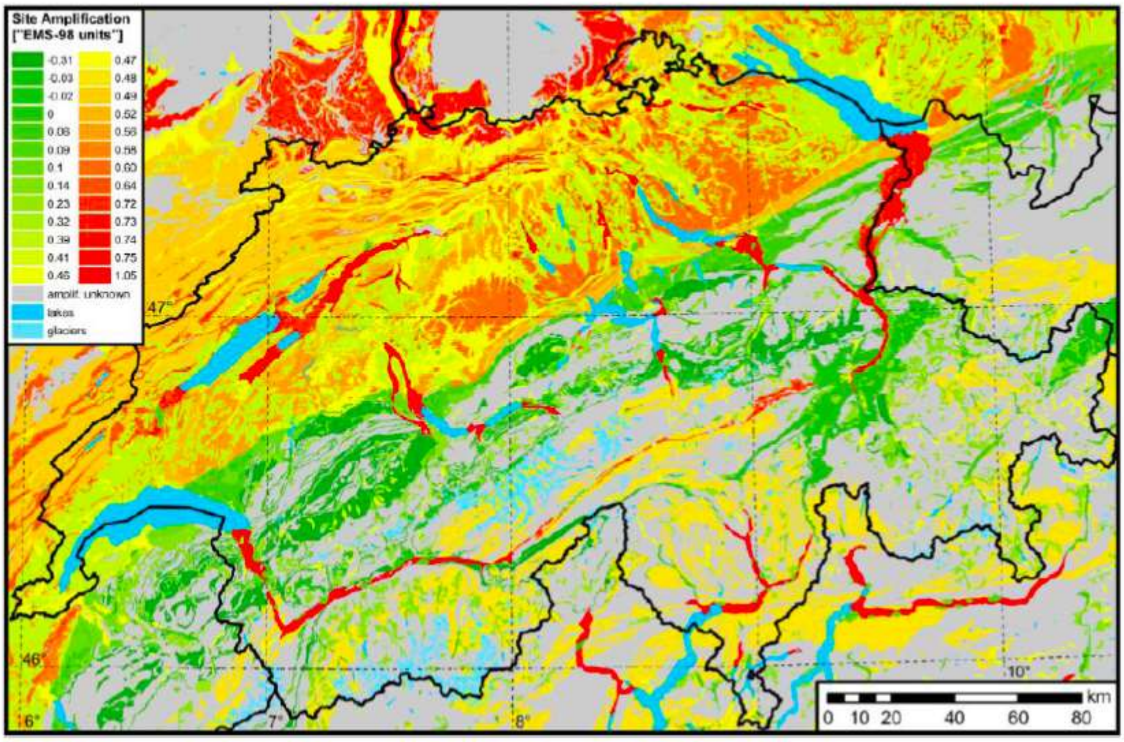

Figure 15: Indicative site amplification map for Switzerland (Fäh et al., 2011)

2.6 Earthquake risk

Seismic hazard assessment is only the first step in assessing and limiting the risk. Seismic risk is by definition a combination of seismic hazard, local soil conditions, exposed built environment and population as well as vulnerability of the exposed structures (Figure 16).

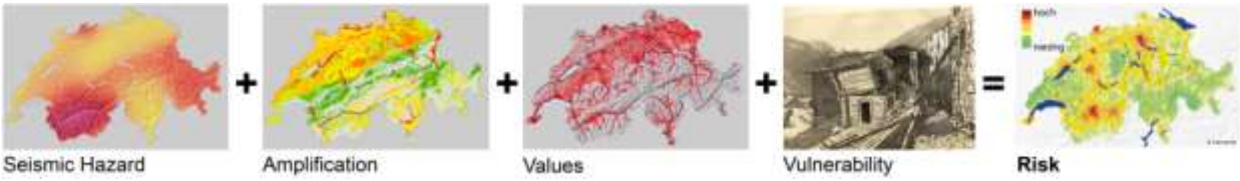

Figure 16*:* Seismic risk is a combination of seismic hazard, local soil conditions, exposed built environment and population, and vulnerability of the exposed structures.

The indicative risk map of Switzerland in Figure 17 shows the differences between seismic risk and hazard. While the cantons of Wallis and Basel are exposed to a high seismic hazard, hot spots of seismic risk do not coincide with these areas. Local soil conditions, exposed structures and vulnerabilities contribute considerably to the final risk map. One example would be that, despite the fact that the city of Zurich is situated in an area with low seismic hazard, it is considered a high-risk area, especially because of the high exposure of the built environment and population.

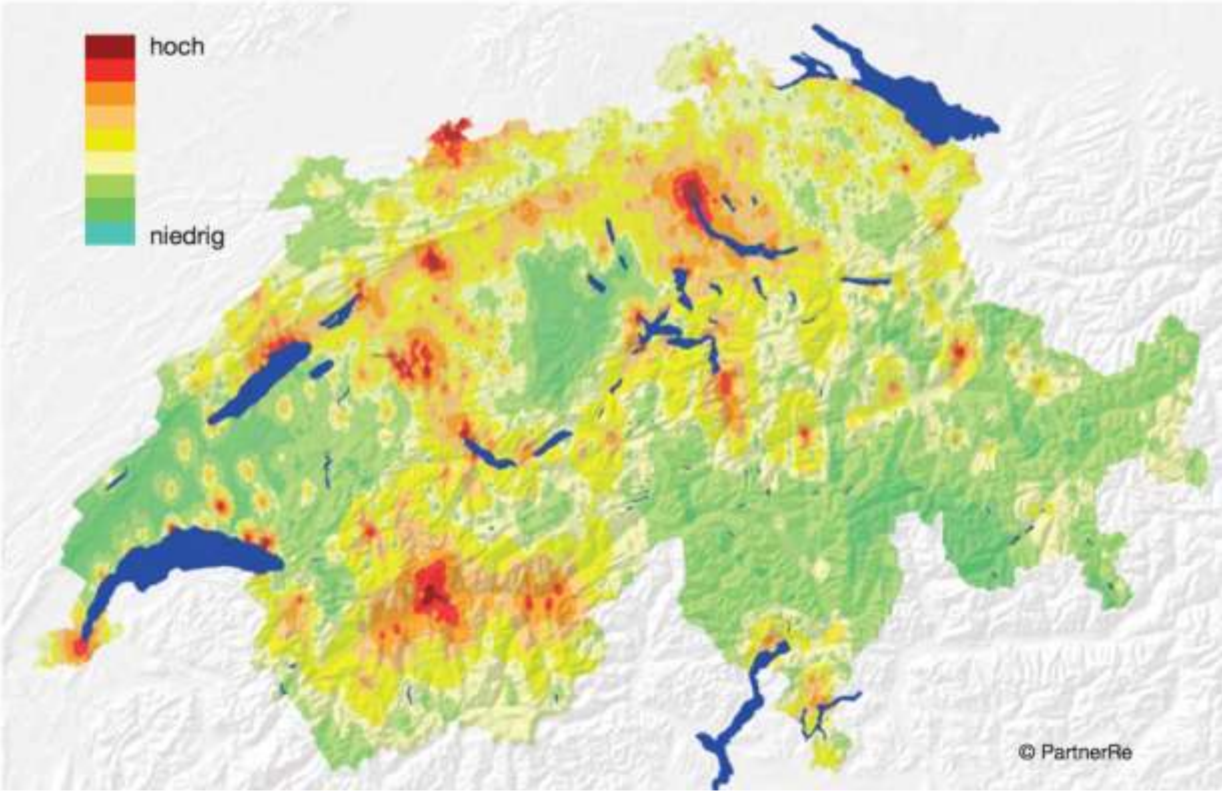

Figure 17: Indicative seismic risk map of Switzerland. The risk is measured by annualized financial losses per square kilometre.

The map in Figure 17 is only indicative: it remains largely unclear what damage earthquakes could cause to buildings and infrastructure. In 2017, the Federal Council has commissioned the SED, in cooperation with the Federal Office for the Environment (FOEN) and the Federal Office for Civil Protection (FOCP), to plug this gap and devise a first national seismic risk model by 2022.

3. Induced seismicity – background

3.1 Definition and terminology

Earthquakes in response to industrial activity have been labelled with many adjectives: man-made (anthropogenic), artificial, induced or triggered. Some researchers have proposed to classify man-made earthquakes on a physical basis as 'induced' if the human activity causes a stress change that is comparable in magnitude to the shear stress acting on a fault to cause slip, or as 'triggered' should the stress change only be a small fraction of the ambient level (e.g. Bossu, 1996; McGarr and Simpson, 1997).

Unfortunately, scientific literature has never consistently used these definitions, and many cases that are commonly labelled 'induced' should correctly be labelled 'triggered' when following the definition above (McGarr et al., 2002). Furthermore, there is a continuous gradient between the two definitions and the classification strongly depends on the physical model used. The exact contribution of tectonic stresses versus human-induced perturbations is generally unknown, making a distinction highly arbitrary. In addition, in the public perception and also in legal implications this distinction is irrelevant at best, but more likely adds confusion.

In the seismology community, triggered has an additional meaning: earthquakes caused by earlier earthquakes are triggered by the previous earthquake (Freed, 2005). This process applies to natural and man-made earthquakes alike. To avoid any confusion between the two kinds of triggered earthquakes, we follow the suggestion of the US Geological Survey (Rubinstein et al., 2015) and exclusively use 'induced' to describe all anthropogenic earthquakes in the context of this good practice guide.

3.2 Differences between natural and induced earthquakes

While the size of induced seismic events is typically smaller than the largest observed natural events in the same location, they are governed by the same earthquake physics and are generally indistinguishable from natural events (i.e., Deichmann and Giardini, 2009; Goertz-Allmann and Wiemer, 2013). One of the key challenges for some projects is indeed to separate natural and induced events in an objective and transparent manner, for example, when insurance and communication issues are concerned. This is covered in more detail in Section 5. However, it is important to realize that induced earthquakes differ in three important aspects from natural earthquakes:

- Because induced earthquakes are caused by human activity, the public reaction and legal implications are fundamentally different. People will be much less tolerant of induced earthquakes than of natural earthquakes of the same size, especially for higher magnitude events. They will expect compensation for damages.
- While natural earthquakes can neither be controlled nor predicted, mitigation and control are to some extent possible for managing the hazard and risk posed by induced seismicity. A causal link exists between the action (e.g., fluid injection volumes and pressures) and the reaction of the ground. However, the physical mechanism may not always be clear, and there may be substantial delays in the reaction.
- Induced earthquakes are often very shallow, and may occur near urban areas, which generally increases the level of ground shaking that the population and the building stock are exposed to.

3.3 Mechanisms of induced seismicity

Induced earthquakes are caused by a range of physical mechanisms, acting at different spatial and temporal scales. In a typical geothermal application, these various mechanisms will act together to a varying degree. Note that to a lesser extent it is also possible that the earthquake rate is actually locally *reduced* by human activity; however, given the generally low background seismicity in Switzerland, a rate reduction may often be difficult to detect.

The primary physical mechanisms are listed below and shown schematically in Figure 18.

Pore pressure changes: Increasing the pore pressure on pre-stressed faults may eventually cause these faults to rupture, releasing a (generally small) fraction of the tectonic stresses accumulated over centuries. A reduction of pore pressure alternatively will lead to stabilization, hence a reduction in earthquake rate. A special natural case of pore-pressure changes are rain-triggered earthquakes, documented in Switzerland by Husen et al. (2007).

Earthquake-earthquake interactions: The static and dynamic stress changes of induced earthquakes may in themselves act as triggers for additional earthquakes (Catalli et al., 2013). These stress changes can in some cases also inhibit further seismicity. Triggering of small earthquakes by passing seismic surface waves from a large event has been observed in rare cases thousands of kilometres from the epicentre (Hill and Prejean, 2007).

Deformation related changes: Volume changes in the underground through injection or extraction of fluids (i.e., hydrocarbon or geothermal extraction) or material (i.e., mining) will change the strain/stress conditions on nearby faults that may be tectonically pre-stressed (e.g. Segal, 1989; Gibowicz and Lasocki, 2001). If the loading locally exceeds the critical fault strength, an earthquake will be induced. Load changes at the surface of the Earth through reservoir impoundment are a specific case of deformation-related changes, as is thermo-elastic deformation (see below).

Temperature changes: Cooling or heating of the reservoir rock by injecting fluid causes local thermal contraction or expansion. Cooling opens fracture apertures; thereby changing the permeability, flow velocity, pressure gradient and injectivity. Thermo-elastic deformation also locally perturbs the state of stress (Murphy, 1978). This potentially releases locked segments of pre-stressed fracture interfaces.

Chemical alterations: Through chemical alteration by hydrothermal fluids, clay formation and mineral deposition, existing bonds on pre-existing and pre-stressed faults can be altered. If the bonds are weakened, induced earthquakes may prematurely release a fraction of the tectonic stresses. If the bonds are strengthened, ductile deformation (or creep) can transition into 'stick-slip' (seismic) deformation (e.g. Atkinson, 1984; Marone, 1998).

Figure 18: Schematic representation of the physical mechanisms that can induce earthquakes.

While there is a reasonable understanding of the underlying physical, chemical and geomechanical processes at work, at least in a macroscopic sense, forecasting induced seismicity remains a major challenge during all stages of underground projects. The problem of induced seismicity partially defies the current state-of-the-art in modelling and risk assessment concepts, because:

- The Earth crust is critically stressed in most places and crisscrossed with faults of all sizes. Both the location and current loading status of these faults are rarely known. The current stress level of faults can in general not be imaged using geophysical techniques.
- Stress distribution and material properties on the reservoir scale are highly heterogeneous and largely unknown.
- Earthquake ruptures are complex and highly dynamic processes; predicting with confidence how large a rupture may grow is currently impossible. Run-away ruptures that rupture beyond the reservoir area, releasing stress on tectonically pre-loaded faults, cannot be ruled out.
- The risk profile and public discussion is often dominated by infrequent and rare large events (low-probability – high-consequence events), where few or no observations exist and models are extrapolated well beyond their calibrated range.

As a result, the forecast of induced seismicity and the hazard and risk that it may pose is often highly uncertain. In our understanding, these uncertainties as well as the variability of the relevant parameters must be captured to deliver a robust risk assessment (i.e., Baisch et al., 2009; Mignan et al., 2015; Figure 19). Induced seismicity management is consequently increasingly moving away from mostly deterministic approaches to Probabilistic Seismic Hazard and Risk Assessment (PSHA/PSRA). Analogously to other PSHA studies, the variability of ground motion predictions is a major contributor to uncertainty (Douglas et al., 2013). However, as opposed to time-independent PSHA, the problem of induced seismicity is very much time-dependent and related to operations. Thus, the "source" part of PSHA is much more relevant and coupled to mitigation strategies.

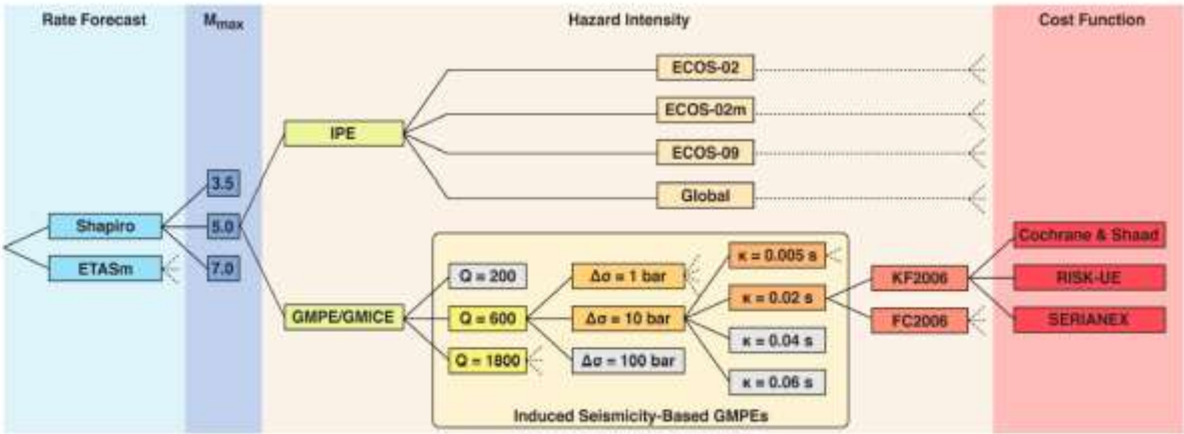

Figure 19: Example of a logic tree designed to capture the uncertainty in induced seismicity hazard assessment for the Basel geothermal project (Mignan et al., 2015).

3.4 Induced seismicity in the context of deep geothermal energy

3.4.1 Types of geothermal energy systems

Based on targeted depths, geothermal projects can be subdivided into 'near-surface' and 'deep geothermal projects' (Hirschberg et al., 2015). Examples of typical applications for near-surface geothermal projects are (groundwater) heat pumps or ground-coupled heat exchangers, both widespread in Switzerland. As a general rule, a project is considered a deep geothermal energy project from depths of 400-500 meters downwards. Shallow geothermal projects are often operated as closed systems, where no fluids are exchanged with the underground and thus the dominant triggering mechanisms for induced seismicity are not effective. Such shallow systems are not known to have caused earthquakes.

Depending on the reservoir temperatures and exploitation types, deep geothermal energy projects can be further subdivided. Electricity production through geothermal energy is worldwide dominated by high-enthalpy (high-temperature) reservoirs, often in the vicinity of volcanic areas, where underground temperatures tend to be in the order of several hundred degrees centigrade. Low-enthalpy reservoirs can be found anywhere else, with the difference that deep wells are necessary to get target temperatures of more than 110-130 degree centigrade in order to produce electricity. Low-enthalpy reservoirs can be subdivided further into three different types: hydrothermal and petrothermal systems as well as deep borehole heat exchangers. The Swiss examples are Basel (2006, petrothermal), St. Gallen (2013, hydrothermal), and Zurich (2010, deep borehole heat exchanger).

Hydrothermal systems target permeable rock formations where water ideally flows already (i.e. deep aquifers). The St. Gallen geothermal project is an example of a hydrothermal system, where a fault zone in the Mesozoic sediment sequence was targeted. On the contrary, petrothermal systems usually are not situated in permeable rock formations, which means that to achieve necessary flow rates, permeability needs to be enhanced by means of geo-engineering. Therefore, this type of geothermal energy is also called ‘Enhanced or Engineered Geothermal System’ (EGS).

An overview of all the above-mentioned types of use are illustrated in Figure 20.

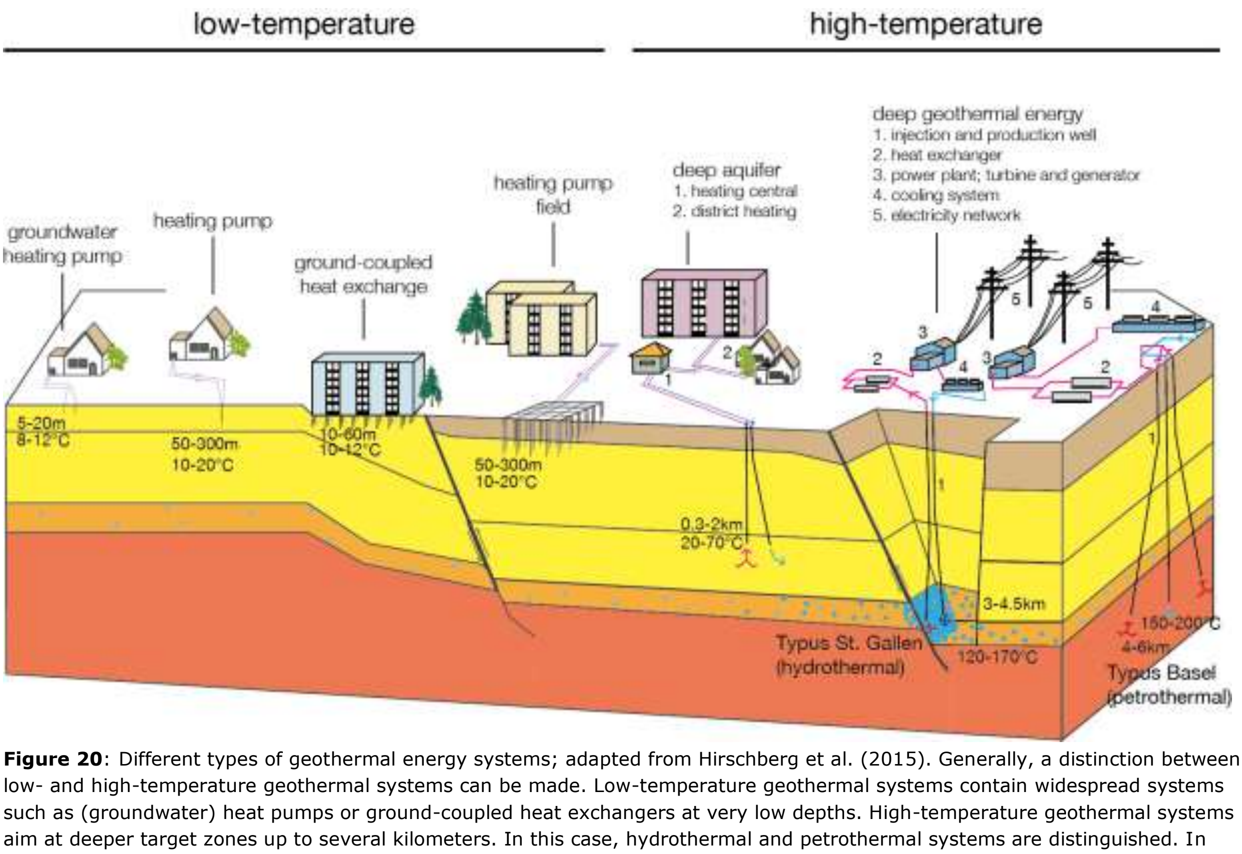

Figure 20: Different types of geothermal energy systems; adapted from Hirschberg et al. (2015). Generally, a distinction between low- and high-temperature geothermal systems can be made. Low-temperature geothermal systems contain widespread systems such as (groundwater) heat pumps or ground-coupled heat exchangers at very low depths. High-temperature geothermal systems aim at deeper target zones up to several kilometers. In this case, hydrothermal and petrothermal systems are distinguished. In hydrothermal systems, permeable rock formations where water circulates already are the target. In contrary, petrothermal systems aim at formations that are not permeable enough for water to circulate. Reservoir needs to be engineered then by injecting water at high pressure to enhance permeability.

3.4.2 Challenges for deep geothermal energy systems

Induced seismicity is not at all exclusive to deep geothermal energy systems. However, deep geothermal systems are especially challenged, because of the following reasons:

- Deep geothermal energy projects are often planned near urban areas, because district heating is commonly the primary target. But also in the case of electricity production, local heat use will greatly enhance the economics of the systems. Because risk is the product of hazard, exposure and vulnerability, the induced seismicity risk of deep geothermal projects near urban areas is much higher than in rural areas. While some nations, such as Australia, have the option of minimizing the exposure and hence the risk by avoiding settlements, this alternative is not available for deep geothermal projects in densely populated Switzerland.
- In the case of EGS, induced earthquakes are the required tool for creating a reservoir, and the economic success in terms of heat output is directly dependent on the number and size of induced events. Balancing reservoir creation and seismic hazard is thus needed, although this task is not yet well understood.
- In the case of deep hydrothermal projects, target zones are often major fault zones, because the permeability is typically much higher there. Since the existing pre-stresses and the potential for reactivation cannot be imaged directly through geophysical methods, there is a danger that targeted fault zones turn out to be more seismogenic than it was hoped for (as e.g. in St. Gallen, 2013, Diehl et al., 2017b).
- Deep geothermal systems, especially EGS, are new technologies, triggering a different and generally more sceptical risk perception as compared to established technologies such as mining or oil and gas production. There is also limited experience, empirical evidence and good practice to draw from.

As a consequence of the magnitude 3.4 earthquake induced during the 2006 Basel EGS project (with claimed damages over 6 million CHF), it is now universally accepted that the future development of geothermal systems near urban areas critically depends on the ability to assess and mitigate the nuisance and potential seismic risk posed by induced seismicity (Giardini, 2009; Kraft et al., 2009; Mena et al., 2013; Mignan et al., 2015). However, induced seismicity risk management is currently a substantial scientific challenge because not enough reliable and validated methodologies and tools to assess and monitor the risk exist (e.g., Giardini, 2009; Majer et al., 2012). This is a result of two factors: Our limited understanding of the physical processes taking place and, even more so, our limited knowledge of the physical conditions, such as 3D stress and strength heterogeneity, pre-existing faults, permeability distribution at the depth where the reservoir creation is taking place.

Consequently, induced seismicity related to GeoEnergy applications is one of the focus points of the Swiss Competence Center for Energy Research – Supply of Electricity[17] (SCCER-SoE), and is prominently featured on the national Roadmap for Deep Geothermal Energy in Switzerland[18].

3.5 Pre-drilling indicators of seismogenic response

Ideally, operators and regulators would like to have good knowledge of the seismic response of the underground before permits are given and before costly drilling operations are started. However, the vigour of the seismic response of the underground to geothermal operations at a given location is difficult to forecast with confidence before the in-situ conditions are well known, and even then surprises and changes in the characteristics with time are common.

[17] http://www.sccer-soe.ch [accessed: 18 Sep. 2017]

[18] http://www.sccer-soe.ch/export/sites/sccersoe/aboutus/.galleries/dwn_roadmaps/DGE_Roadmap_2014_Summary.pdf [accessed: 18 Sep. 2017]

Before the start of a project, there are typically only general indicators of average behaviour that can be used in combination to get a rough projection of the expected induced seismicity:

Injected volume: The larger the volume of rock affected by stressing changes, the more events are likely to happen. This is a first order geometrical effect. Whether or not the maximum possible event size is also scaling with the volume or fault area affected by the geothermal operation is currently a debated issue (Baisch et al., 2010; Gischig and Wiemer, 2013; McGarr, 2014).

Hydraulically bounded versus hydraulically open systems: In an ideal hydraulically bounded system, the operation will reach a steady-state and pore pressure changes will remain confined to a certain volume surrounded by a hydraulic barrier. Seismicity in such systems should level off with time (e.g., Soultz-sous-Forêt, F). In open systems, the poroelastic footprint is growing with time and seismicity in such settings will be more variable, sudden increases being possible when critically stressed patches are reached by the poroelastic changes. Seismicity in such setting can be sporadic (Landau, D), increasing with time (Groningen Gas Field, NL) or more or less steady (Paradox Valley, USA).

Depth of geothermal operation: Deeper systems are generally believed to be producing more induced earthquakes, as a consequence of the strength profile of the Earth crust. Differential stresses increase with depth; natural earthquakes are likewise less frequent in the top 1-3 kilometres of the earth crust. Modelling suggests that the increase in seismic response due to the increase in depth will overcome the geometrical effect of the decay in ground motions with distance (Gischig & Wiemer, 2013). However, there is so far surprisingly little empirical evidence for the depth dependence (Figure 21).

Reservoir Rock type: Crystalline basement rocks are typically believed to be more seismogenic than sedimentary rocks (Evans et al., 2012).

Background seismicity: The assumption that areas of lower natural seismicity also are areas less likely to respond with high levels of induced seismicity, or with lower maximum magnitudes is intuitive. Evans et al. (2012) suggested, based on a European database, that indeed areas with lower background hazard (defined arbitrarily as peak ground acceleration, PGA, values below 0.08 g) also have lower maximum observed magnitudes. Based on the Evans et al. (2012) data and a database updated with data from outside of Europe, Wiemer et al. (2015) conclude that the hypothesis of low-PGA regions producing lower maximum magnitude events can be rejected.

Pore pressure change: In general, the higher the (differential) pore pressure changes the underground is subjected to and the more rapid these changes are, the more likely are induced events. Seismicity often starts once the pressure changes have exceeded a certain minimal threshold. On the other hand, it is known that faults that are very close to failure can be triggered at very small pore pressure changes.

Proximity to critically pre-stressed and extended seismogenic faults. Injections near known active fault systems greatly enhance the chance of inducing earthquakes. For some applications, such as waste-water disposal, the rule of thumb therefore is to 'stay away from active faults' (Zoback et al., 2012).

Stress and fracture heterogeneity: The in-situ state of stress clearly plays an important role in determining the seismic response of the underground. A shear failure on a pre-existing fault can only be induced if differential stresses are non-zero. In regions of nearly lithostatic stress conditions ($\sigma 1 \approx \sigma 2 \approx \sigma 3$), inducing larger earthquakes is much less likely. Likewise, the complexity and heterogeneity of stress fields and the fracture network are important, but often poorly known before drilling.

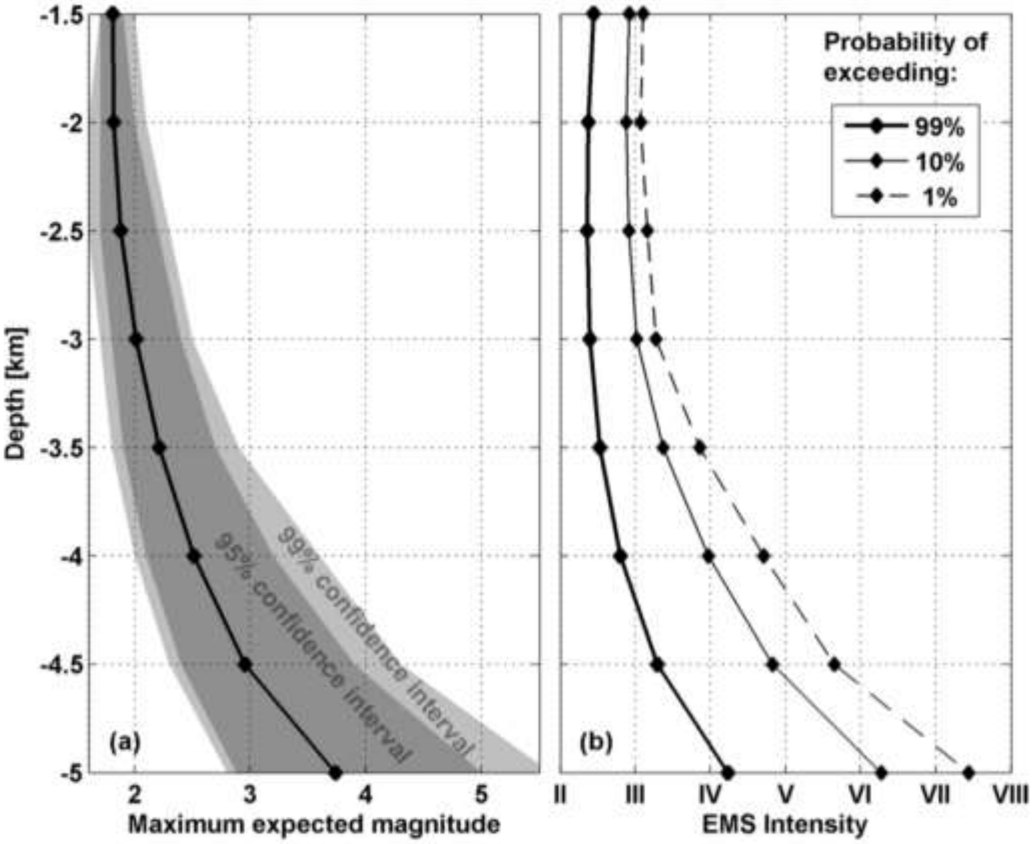

Figure 21: Left: Depth dependence of the maximum expected magnitude derived from 1000 model realizations. Also shown is the 95% and the 99% confidence intervals. Right: Depth dependence of hazard expressed as the EMS intensity exceeded with a probability of 99%, 10% and 1%. Shorter travel distances of seismic waves at shallower depths are outweighed by lower magnitudes expected due to a depth dependence of b values. Figure from Gischig and Wiemer (2013).

Size distribution of natural earthquakes: Areas where the relative size distribution of natural earthquakes (b-value of the Gutenberg-Richter law) is shifted towards high values (b > 1) may also produce induced seismicity characterized by high b-values. Gischig et al. (2014) suggest that these may be favourable conditions for the creation of a geothermal reservoir with acceptable seismic hazard. Volcanic or geothermal regions, such as the Geisers (United States), Taupo (New Zealand) or parts of Iceland, are typically characterized by high b-values and shallower reservoirs at lower differential stresses, which may explain why these regions had fewer problem with induced earthquakes despite having been in production for many years.

Traffic light settings: Potentially damaging events are less likely to occur when traffic light systems are set conservatively, thus when interruption thresholds are set lower and injections therefore interrupted earlier. However, more conservative traffic lights will have a strong impact on the commercial success rate of the projects (Gischig et al., 2014).

4. Case history of induced seismicity related to geothermal in Switzerland

4.1 The Basel "deep heat mining" project (petrothermal project, 2006)

The Basel Deep Heat Mining project (Häring et al., 2008) aimed to become one of the first commercial power plants based on the EGS technology. It was planned to enhance reservoir permeability at about 4 – 5 km depth in the crystalline basement by injecting fluid at high pressure over a time period of more than two weeks. A seismic monitoring system was installed along with a hazard and risk management scheme ('traffic light system' following Bommer et al., 2006). The monitoring system included six borehole sensors at depths between 300 and 2700 meters.

The first microearthquakes were detected starting from October 9, 2006. More than 160 of these events were associated with a water-kick and subsequent well shut-in between October 15 and 16, 2006. Only four of these events could be located; they occurred when water was pumped out of the well to reduce overpressure. Further 120 events occurred during the cementation of a casing string on November 11, 2006. The largest event was also detected by the SED and reached a magnitude of M_L 1.4. Between November 25 and 26, a pre-stimulation test was performed with stepwise increasing injection rates reaching pressures of up to 7.6 MPa. More than 140 microearthquakes were detected after the injection pressure had reached 5 MPa. All locatable earthquakes of the periods described above occurred in a distance of less than 100 meters from the wellbore at a depth of about 4400 meters, where an infiltration zone was detected in subsequent analyses (Ladner and Häring, 2009).

During the main EGS reservoir stimulation, approximately 11,500 m^3 of water were injected at high pressures between December 2 and 8, 2006 (Häring et al., 2008). In the early hours of December 8, after water had been injected at progressively higher flow rates up to 55 l/s and at wellhead pressures up to 29.6 MPa over a 16-hour period (Häring et al., 2008), a magnitude M_L 2.6 event occurred within the reservoir. This exceeded the safety threshold for continued stimulation so that the injection was first reduced and stopped a few hours later, with the well shut-in. In the afternoon and evening of the same day, two additional events of magnitude M_L 2.7 and M_L 3.4 occurred within the same source volume. As a consequence, the well was opened and in the following days about one third of the injected water volume flowed back out of the well (Häring et al., 2008). Though the seismic activity declined rapidly thereafter, three more events with $M_L > 3$ occurred in January and February 2007.

These earthquakes caused aversion against the project among the population and media which then led to the temporal suspension of the experiment. In 2009, the project was fully cancelled as a consequence of a comprehensive risk study (SERIANEX, Baisch et al., 2009). Allegedly, damage caused by the earthquakes included mostly fine cracks in plaster which corresponds to an EMS intensity V. Insurance claims by homeowners reached about 6 million CHF, most of which were also paid for. The SERIANEX risk study was subsequently repeated and extended by Mignan et al. (2015), although the major findings did not change.

The well was then kept open and water was flowing out in regular geysering events until January 2011, when the well was shut-in and the wellhead pressure gradually increased again. Over the period 2008–2011, the seismic activity remained below the current automatic detection threshold of the SED (approx. M_L 0.9). In 2012 and 2013, the activity picked up again with seven detected events with magnitudes between M_L 0.9 and 1.8 (Diehl et al., 2014b). For almost a year thereafter, activity remained below the SED detection threshold until the occurrence of an M_L 1.6 event on December 23, 2014. The seismicity remained on an elevated level until May 2015 with three more earthquakes above the SED detection threshold. After that, no earthquake above the threshold was detected for more than a year. In June 2016, the seismicity increased again, even stronger than before. A M_L 1.9 earthquake was detected on October 2, and the highest, post shut-in earthquake rates occurred between

January and March 2017. The four strongest earthquakes in the period had magnitudes between 1.5 and 1.7.

This seismicity increase in early 2017 consisted of swarms of microearthquakes with phases of increased activity over a number of weeks, being followed by quieter periods. None of these earthquakes were felt by the public. In early 2017, the seismic activity had also shifted to the southern and northern edges of the previously active areas of the reservoir, suggesting that the artificially induced fractures were spreading out into areas that had not been active since early 2007 or not at all before. In addition, measurements showed that the hydraulic pressure in the reservoir (pore pressure) had steadily increased since the borehole was closed in 2011. A detailed SED study indicated that the increased pressure was responsible for the increase in seismicity, and that the seismic activity would most probably subside again in the long term if the borehole was opened. In late March 2017, the Department of Health of the Canton of Basel and *Industrielle Werke Basel* (IWB) decided to re-open the borehole and to slowly reduce the wellhead pressure, that had reached 8.2 bar, in weekly steps of about 1 bar. This procedure was started in mid-July 2017 and lasted until the end of October 2017. As a consequence, the seismicity reduced to extremely low rates of 1-4 microearthquakes with magnitudes below M_L 0.0 per month.

The Basel data have been the basis of countless scientific studies and in this sense have been an important contribution for advancing the understanding of EGS systems. This case illustrates the importance of pilot and demonstration projects for advancing our understanding. Without the drilling, the subsequent stimulation and the high resolution monitoring, very little would have been learned. Based on that data, Mena et al. (2013), Gischig and Wiemer (2013), Goertz-Allmann and Wiemer (2013) and Gischig et al. (2014) developed stochastic forecasting models for induced seismicity. Their simulation results indicate that the vigour of the seismic response, and, given the planned injection strategy, the likely occurrence of the M_L 3.4 event, could have been estimated with confidence already after 2-3 days of stimulation. Such forecasting models were not in place in 2006, but are available today (see Section 11).

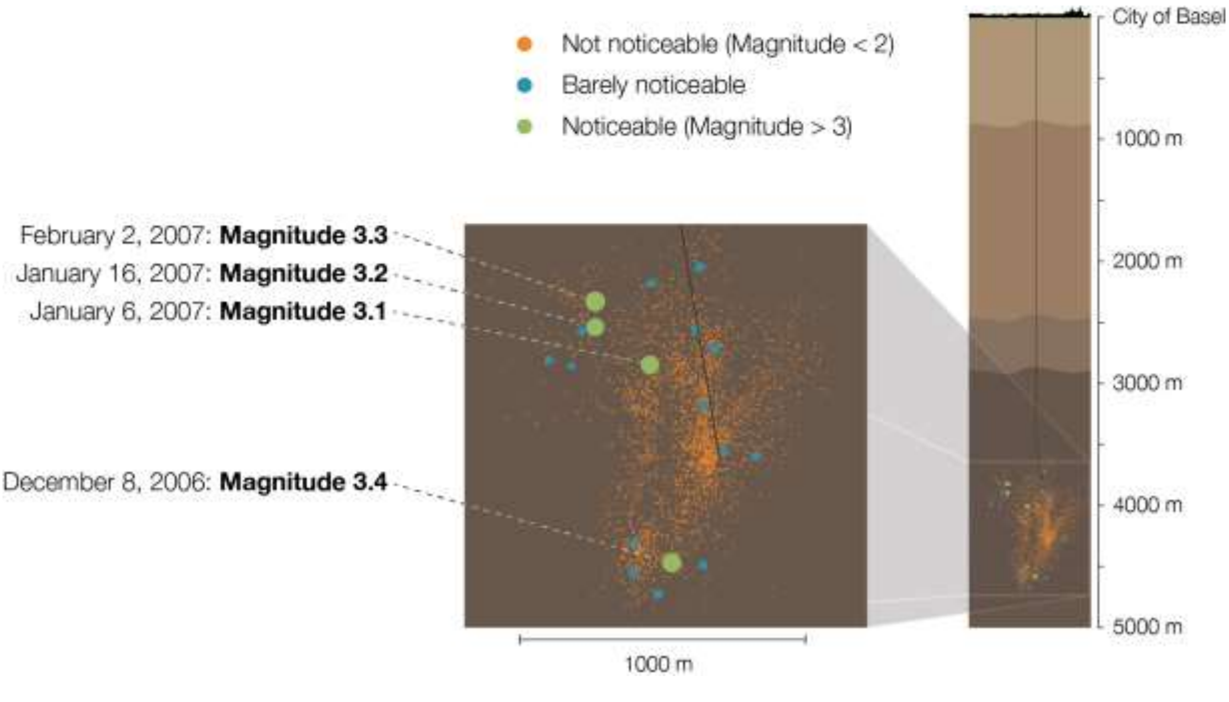

Figure 22: Seismicity observed during and following the 2006 Basel EGS reservoir stimulation. Events above M_L 3 are pointed out.

4.2 The St. Gallen hydrothermal project (2013)

The St. Gallen geothermal project targeted the same geological layers, the Malm and Muschelkalk of the Molasse sedimentary basin, that have been tapped into by a number of successful deep geothermal projects in southern Germany. To find the most favourable target for the drilling, a high-resolution 3D seismic survey was conducted around St. Gallen in 2010, covering 310 km^2. The survey revealed a pronounced shear zone (Figure 23), oriented NNE-SSW with a length of about 30 km, termed the St. Gallen Fracture Zone, SFZ (Heuberger et al., 2016; Diel et al., 2017). The project operators – the public utility company of St. Gallen – concluded that this fault zone was hardly seismically active, based on the lack of recent seismic activity.

The SED had installed a seismic monitoring network in early 2012, consisting of six three-component surface seismometers and one shallow (depth of 205 meters) three-component borehole station. Drilling commenced in early 2013 and the target depth of 4450 meters was reached in early July. The reservoir characterization started on July 14 with an injectivity test (Period 1, Figure 24), when cold water was injected into the open-hole section. In total, 12 micro-earthquakes were detected, all of them of magnitude M_L 0.9 or below. On July 17, two acid stimulations were performed, each injecting 70 m^3 of diluted hydrochloric acid into the reservoir (Period 2, Figure 24). The seismicity during these tests did not exceed M_L 1.2 and was judged to be well within the expected range (Edwards et al., 2015).

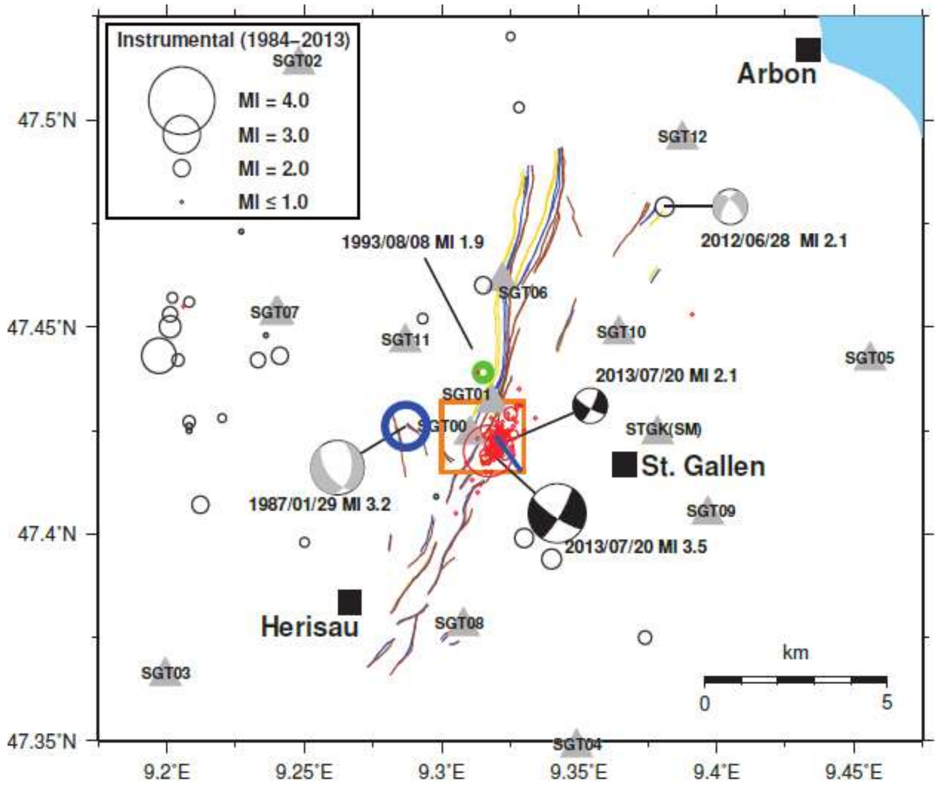

Figure 23: St. Gallen and surroundings, including seismic stations (grey triangles, named SGTxy) used to survey induced seismicity, seismic events (circles) and known faults (colored lines). The straight blue bold line corresponds to the surface projection of the deviated borehole GT-1.

Starting around noon on July 19, methane entered the borehole from presumably Permo-Carboniferous sediments below the injection interval and caused a 12-meter high blow-out (sgsw, personal communications 2013). The borehole was immediately closed and well-head pressure rapidly rose to about 90 bar. Operators decided to start to pump cold water into the well in order to control the pressure build-up. Over the next 18 hours, a total of about 700 m^3 of water was injected into the well, causing the pressure at the well-head to decrease steadily. However, seismicity started to suddenly increase at 7 pm local time on July 19, once about half of the total volume had been injected and well-head pressures had decreased to about 25 bar.

The initial event of the 'well control' sequence, with a magnitude M_L 1.6, triggered the 'yellow' threshold of the so-called "traffic light system" in operation that requested for stopping the pumps. However, because of the ongoing well-control operation, stopping the pumps would likely have caused a renewed increase in the gas content and wellhead pressure, possibly to levels dangerous for the equipment and staff. Operators therefore decided to continue pumping. The seismicity during this period (Period 3, Figure 24) intensified, with a M_L 2.1 event at 12:30 a.m. on July 20. Seismicity remained constrained to within a few hundred meters of the borehole. At 5:30 local time, the largest event of the sequence occurred, with a magnitude of M_L 3.5 (M_w 3.3). The earthquake initiated near the borehole. Only a few dozen reports of damage were received, as compared to several thousand in the case of Basel. For a detailed comparative analysis of these two earthquakes, consult Edwards et al. (2015).

The well-control phase (Period 3, Figure 24) ended on July 25, when the operator managed to close the open-hole section of the wellbore with back-fill material. After an initial risk assessment and cool-down period of four weeks during which the seismic activity steadily decreased, the city council decided to continue the project, clean the well and conduct a production test. The activities at the wellbore restarted on August 24. From September 15 onwards, more than 2'000 m^3 of drilling mud were lost gradually into the formation during the well cleaning activities and the seismic activity immediately restarted. The maximum magnitude throughout this period was M_L 1.7 on October 2 (Period 4, Figure 24).

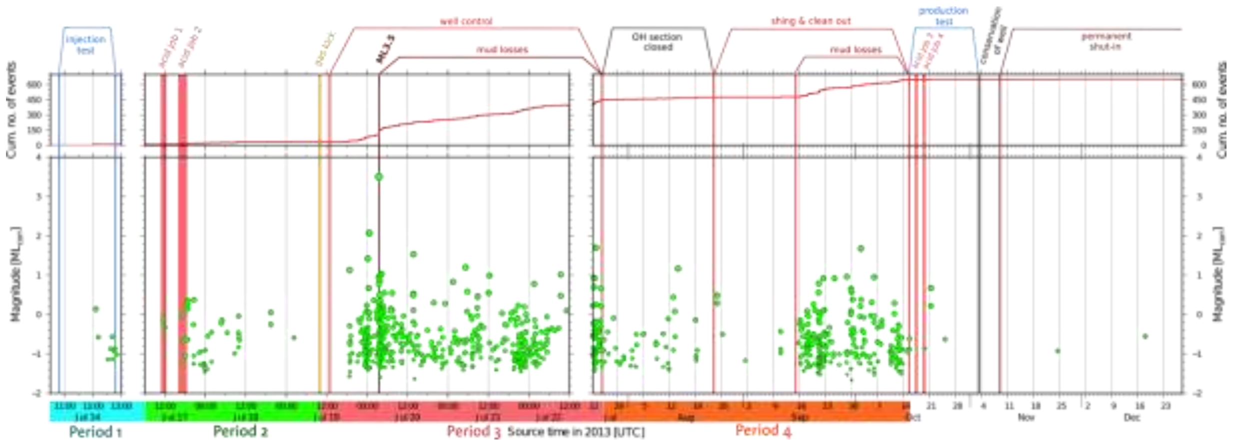

Figure 24: Temporal evolution of the St. Gallen induced earthquake sequence. Horizontal axis indicates source time in UTC. Please notice the different scales in the different periods. Green dots indicate the magnitude (M_{Lcorr}, Edwards et al., 2015) of 835 detected earthquakes. The cumulative number of events is given as a red line in the top panel. Activities at the wellbore are indicated at the top of the figure (see text for details; Kraft, 2016).

Once the production test started on October 15, seismicity essentially stopped immediately along the entire activated fault system. This is additional evidence that the seismogenic fault segment of the SFZ is highly sensitive to pore-pressure changes and can be turned on and off easily. Only two events with magnitudes M_L -0.5 were detected until the end of 2013. In the period 2013–2015 only a single earthquake (April 19, 2015, M_L 0.8) at the northeastern end of the previously active seismic volume was detected by the SED (Diehl et al., 2017b). The evaluation of the production test and logs shows that flow is limited to the fracture zone. While the temperature at depth is with more than 140 °C within the projected range, the estimated production rates of 5 l/s are much below the commercial minimal target of 50 l/s. The operator finally decided to shut-in the well. The implications of the St. Gallen project are significant, especially for hydrothermal projects, since the project revealed that the current understanding of and management strategies for induced seismicity are limited and need to be reconsidered in a number of areas:

- Hydrothermal systems in sedimentary rocks were so far considered benign with respect to induced seismicity but St. Gallen showed that they are able to induce events similar in size to those induced by EGS. As 3D seismic surveys become ever more capable of imaging fault system targets for drilling, our ability to judge if a fault is critically pre-stressed remains poor and unpleasant surprises are possible.

- The M_L 3.5 earthquake and overall activity of the sequence lie well outside of the scaling laws that relate the injected volume of water and the maximum expected magnitude. This suggests that these scaling laws do not describe a hard truncation and that run-away ruptures must be considered possible.
- The seismic response to the injectivity test as well as to the acid stimulations did not suggest that such a large event was possible. This lack of predictability of the system limits near-real time hazard assessment.
- Traffic light systems to manage induced seismicity cannot always be engaged as planned, a fact so far ignored in risk assessment. Future projects will have to also consider the coupling and feedback between hazards.

5. Project accompanying assessment of induced seismicity concern

5.1 Induced seismicity risk governance of deep geothermal projects

We are proposing here induced seismicity risk governance that combines three elements: complete project life cycle, socio-technical approach and context dependency. The complete project life cycle perspective is adopted because induced seismicity requires measures from the initial exploration stage until the end of the project and beyond, because seismicity can occur decades later after initial stimulation and operation (Ellsworth, 2013). The socio-technical approach is used because induced seismicity is a complex risk that requires combining primarily technical elements (initial hazard and risk assessment, insurance and structural building reinforcement, monitoring, traffic lights) as well as public engagement (social site characterization, information, consultation, collaboration and empowerment). The context dependency means that various geothermal energy projects are different in terms of concerns about seismic hazard, risk, and social context and thus require different risk governance processes. A new Geothermal Risk of Induced seismicity Diagnosis (GRID) scoring approach is proposed for categorizing geothermal projects (Trutnevyte & Wiemer, 2017). Based on the GRID scores, different risk governance processes are then tailored to the specific project category. In many projects, risk governance can be very simple, involving few actors and largely limited to risk assessment based on empirical experience. In other contexts, it can require much more involvement. These cases can be distinguished using the GRID scores.

This good practice guide focuses only on one element of risk governance: risk assessment and mitigation, including monitoring strategies for individual geothermal projects. Elements of stakeholder and public engagement are not discussed, because they are not part of the SED core expertise. In collaboration with the SED, these elements have been elaborated as part of Task 4.1 "Risk, safety and societal acceptance"[19] and are described using the same framework by Trutnevyte & Wiemer (2017). We thus recommend to both operators and regulators to adopt a holistic view of induced seismicity, not only focusing on hazard and risk assessment but also on a wider risk governance point of view (Fischhoff, 2015; Stern & Fineberg, 1996).

5.2 Existing frameworks for induced seismicity management

Several frameworks for induced seismicity assessment and management exist (Table 3). The most detailed framework was developed by the US Department of Energy for EGS projects (Majer et al., 2012; 2013). This framework has both breadth and depth: it covers elements from preliminary screening to seismic hazard and risk assessment, monitoring and risk management. The framework of Bommer et al. (2015) focuses on risk rather than hazard management of induced seismicity. The authors argue that success of induced seismic hazard control has not yet been proved and the focus shall shift to adaptation measures, such as insurance, structural retrofitting or at time relocation of the exposed population. Wiemer et al. (2015) provide a list of recommendations, but not an integrated framework, for hazard and risk assessment, seismic monitoring and traffic light systems. Zoback (2012) proposes a five-point checklist for induced seismicity management: avoiding active faults, installing seismic monitoring, minimizing pore pressure changes at depth, establishing modification protocols and being ready to alter plans.

Although induced seismicity does not concern all geothermal projects, none of the existing frameworks provide clear guidance for geothermal project operators on how to assess whether their project can be prone to induced seismicity and what assessment and manage-

[19] http://www.sccer-soe.ch/research/future-supply-of-electricity/task4.1/ [Accessed: 18 Sep. 2017].

ment measures are needed. Geothermal Risk of Induced seismicity Diagnosis (GRID) is proposed in the next section.

Table 3: Existing frameworks for assessment and management of induced seismicity

Framework	Majer et al.		Bommer et al., 2015	Wiemer et al., 2015	SED risk governance workflow (Sections 6-10)
	2012	2013			
Scope	geo-thermal	geo-thermal	all induced seismicity	geother-mal	geothermal
Country of application	USA	USA	generic	Switzer-land	Switzerland
Preliminary screening	brief	detailed	-	-	detailed
<u>Seismic hazard</u>					
Assessment					
• Empirical seismic hazard study	brief	detailed	brief	brief	brief
• Probabilistic seismic hazard study	brief	detailed	brief	brief	brief
• Secondary hazards	brief	brief	brief	-	brief
Management					
• Seismic monitoring	brief	detailed	brief	brief	brief
• Magnitude-based traffic light systems	brief	brief	brief	brief	brief
• Risk-based traffic light systems	brief	brief	brief	brief	brief
• Adaptive risk-based traffic light systems	-	-	brief	brief	brief
<u>Seismic risk (exposure and vulnerability of structures and population)</u>					
Assessment					
• Macroseisimic intensity- or engineering-based risk study	brief	detailed	detailed	-	brief
Management					
• Building monitoring	-	detailed	brief	-	brief
• Insurance and liability	brief	brief	brief	-	brief
• Structural retrofitting	-	-	detailed	-	brief
• Relocation of the population	-	-	brief	-	-

5.3 Evaluation of the GRID scores

The complexity and case-specific nature of geothermal energy induced seismicity requires the combination of technical elements with stakeholder and public engagement when clarifying and managing the associated risk. Trutnevyte & Wiemer (2017) have proposed a new scoring approach to Geothermal Risk of Induced seismicity Diagnosis (GRID) for categorizing the different geothermal projects in terms of concern about seismic hazard, risk, and social context and thus require different risk governance processes. GRID approach is also adopted in this guide.

The GRID scores are derived from indicators that describe concern about seismic hazard, risk (in terms of secondary hazards, exposure and vulnerability), and social context. The GRID scores are dependent on, but not exactly proportional to, the level of seismic hazard or risk. The GRID scores reflect the concern level rather than hazard or risk level, meaning that higher concern requires more thorough risk governance. For example, according to social amplification of risk (Kasperson et al., 1988), social concern, such as lack of trust in the operator or widespread public worry about induced seismicity, increases the GRID scores and thus risk governance requires more attention than purely defined by the risk level. That means that projects with relatively low hazard, but high social concern would still need some type of hazard and risk assessment or monitoring in order to address the social concern. Another example is the separation between background and induced seismicity. Although the influence of background seismicity on the induced seismicity hazard is debated, higher background seismicity is still assumed to increase the GRID scores because more measures are required to determine an induced event with confidence for liability purpose.

The GRID scores should be evaluated at a planning stage of a geothermal project. The scores are based on data that are generally available before the initial risk study and before the first geothermal well is drilled. After the drilling, when new data become available, or if project plans change, the GRID scores should be re-evaluated.

The GRID scores are by design relatively simple, rule-of-thumb type of scores. Their strength lies in the multiple socio-technical elements that are combined. The simplicity is adequate in order to enable a fast and open-to-discussion manner for characterizing a geothermal project at hand. This evaluation and discussion is helpful not only for defining the project category, but also for thinking through the various relevant elements for risk governance in detail.

We recommend that the GRID scores should be evaluated by at least three parties: the project operator, the licensing regulator or authority, and one or two independent experts. Since some indicators, especially those related to social concern, are defined qualitatively, the GRID scores need to be mapped by every individual party separately, rather than converging all the views into a single average score. Values that are unknown or that can change during the course of the project (e.g., injection rates) can be given with uncertainty bounds

Drawing from recommendations by Mastrandrea et al. (2010), we suggest that:

- Each party writes down its individual GRID assessments before entering into a group discussion;
- The results of the individual assessments are shown and discussed in the group, especially addressing the points where assessments diverge;
- Each party can revise their individual assessments after the group discussion and this revision needs to be documented. The GRID scores should not be aggregated across the parties in order to transparently document the remaining points of judgment divergence;
- The licensing authority/regulator could decide on the final category of the project based on these GRID scores. This category determines what risk governance processes need to be adopted as described in Section 6. One suitable decision heuristic in line with a precautionary approach, for example, is to choose the category where the highest GRID score of any party falls.

The list of indicators used to evaluate the GRID scores is provided in Table 4. All indicators are assigned values of 0 (little concern), 1 (medium concern), and 2 (high concern). The definition and values of indicators are customized to Switzerland.

The GRID scores are evaluated by summing and plotting the indicators of seismic hazard concern versus concern about secondary hazards, exposure and vulnerability. Social concern is assumed to “amplify” these concerns by shifting the scores by 0.5 on both hazard and risk axes for every social concern point. Trutnevyte & Wiemer (2017) provide detailed explanation of the method.

Table 4: Indicators for the GRID scores

SEISMIC HAZARD CONCERN	0 (little concern)	1 (medium concern)	2 (high concern)
Depth of the reservoir	< 1 km	1 - 3 km	> 3 km
Cumulative injection volume during stimulation	<1,000m^3	1,000-10,000m^3	>10,000m^3
Daily injection or extraction volume during operation	<1,000m^3/day injection or <5,000m^3/day extraction	1,000-10,000m^3/day injection or 5,000-50,000m^3/day extraction	>10,000m^3/day injection or >50,000m^3/day extraction
Rock type	Sediments	Within 500 meters from the crystalline basement	Crystalline
Separation between back-ground and induced seismici-ty	≤0.6 m/s^2 dimensioning value a_{gd} from SIA (2003), defined as maximum PGA on Ground Class A of natural seismicity with a 475-year return period*	<1.3 m/s^2 dimensioning value a_{gd} from SIA (2003)*	≥1.3 m/s^2 dimensioning value a_{gd} from SIA (2003)*
Fluid injection pressure	<0.1MPa	0.1-1MPa	>1MPa
Distance to known and potentially active faults with length greater than 3 km	>5 km	2-5 km	<2km
CONCERN ABOUT SECOND-ARY HAZARDS, EXPOSURE AND VULNERABILITY (within a radius of 5 km)	0 (little concern)	1 (medium concern)	2 (high concern)
Local site amplification (within a radius of 5 km)**	No buildings or infrastructure on soft soils (Ground Class D, E, F in SIA (2003))	<10% of buildings or infra-structure on soft soils (Ground Class D, E, F in SIA (2003))	≥10% of buildings or infrastructure on soft soils (Ground Class D, E, F in SIA (2003))
Exposed population (within a radius of 5 km)	Remote (<100 inhabitants)	Rural (100-20,000 inhabit-ants)	Urban (>20,000 inhabitants)
Industrial or commercial activity (within a radius of 5 km)	Low activity	Medium activity (≥1 enter-prise with 100-499 employ-ees or ≥1 industrial installa-tion of a particular value)	High activity (≥5 enterprises with 100-499 employees or >1 enterprise with over 500 employees or ≥2 industrial installation of a particular value)
Importance of buildings and infrastructure (within a radius of 5 km)	No buildings or infrastructure of Class II or III, as defined in SIA (2003)	Buildings or infrastructure of Class II (SIA, 2003); no build-ings or infrastructures of Class III (SIA, 2003)	Buildings and infrastructure of Class III (SIA, 2003)
Infrastructures with consid-erable environmental risk (within a radius of 5 km)	None	-	One or more
Unreinforced cultural herit-age (within a radius of 5 km)	<5% buildings listed as important local, regional or national herit-age sites	5-10% buildings listed as important local, regional or national heritage sites	>10% buildings listed as important local, regional or national heritage sites; or any buildings listed as important international heritage sites
Susceptibility to secondary hazards (within a radius of 5 km)	Very low	Exists	High
SOCIAL CONCERN	0 (little concern)	1 (medium concern)	2 (high concern)
Potential for concern in the general population	None	Exists	Significant
Vulnerable or strongly opposing stakeholders	None	Exist	Significant
Negative experiences with similar projects	None	Exist	Significant
Lack of trust in the project operators or authorities	None	Exists	Significant
Benefits to the local commu-nity	Direct benefits with or without monetary compensation	Monetary compensation only	None

* http://www.sgeb.ch/fachpublikationen/SGEB04.pdf [Accessed: 4 Sep. 2017].
** If no ground class is available, one can use Figure 15 (Faeh et al., 2011).

Figure 25 shows an example how the Basel, St. Gallen, and Riehen geothermal projects could have scored at the planning stage (Trutnevyte & Wiemer, 2017). For comparison, a hypothetical Basel-type plant, located in a low risk area, but with high social concern, is also presented. The diverse opinions of the three parties are mapped.

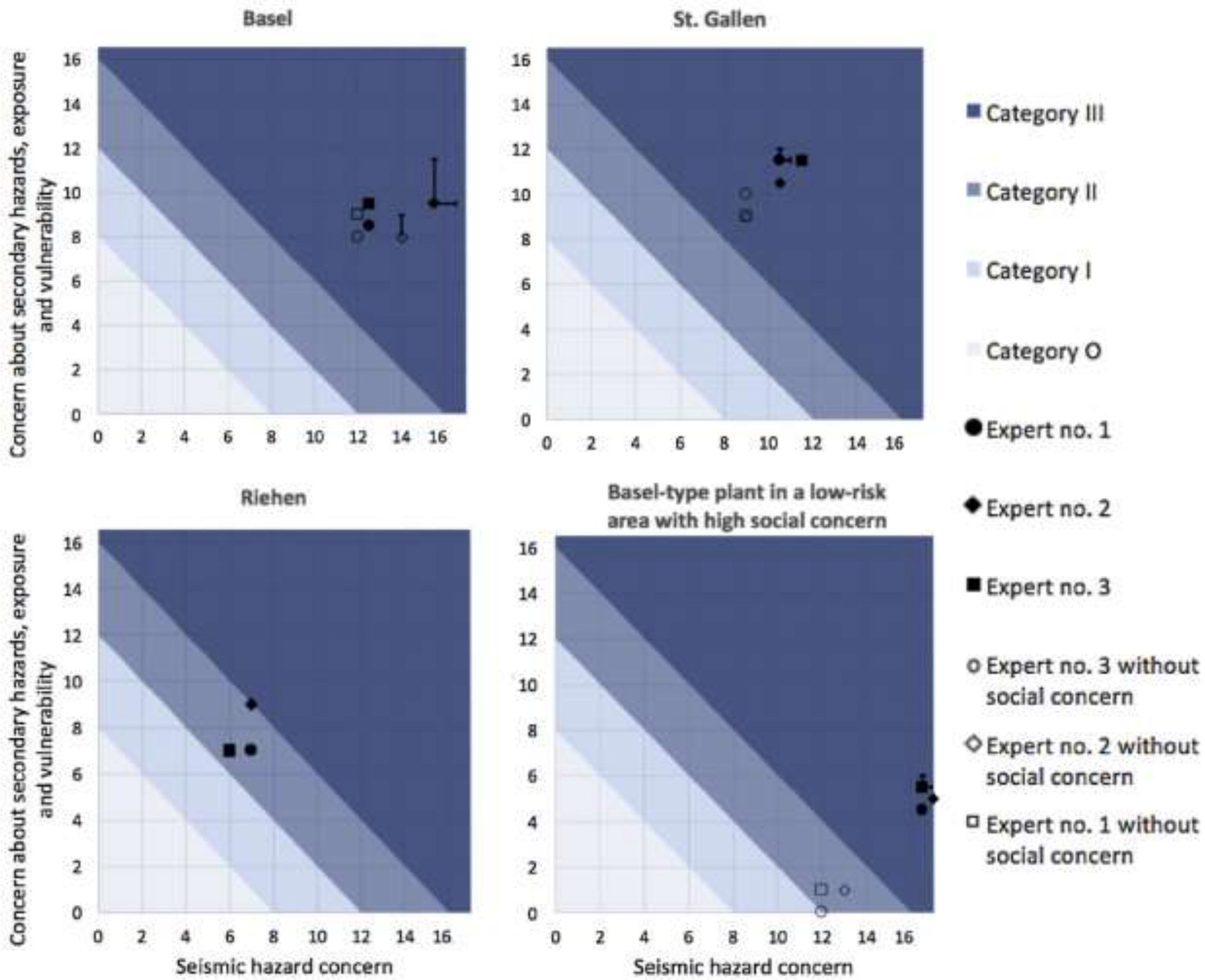

Figure 25: GRID scores for four geothermal projects

Using the GRID scores, four categories of geothermal projects in terms of concern about induced seismicity hazard, risk and social context are defined (Figure 25):

Category 0:

Induced seismic hazard, risk and social concerns are very low or absent and no dedicated induced seismicity risk gov-ernance is needed. Typical projects whose GRD scores fall in category 0 are, for example, closed systems where no fluids are exchanged with the under-ground, deep heat pumps or exploration drills that are situated in a low-risk area without signs of social concerns.

Category I:

Perturbations of the stress field in the underground may be expected, but damaging events are very unlikely and there is no significant social concern to be addressed. Typical projects in this category are hydrothermal projects in existing aquifers, with a depth of 0.5–3 km, if they do not target active fault systems, perform substantial stimulation, and if they are located in a low-risk area without social concern potential.

Category II:

Induced seismicity is possible, damaging events and social concern cannot be excluded. Typical projects whose GRID score fall into this category may be hydrothermal projects in existing aquifers with depths of more than 3 km, possibly near known fault systems, but that do not plan to perform substantial stimulation, and perturb the pore pressure and stress outside the immediate vicinity of the well. These projects may also be located in medium- to high-risk areas or can show evidence of social concern.

Category III:

Induced seismicity is likely, damaging events and significant social concerns are possible and require thorough risk governance measures. Typical projects in this category are EGS projects in basement rocks with depths below 3 km, possibly near known fault systems, and plans to perform substantial stimulation and reservoir enhancement. Seismicity will certainly occur and felt events are likely. Even in low-risk, low-social concern areas, these projects require substantial risk assessment, monitoring, mitigation, and public engagement.

On the basis of these categories, induced seismicity risk governance measures can be tailored to individual projects. Technical measures of hazard and risk assessment, seismic monitoring, and hazard and risk mitigation are described in the next sections. Stakeholder and public engagement measures fall outside the expertise of the SED, but are elaborated further by Trutnevyte & Wiemer (2017).

6. Risk assessment in all project phases

To reduce the risk of induced seismicity as much as feasible, various risk assessment techniques are needed in all project phases. With increasing project progress, more knowledge about the underground and its seismic response to geothermal operations is available. Thus, it is sensible to continuously integrate this new knowledge and update early hazard and, if any, risk studies, especially for Category II and III projects. Starting the seismic monitoring of the underground well before the project starts allows verifying the performance of the system and to record a number of small earthquakes that can help calibrate the local magnitude determination to the official magnitude, provided by the SED.

In Section 6.1 – 6.4 we list suggestions for tailor-made risk governance measures for different GRID categories. The risk governance framework in this report covers the role of four actor groups: (i) project operators, (ii) licensing authorities and/or regulators, (iii) independent experts, and (iv) stakeholder groups and the general public, see Figure 26–28. There are also other actors involved, like e.g. (re-)insurance companies or construction companies, but these actors are not explicitly shown in the figures, due to their relevance to a specific measure only.

6.1 Category 0 projects

Typical Category 0 projects are, for example, closed systems where no fluids are exchanged with the underground. Deep heat pumps or drill sites for exploration where no stimulation is planned are examples of Category 0. Based on the rich empirical data of past projects, the shallow depths as well as the minimal perturbations of the local stress field, it is highly unlikely that such projects will cause induced seismicity. Therefore, in our judgment, no dedicated induced seismicity hazard and risk assessment is required. Seismic monitoring is not needed either.

Even in Category 0 projects, operators or regulators may voluntarily add elements of monitoring as a transparency and trust building measure, especially if the societal concern is high (at times high concern can lift the project to the next category; see Figure 25).

6.2 Category I projects

Typical projects that fall in this category are hydrothermal projects in existing aquifers with a depth of 500 to 2000 meters if they do not target active fault systems, if they do not perform substantial stimulations and if they are situated in a low-risk area without signs of social concern. For Category I, there is sufficient experience from systems in similar tectonic environments and from simplified considerations to ensure that felt induced seismicity is highly unlikely.

Figure 26 shows the proposed risk governance measures for Category I projects. Although induced seismicity that is felt at the surface is highly unlikely during such projects, it should be considered during all of the project phases. The small possibility of induced earthquakes should be openly communicated and reflected on as part of the licensing.

6.2.1 Hazard assessment in the planning and operation phase for Category I

The planning phase is defined as the period between the first ideas about the project to the start of drilling the first geothermal well. Depending on the geothermal project, this phase may include several studies such as seismic surveys or resource exploration. They may have been conducted before the actual hazard and risk assessment. Ideally, seismicity has been covered as one factor in these studies, which serve as a starting point for hazard and risk assessment.

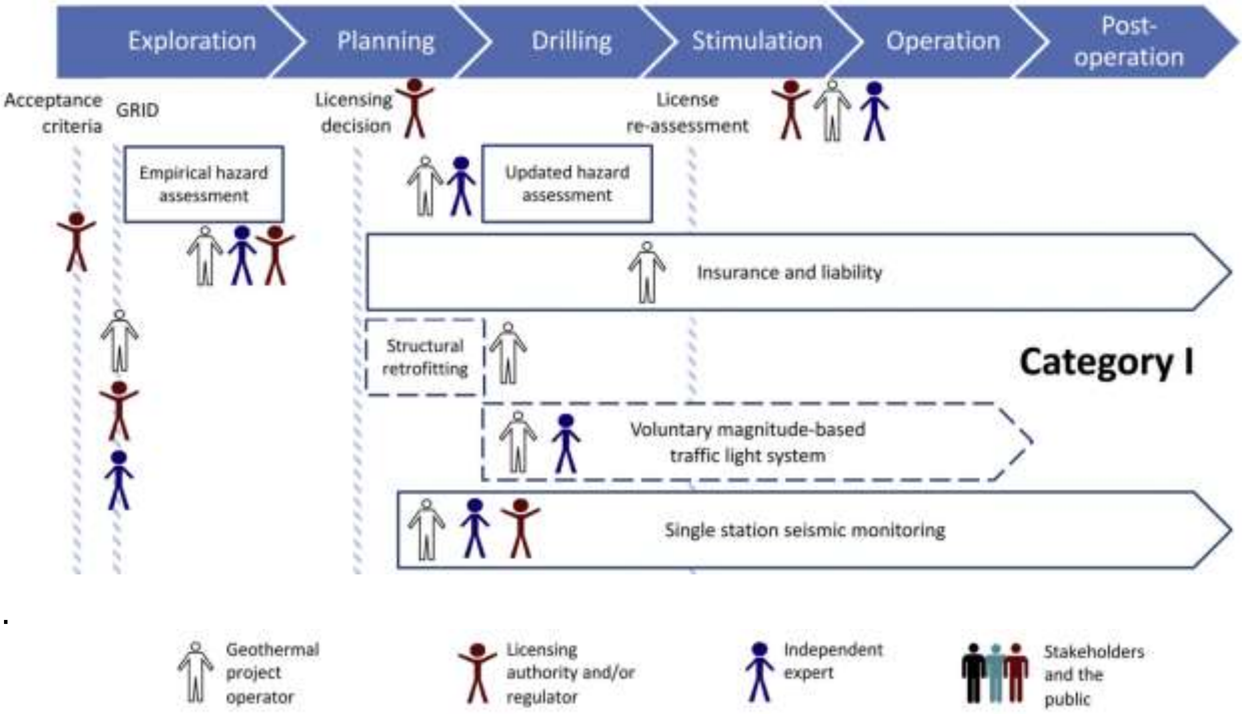

Figure 26: Risk governance measures for GRID Category I projects

As part of the licensing and environmental impact assessment, a dedicated induced seismicity hazard assessment should be conducted by the operator or an independent consultant. This study should result in a written expertise, which for Category I projects can be quite limited. The licensing authority, possibly involving additional independent experts such as the SED, should review it.

The following topics should be covered in this hazard and risk assessment:

- **Introduction and context:** Purpose of the study, description and roles of the involved parties.
- **Project description**. Description of the project setting, geological and seismo-tectonic context, historical and instrumental seismicity record near the project, existing seismic monitoring, and planned activities (injections planned, time-lines, operating conditions).
- **Hazard and risk assessment**: As induced seismicity may be expected, even if damaging events are unlikely, induced seismicity hazard assessment should be conducted as part of the environmental impact assessment. A seismic hazard assessment, based on analogues, empirical data, and scenario calculations, is sufficient. The key uncertainties should be mentioned in order to decide, during the review process, whether additional uncertainty analysis is warranted. This assessment should analyse the natural seismicity in a 10 km radius from the project site, quantify the stress changes in the well's vicinity, and assess the median annual probability of an induced event of $M_L \geq 2$. If this annual probability exceeds 1%, we suggest that such projects would be moved to GRID Category II (see Section 6.3). Risk assessment in terms of exposure and vulnerability should be conducted only for those buildings and infrastructure, if any, that are considered especially vulnerable to low magnitude events, such as heritage masonry structures or Class II and Class III structures (SIA, 2003). Such risk assessment could be based on analogues, empirical data and scenario calculations. Sources of key uncertainties should be mentioned in order to help decide, during the review process, whether in-depth analysis is needed.
- **Proposed monitoring and mitigation strategies**: The monitoring and data access strategy should be outlined, including strategies if unforeseen seismicity occurs.

Monitoring should include a single seismic station, not more than 1.5 times the operation depth away, installed for a continuous record of event counts. Rough estimates of distance to the station are possible with such a station. The station should start operating at least three months prior to stimulation in order to establish a background record of seismicity. It needs to run until the end of the operation, including a six-month post-operation phase. A voluntary magnitude-based traffic light system, as described for Category II, could be installed.

- **Summary and recommendations.**

Insurance policies for induced seismicity and procedures to link these damages with an induced event are necessary. Before a possible borehole stimulation, the state of buildings and infrastructure items in Class III should be documented (Majer et al., 2013). Building monitoring should be applied to selected buildings with higher damage concerns, such as heritage or Class III buildings.

6.3 Category II projects

Typical projects in this category may be hydrothermal projects in existing aquifers with depths of more than 3000 meters, possibly near known fault systems, but that do not plan to perform substantial stimulation and do not anticipate to perturb the pore pressure and stress field in the underground outside of the immediate vicinity of the well. These systems, that could be operated as singlet or duplets, may be located in medium- to high-risk areas and can show evidence of social concern. For Category II projects, enough experience to base a hazard and risk assessment solely on empirical data is typically missing. Therefore, modelling, monitoring, mitigation and updating of the initial assessment as new data arrive become required as compared to Category I projects.

Figure 27 shows the proposed risk governance measures for a Category II project. Because inducing earthquake during stimulation and operation is a possibility, induced seismicity must be considered during all project phases and the possibility of induced earthquakes should be openly communicated and reflected on as part of the licensing.

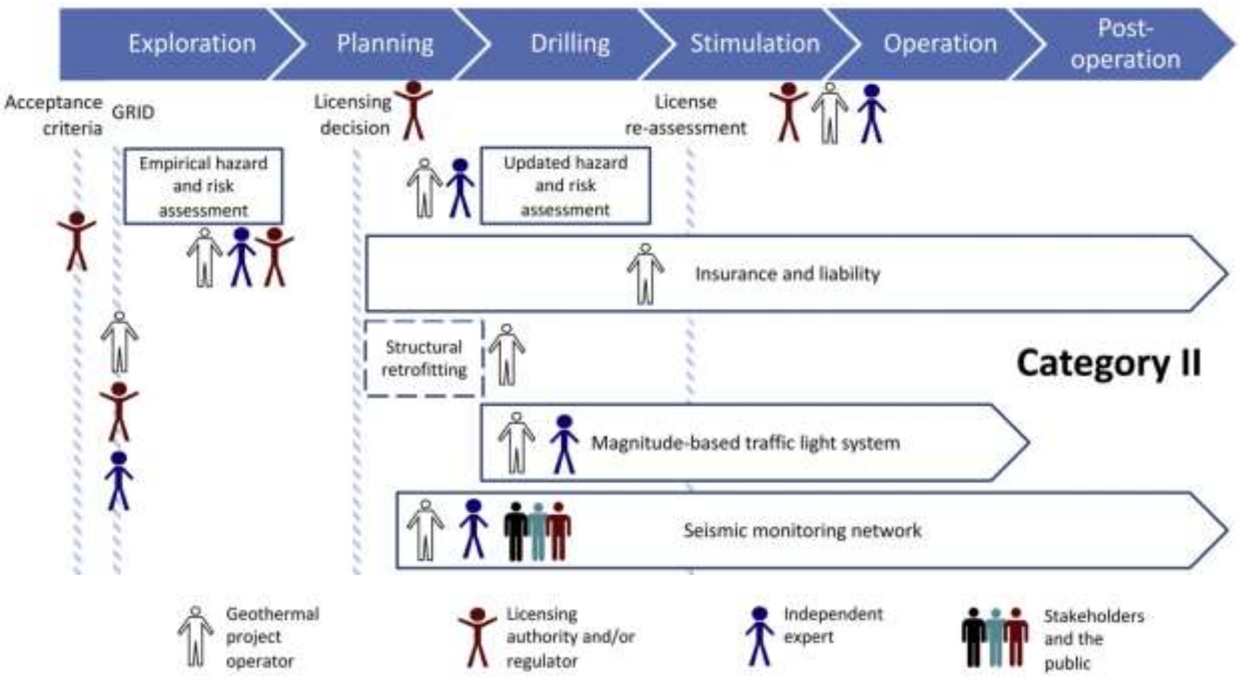

Figure 27: Risk governance measures for GRID Category II projects

We recommend that the operator or an independent consultant conducts a dedicated induced seismicity hazard and risk assessment as part of the environmental impact assessment and licensing. This study should result in a written expertise. It should be reviewed by the licensing authority and by independent experts, for example, by the SED.

6.3.1 Hazard and risk assessment in the planning phase for Category II

The following topics should be covered in the hazard and risk assessment in the planning phase:

- **Introduction and context:** same as for Category I.
- **Project description**: same as for Category I.
- **Hazard and risk assessment**: For Category II projects, induced seismicity hazard and risk should also be assessed as part of the environmental impact assessment. In addition to the empirical, scenario-based hazard assessment, recommended for Category I projects, uncertainties should be explicitly quantified, accounting for alternative models and mechanisms. Scenario calculations should cover both expected induced seismicity and ground shaking impacts. The worst-case scenario should be quantified, too, such as the magnitude of a two-sigma event with an annualized probability below 5% and its impacts. If the median annual probability of $M_L \geq 3$ exceeds 1%, such projects should be moved to GRID Category III (see Section 6.4). The assessment should already cover the measures of seismic monitoring, traffic light system, and emergency procedures. Like for Category I, risk assessment should be conducted only for those structures or infrastructures, if any, in Class II and III (SIA, 2003), and vulnerable heritage sites.
- **Proposed monitoring and mitigation strategies**: The monitoring, data access and archiving strategy should be outlined, including strategies if unforeseen seismicity occurs. As induced seismicity and associated risk and social concerns are considered possible, seismic monitoring should enable the detection of felt earthquakes and their location, as well as enable the functioning of the magnitude-based traffic light system. A seismic network of at least four continuously recording stations must be placed around the site with one station in the center. The aim is to achieve a complete detection of $M_L \geq 1$. The distance to the expected source should be about two times the planned geothermal operation depth, but less than 10 km. The central station should also be equipped with an accelerometer to allow recording of strong motions up to 1 g. A notification and alarm system should be set up to provide real-time information to the operator and regulator about automatically detected and located earthquakes. The monitoring should start at least six months before the drilling. The conventional, magnitude-based traffic light system should be coupled to a list of mitigation actions. Such a system steers the operation to continue as planned (green), continue without increasing (yellow), stop (orange), or release fluids out of the well (red) on the basis of observed local magnitude and peak ground velocity (Figure 31a). Projects should define the function and members of an independent expert panel that can be called upon in order to quickly advise the operator and regulator in case of unexpected events.
- **Summary and recommendations.**

The same recommendations apply as in Category I regarding the question of insurance against damages by induced earthquakes.

6.3.2 Hazard and risk assessment during the stimulation phase for Category II

A formalized mechanism to update the hazard and risk assessment as new data arrives during the drilling, stimulation or operation phase should be foreseen and implemented. The assumptions made in the hazard and risk assessment should be systematically checked against new observations in order to ensure that the pre-defined acceptance criteria are not exceeded.

Seismic monitoring must be fully operational during the stimulation phase and monitored in real time. If during an acid stimulation or pressure test an event of magnitude of $M_L \geq 1.0$ is detected within 2.5 km of the project, the stimulation operations should be stopped and the seismic hazard re-assessed.

6.3.3 Hazard and risk assessment during the operation and post-operation phases for Category II

Seismic monitoring of the project, coupled with the conventional, magnitude-based traffic light system and mitigation actions, should continue during the operation phase and at least six months of the post-operation phase, demonstrating that no events are occurring; this for two reasons:

- In other projects it has been observed that induced seismicity can occur even after years of earthquake-free operations.
- The distinction of induced versus natural seismicity relies on a good local network coverage.

If during the operation an event of magnitude $M_L \geq 1.5$ is detected within 2.5 km of project, first mitigation steps should be taken.

6.4 Category III projects

Typical projects in this category are petrothermal (EGS) projects in basement rocks with depths of more than 3000 meters, possibly near known fault systems, and planning to perform substantial stimulations and reservoir enhancement. Seismicity in such systems is often not a side effect but a required tool to enhance permeability. Seismicity will certainly occur, felt events are likely. Even in low-risk, low-social concern areas, these projects require substantial risk assessment, monitoring, mitigation, and public engagement.

Figure 28 shows the proposed risk governance measures for a Category III project. For Category III, a participatory risk governance process is highly advisable. We recommend that a dedicated induced seismicity hazard and risk assessment is conducted by the operator or an independent consultant as part of the environmental impact assessment and licensing. This study should result in a written expertise. It should be reviewed by the licensing authority, and reviewed by independent experts such as the SED as part of a participatory review process.

6.4.1 Hazard and risk assessment in the planning phase for Category III

The following topics should be covered in the hazard and risk assessment:

- **Introduction and context:** same as for Category I.
- **Project description**: same as for Category I.

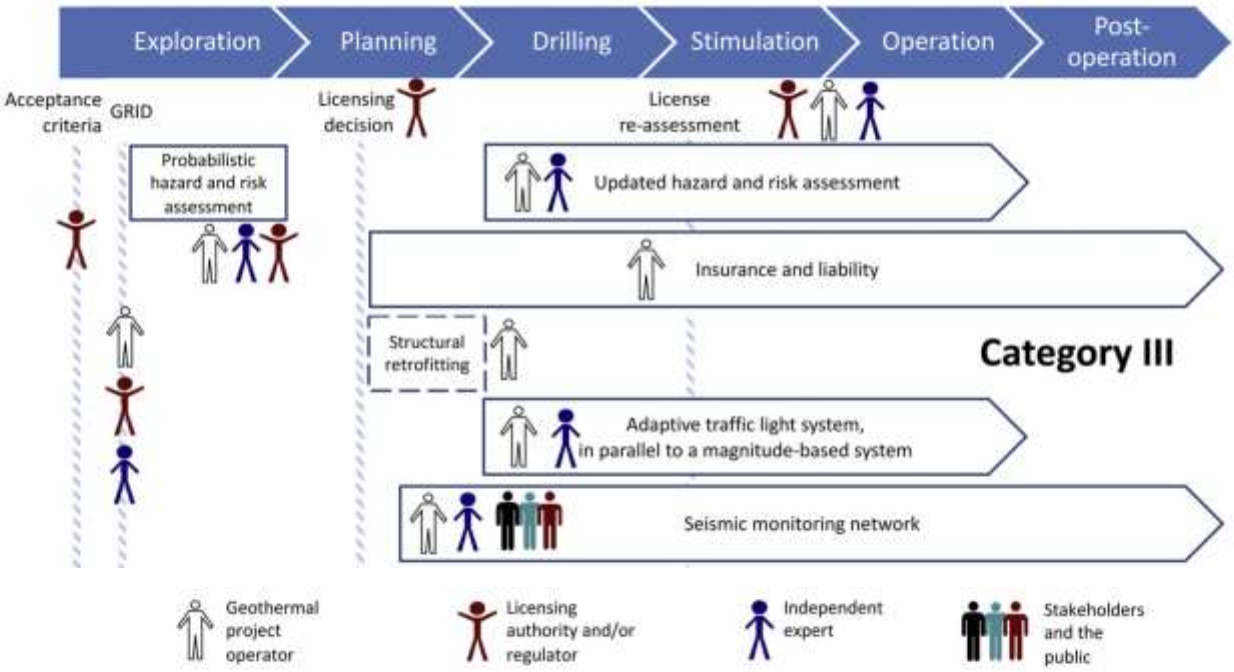

Figure 28: Risk governance measures for GRID Category III projects

- **Hazard and risk analysis**: Since induced seismicity is likely, and damaging events cannot be excluded, a dedicated study of induced seismicity hazard and risk assessment is recommended. Such a study should include a detailed risk assessment in terms of financial losses and personal risk. Analytical probabilistic risk assessment of the specific building and infrastructure items is preferable to empirical approaches. It is thus recommended to characterize seismic hazard using Ground Motion Prediction Equations (Bommer et al., 2015) instead of macroseismic intensities (Grünthal, 1998).

  This hazard and risk assessment should be fully probabilistic. Logic-tree analysis could be used to explicitly account for both aleatory and epistemic uncertainties (Mignan et al., 2015). Seismicity forecasting models should consider the expected hydraulic footprint of the stimulation and be coupled to one or several geomechanical models (Wiemer et al., 2015). A strategy for calibration and validation of the hazard and risk model, once the drilling has been completed, should be defined. Low-probability – high-consequence events should be evaluated.

- **Proposed monitoring and mitigation strategies**: The monitoring, data access and archiving strategy should be outlined, including strategies if unforeseen seismicity occurs. Since induced seismicity is likely, and damaging events cannot be excluded, a seismic monitoring network as described in Category II should be installed. The aim is to achieve a complete detection of $M_L \geq 0.5$ with automatic detection algorithms. In addition to the accelerometer of the central station, multiple accelerometers could be installed, especially in areas with higher damage concerns, such as heritage or Class III buildings. The network needs to start at least six months before drilling.

  The planned measures of structural retrofitting, seismic monitoring, and traffic light systems should be assessed. Emergency procedures should be delineated. In parallel to the conventional magnitude-based traffic light system, an adaptive traffic light system should be installed as well (Section 11.3 and Figure 31b).

  Projects should define the function and members of an independent expert panel that can be called upon in order to quickly advise the canton and operators in case that unexpected events occur.

- **Summary and recommendations.**

Since induced seismicity is likely, and damaging events are possible, in addition to the insurance of GRID Categories I and II above, a mechanism to monitor the shaking of selected buildings and infrastructure items as a means to clarify the liability should be organized. Documentation of the state of buildings, as well as building monitoring, should be done for Class II and III buildings. A denser building monitoring network, including Class I buildings, with the engagement of the population, is recommended. As a detailed documentation of the state of buildings can be expensive and face privacy issues, voluntary documentation by building owners through crowdsourcing could be set up (Douglas, 2016).

6.4.2 Hazard and risk assessment during the stimulation phase for Category III

The stimulation phase should be processed by dedicated tests that provide input to calibrate and, as much as feasible, validate the forecasting models and assumptions made in the initial hazard and risk assessment. For example, an injectivity test could be conducted in order to calibrate the seismic response and ground motion prediction models and in order to provide additional constraints on the earthquake location model. The assumptions made in the hazard assessment should be systematically checked against new observations in order to ensure that the pre-defined acceptance criteria are met. A formalized mechanism to update the hazard assessment as new data arrives during the drilling, stimulation or operation phase should be foreseen and implemented. The project should ensure that the seismicity to be expected with the planned stimulation strategy remains at all times within the acceptability criteria of the project.

A suitable strategy could be to adopt a phase-wise approach, where the reservoir is built in small steps, each followed by a (rapid) re-assessment of the seismic hazard and risk as a way of risk mitigation.

Seismic monitoring must be fully operational during the stimulation phase and monitored in real time. The conventional and adaptive traffic light systems should be running automatically. Real-time information on the evolving seismicity and on the forecast of the seismicity to be expected in the next, for example, 24 hours, should be provided in a fully transparent way to all parties, including the general public.

6.4.3 Hazard and risk assessment during the operation and post-operation phase for Category III

Seismic monitoring of the project, coupled to a conventional traffic light system and mitigation actions, should continue during the operation phase and as well as post-operation, for three reasons:

- In other projects, it has been observed that induced seismicity can occur even after years of earthquake-free operation. New clusters of seismicity may occur.
- Changes in the production regime are likely and may be correlated with changes in the observed seismicity.
- The distinction of induced versus natural seismicity relies on a good local network coverage.

Seismic monitoring during the post-operation phase should continue, without reducing the number of stations, until the seismicity returns to pre-stimulation levels. Active steps to reduce the seismic activity should be tested, for example, by reducing the reservoir pressure by pumping out fluids from the reservoir.

Depending on the reservoir type, this time period can vary dramatically. 11 years after the stimulation, the Basel reservoir is still at an elevated level of activity (Kraft, 2016). The seismicity in the St. Gallen reservoir, however, stopped essentially after the production test (Diehl et al., 2017b).

7. Suggestions for hazard and risk acceptance criteria

The exploitation of deep geothermal energy is, like all energy production, not risk-free and while operators can minimize the risk of induced seismicity, they cannot generally reduce it to zero. Therefore, like for all other technologies, a balance between risk and potential benefits is required (Fischhoff, 2015). Risk-cost-benefit analyses offer a transparent pathway to assemble and integrate relevant evidence to support such complex decision-making processes under high uncertainties and significant knowledge gaps.

In the end, clear acceptance criteria or thresholds need to be set by the regulator as targets to be met by the operator throughout the project cycle. Setting these criteria is within the responsibilities of the cantonal or municipal regulatory authorities; it is not a task of the SED. However, as no existing regulations from within or outside Switzerland exist or can readily be applied, the SED is making non-binding recommendations ("Empfehlungen") in the next sections.

7.1.1 OPAM

The SED considers the OPAM "*Ordonnance sur la protection contre les accidents majeurs*" regulation[20], applied frequently in the chemical industry and referred to in the Basel SERANEX study (Baisch et al., 2009), to be problematic for induced seismicity or earthquake-related risks overall, for several reasons:

- Extrapolating Probabilistic Seismic Hazard and Risk Assessments to annual probabilities as low as 10^{-7} or even 10^{-11} is generally considered problematic. The Swiss national PSHA model, for example, is valid only down to 10^{-4}.
- OPAM thresholds are based on median risk estimates.
- OPAM is not consistently used in other energy technologies, such as hydro-dams.

While OPAM can be instructive to compare the risk profiles of different technologies, one needs to be aware that the numbers computed may not be comparable between technologies because the way uncertainties are considered is not standardized.

7.1.2 Suggested acceptance thresholds

Category I projects: It is considered very unlikely that these projects will cause induced earthquakes. The recommended thresholds are:

- A hazard study should establish that the median annualized probability of inducing a $M_L \geq 2.0$ event during the stimulation or operation is below 1%.
- Seismic monitoring should establish that no events with M_L greater than 1.0 are induced in the vicinity of the well.
- If these thresholds are exceeded, the project should be considered as Category II.

Category II projects: Category II projects are unlikely to cause felt or damaging events, but the uncertainty in the assessment is larger than for Category I projects, and limited experience exists. These thresholds are suggested:

- A hazard study should establish that the median annualized probability of inducing a $M_L \geq 3.0$ event during the stimulation or operation is below 1 %. This assessment need to be updated as new data becomes available.
- If this threshold is exceeded, the project should be considered as Category III.

[20] https://www.admin.ch/opc/fr/classified-compilation/19910033/201506010000/814.012.pdf [Accessed: 18 Sep. 2017]

- Insurance coverage for potential damages by induced events should be explicitly included in the overall insurance policy.
- An adequate seismic network is in place that can drive a conventional traffic light system coupled to mitigation measures.

Category III projects: Seismicity is likely to occur and needs to be limited to acceptable levels. A Probabilistic Seismic Hazard and Risk Assessment in terms of fatalities and financial losses should be conducted. We suggest that operations shall be considered acceptable if:

- A full Probabilistic Seismic Hazard and Risk Assessment is conducted initially and updated as new data arrives, based partially on in-situ validation experiments such as test stimulations.
- The annualized local personal risk (LPR) is below the threshold of 10^{-6} at any point in time of the project. The LPR can be defined as "*the probability of death of a fictional person who is permanently in or near a building*"[21]. The LPR is adapted as new data becomes available.
- Operators demonstrate insurance coverage for the potential losses at the median annual exceedance probability of 10^{-4} or below.
- Accepted mechanisms are in place to establish under which conditions homeowners are compensated for potential damages (crack protocols, vibration monitoring).
- An adequate seismic network is in place that can drive a conventional and adaptive traffic light system.

[21] LPR focuses on the risk to people inside a building and assumes that the fictional person is present inside the building 100% of the time. The location of the person is uniformly and randomly distributed inside the building, i.e. if 10% of the building collapses there is a 10% probability that the fictional person will be in the collapsed part of the building.

8. Suggestions for modeling induced seismicity rates, hazard and risk

Over the past five years there has been rapid progress in the scientific community that develops induced seismicity forecasting models. Induced seismicity models can be grouped into three classes (e.g., Gischig and Wiemer, 2013; Gaucher et al., 2015): statistical, physics-based, and hybrid. In general, statistical models for induced seismicity (Reasenberg and Jones, 1989; Hainzl and Ogata, 2005; Bachmann et al., 2011; Mena et al., 2013) are conceptually and computationally simple and model aleatory uncertainty. But often, they do not attempt to forecast the spatial distribution of earthquakes and do not explicitly account for the governing physical processes, such as fluid flow in fractures, permeability changes, stress interaction. Hence, their ability to predict large events and to forecast for longer periods maybe limited.

Physics-based models (e.g., Olivella et al., 1994; Bruel, 2005; Kohl and Megel, 2007; Baisch et al., 2010; Rinaldi et al., 2015; McClure and Horne, 2012; Wang and Ghassemi, 2012; Karvounis and Wiemer, 2015) do consider some underlying physical processes. But physics-based models are currently too computationally demanding (Mignan, 2015), and often have too many free parameters to be robust and ready for real-time applications. Hybrid models are a compromise between forecast capabilities of physical models and computational efficiency of statistical models. The goal is to include a minimum of physical complexity, and replace more complex physical considerations with statistical methods or stochastic processes.

In the past few years, the SED has developed and systematically validated probabilistic approaches to assess the induced seismic hazard and risk throughout all project phases. The models are used to forecast the seismic response of the underground to injection rates (Bachmann et al., 2011; Mena et al., 2013; Gischig and Wiemer, 2013; Gischig et al., 2014; Karvounis et al., 2014; Király-Proag et al., 2016; 2017). Figure 29 shows the evolution of model complexities of hybrid models that have been developed at the SED.

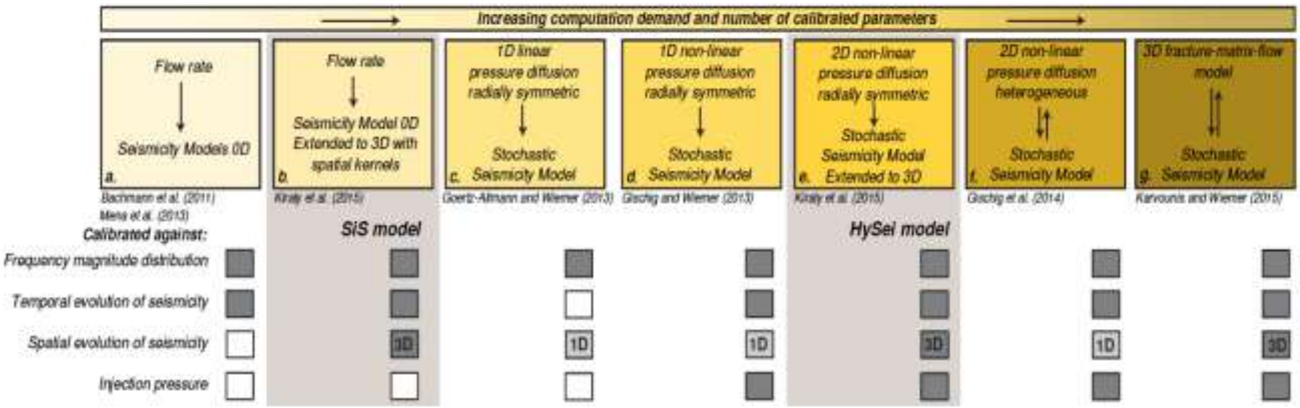

Figure 29: Evolution of induced seismicity models that are potential candidates for an Advanced Traffic Light System in geothermal projects (from Király et al., 2015)

Ground Motion Models are critical elements for translating the forecasted earthquake rates into hazard and risk. These models estimate the distribution of ground motion in a certain area given the properties of the earthquake source (magnitude, style of faulting, depth), the wave propagation (distance of the site from the source), and site response (type of rock and soil that can attenuate or amplify ground shaking). Ground Motion Prediction Equations (Douglas et al., 2013; Edwards and Douglas, 2013) and the Virtual Earthquake Approach (Denolle et al., 2013, 2014) are examples of possible choices to estimate ground motions.

Bommer et al. (2015) and Walters et al. (2015) also provide an overview of approaches and methods suitable for hazard and risk calculations in induced seismicity contexts.

9. Seismic monitoring guidelines

9.1 Goal

With this recommendation, the SED aims to establish a common minimum standard for seismic monitoring of deep geothermal projects in Switzerland that bear the potential of induced seismicity. This standard is designed to ensure the accurate detection (Category I) and localization of felt earthquakes for all such projects (Category II and III). In project phases that imply increased seismic hazard (e.g. reservoir stimulation), geothermal projects need to establish mitigation strategies, that is, Traffic Light Systems (TLS). The standard ensures that seismic monitoring during these phases is of sufficient sensitivity to drive such systems for Category II and III projects.

For advanced purpose, such as the detailed study of the evolution of microseismicity in space and time or the discrimination between natural and induced seismicity, a more elaborated monitoring strategy may be required. This is the case for Category III projects. In the case of detection-only purposes (without earthquake localization), a limited instrumental effort can be sufficient.

Even though this guide is focused on the support of Swiss authorities and project operators in planning and evaluating their monitoring strategies, we hope that these guidelines are also helpful for an international community. The basic outline follows the recently published recommendations of the FKPE working group on induced seismicity (Baisch et al., 2012) and was adapted based on recent experience of the SED in various monitoring projects in the framework of the GEOBEST and GEOBEST-CH projects.

9.2 General recommendations for technical project monitoring

Over the live time of a deep geothermal project many different activities and parameters have to be monitored and documented. This ranges from the feasibility studies over technical, geological, and hydrological reporting during drilling and hydraulic testing to continuous technical monitoring and documentation of operation parameters and activities in the production phase of the project. These data and documents are generated with a substantial logistical and financial effort by the project operator, and often with substantial support by public funding. It is therefore essential that all data and documents refer to common standards and reference systems.

Especially for time series data, this has seldom been the case in past projects. Bringing together data from different measurement systems, as closely related as e.g. well-head and down-hole pressure readings, was often difficult to impossible in the past and sometimes prevented essential analyses to better characterize the geothermal reservoir or to gain a better understanding of induced seismicity. In the following, we give a few basic recommendations to avoid such situations in future projects.

Technical Documentation:

- All documents should refer to an agreed coordinate reference system. In Switzerland we recommend to use Swiss coordinates (CH1903).
- Absolute elevations should be given in the Swiss reference system (CH1903). Relative depth values often used in drilling projects (e.g. true vertical depth, mTVD; measured depth, mMD) must clearly be identified and described with reference to CH1903.
- Time specifications should have an accuracy of at least one minute and should refer to universal time (UTC). Time should always be read from radio-controlled or GPS-controlled clocks. In any case, the time reference system used in the report must be

unequivocally indicated, and must not be changed throughout the report. If time can only be given approximately, uncertainties must be indicated.

- Reports should use SI units for all quantitative parameters. For derived quantities, all assumptions made and transformations used must be indicated.

Time series data:

- All sensor systems in the project must be coordinated to a common time basis. The absolute accuracy must not be less the 1 ms. This can easily be achieved when using GPS-controlled data loggers, and has been an established state of the technology since several years.
- All sensor systems should be recorded digitally, and stored in well-documented and established standard formats.
- The meta data of all sensors and digitizers must be documented. All changes to the sensor systems (e.g. change of sampling rate, change of gain factors, change of sensor or digitizer), failures of equipment or data corruption data should be documented in detail.
- All sensor systems should be digitized with a minimum sampling rate of one sample per second starting with the first hydraulic testing and not ending before at least six months of regular operations of the geothermal plant. Before and after this period minimum sampling rates should not be less than one sample per minute.
- All sensor systems must be digitized using a sufficiently high dynamic range. It is recommended to use at least 16-bit digitizers for all systems.

9.3 Recommendations for seismic monitoring

9.3.1 Operation of a seismic network

This paragraph describes if and what kind of seismic monitoring is recommended for deep geothermal projects in the different GRID categories.

GRID Category 0:

No monitoring necessary.

GRID Category I:

The objectives of the monitoring for Category I project are:

- helping detect and constrain location of microseismicity and potentially felt events,
- providing a continuous record that could be post-processed if problems occur,
- allowing for detailed monitoring (event counts) during pressure and leak-off tests.

To achieve these objectives, one high-quality station should be installed at distance of not more than 1.5 times the planed operation depth of the geothermal operation, if none is already in existence as part of the national network of the SED. This station should be installed no less than three months prior to the stimulation, in order to establish a background record of seismicity. The station should be operated throughout the project operation period and the data should be provided to and archived at the SED, in near-real-time in order to help to constrain the location and source depth of an unforeseen induced or natural felt earthquake close to the geothermal operation. With a single station, only rough estimates of distance to the station and size of the earthquake are possible, and no redundancy exists in case of station failure.

GRID Category II (ensures accurate felt event localization and operation of a traditional, magnitude-based Traffic Light System): For the determination of source parameters, at least four continuously recording stations must be placed around a geothermal system, aiming for a completeness of $M_L \geq 1.0$. The completeness level to be achieved should be modelled as part of the network design, using realistic assumptions about the noise conditions at the recording sites.

The epicentral distance to the expected source region should be about two times the planed geothermal operation depth but less than 10 km. Azimuth gaps of more than 120° between the stations should be avoided. One of the stations should be placed in the centre of the network, close to the expected source region. The recording sites should be chosen in such a way that the measurement accuracy outlined in section 9.3.2 are fulfilled. The central station should in addition be equipped with an accelerometer that allows recording strong ground motions up to 1 g. Existing stations of the SED should be included in the monitoring network, and this may reduce the number of new stations needed, depending in the local density of stations.

GRID Category III (ensures operation of an adaptive Traffic Light System): The Category III network should be extended by a sufficient number of stations to ensure a completeness level of $M_L \geq 0.5$ with automatic detection algorithms. The completeness level to be achieved should be modelled as part of the network design, using realistic assumptions about the noise conditions at the recording sites. Earthquakes down to the completeness level must be located with the measurement accuracy outlined in section 9.3.2. To improve the absolute location accuracy and source depth determination, we recommend performing a calibration of the seismic velocity model (e.g. by calibration shots).

The following applies to all GRID Categories:

- Three orthogonal components of the ground velocity must be measured to allow a clear discrimination of seismic wave types and to use P- and S-waves for earthquake localization.
- Seismic stations must be synchronized to a common time reference with a precision of 1 ms (e.g. by GPS). It is recommended that additional non-seismological measurements and operator activities at the geothermal project are synchronized and referred to the same time reference with the same precision.
- Real-time transfer of continuous waveform data should be implemented and standard formats for waveform and instrument meta data should be used. We recommend the SEED format.
- The monitoring system should be fully operational for at least six months for Category II and II projects and at least three months for Category I projects before the start of the geotechnical operation. This way, it is possible to verify the error-free operation of the system, to record a number of small earthquakes that can help to calibrate the local magnitude determination to the official magnitude provided by SED, and to establish a first order background activity.

9.3.2 Measurement accuracy

For GRID Categories II and III, the monitoring network should ensure a location accuracy of ± 0.5 km horizontally and ± 2.0 km in depth in the expected source region and its direct periphery (within 5 km). It is recommended to perform numerical simulations during the design of the network to verify whether this location accuracy can be achieved. These simulations have to take into account realistic estimates of the involved uncertainties (e.g. precision of onset-time determination vs. signal-to-noise ratio, uncertainty in seismic velocities). For examples of such an approach, see Kraft et al. (2013).

The following applies to all GRID Categories. At each measurement site, compressional waves (P-waves) with amplitudes of 600 nm/s (ground velocity) must be measured with a signal-to-noise ratio (SNR) of at least 6 over the frequency range of 5–40 Hz. In other words, the noise level in the mentioned frequency band should not exceed an amplitude of 100 nm/s with a confidence level of 95% (I95-value, see below), and the recording system must be able to resolve this noise level over the mentioned frequency range.

The 600 nm/s amplitude was defined in order not to miss possibly felt earthquakes (about M_L ~1.8 at 3–5 km depth in sedimentary basins) at stations in epicentral distances of about 10 km and to ensure Category III monitoring requirements for stations in a epicentral distance of up to about 5 km. A simple method to calculate I95-values from ground-motion recordings in the time domain is given by Groos and Ritter (2010).

It is recommended to conduct noise measurements with a duration of at least seven days and noise analyses prior to the installation of a seismic station. The noise level (I95 = 100 nm/s) has to be assured over the total monitoring period. An assessment scheme for site selection is outlined by Plenkers et al. (2015), see also Figure 30.

Should it not be possible to find measurement sites of the mentioned quality, we recommend to use shallow borehole installations (80–150 m depth). If possible, the sensor should be installed below the weathered and alluvial layers in bedrock geology.

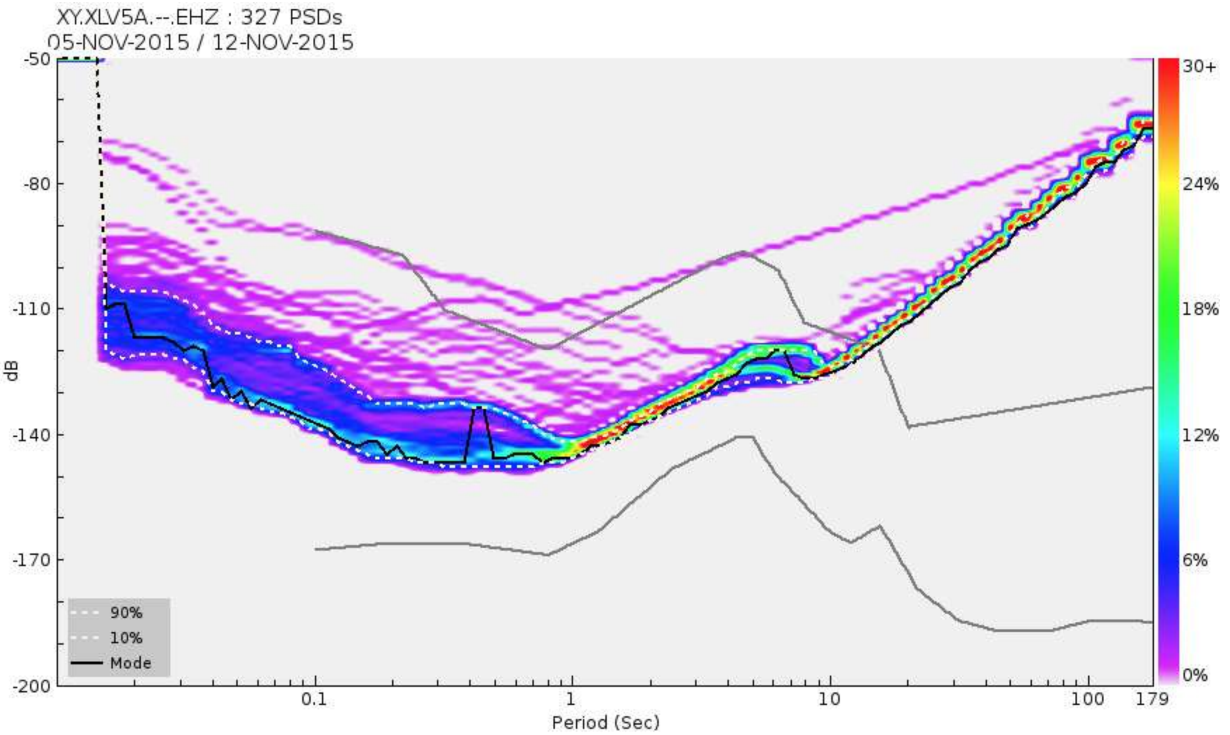

Figure 30: Example of the analysis of a noise measurement at a test site. Color-coded is the spectral energy density at different recording periods.

A quantitative procedure for site selection for seismic stations in urban areas and for the documentation of the decision process to authorities and other stakeholders is detailed in Plenkers et al. (2015).

9.3.3 Integration of seismic data sources

We recommend that seismic waveforms of all monitoring stations are provided in real-time to the SED in order to improve the location capabilities in the area of interest.

Data of vibration monitoring networks (immission monitoring according to SN 640312a) should be adapted to the requirements to record the full waveform of induced earthquakes and merged in a common database.

9.3.4 Transparency

A notification and alarming system should be set up that provides real-time information on automatically detected and located earthquakes and subsequent manual refinements to the operators and involved cantonal and federal authorities. Notifications and alarms should be sent via SMS and email.

We also recommend publishing this information in real-time on a dedicated project page on the internet, which could be hosted at the SED.

We recommend publishing earthquake catalogues and epicentre maps in near real-time on the internet. Seismic waveform data should be opened to research at least after three years in central databases. Such an open data policy will allow transparency, verification and the application of advanced analysis methods.

10. Seismic reflection

10.1 Power and limitation of seismic reflection surveys

Seismic reflection surveying, either by sets of intersecting 2D lines or so-called 3D cubes, is by far the most popular earth resource exploration tool worldwide. The oil industry in particular has been using this method for more than 50 years and today, in almost every sediment basin, seismic reflection data has been acquired. The targets of the oil industry are not too different from the targets of at least part of the operators of geothermal projects. Both parties are interested in imaging sediments layers and faults with the best possible resolution.

One obvious limitation of the method is its inadequacy when it comes to image the crystalline basement. There, the seismic reflection fails because the required impedance[22] contrasts are commonly missing or are erratically distributed. Therefore, for petrothermal projects that are typically located in the crystalline basement, seismic reflection is of little use unless the projected reservoir is located close to the sediment–basement interface and faults that cut this interface (and are as such visible) are a concern.

Geothermal projects on the other hand are typically located in sedimentary layers. Zones of enhanced permeability are commonly associated with fault systems. Here the benefit of imaging these fault systems, most appropriately with a 3D seismic campaign, is two-fold: (a) their orientation, in the context of the present-day stress regime, can be determined precisely and (b) their vertical extension may be identified. The latter can give useful insight into when the fault was last active. Both elements can contribute to a forecast of the probability that the fault system is still active or could be re-activated. Note that in the case of the St. Gallen project and despite the existence of a high-quality 3D seismic survey (Heuberger et al., 2016), the shallow termination of the fault system could not be mapped precisely as the thick Molasse sequence that overlays the Mesozoic target consists of monotonous contrast-poor alternations of sandy layers.

From a communication point of view, the acquisition of reflection seismic data, with its broad visibility in the field, may conduce to an early information and sensitization of the population to the project.

10.2 Recommendations

Depending on the level of concern about induced seismicity, different degrees of effort may be invested in studying existing or even acquiring new reflection seismic data. Note that the project leaders may weight the benefit of acquiring seismic data, in the field or from the data owners, higher for the planning of their operations, say, of their well trajectories, than for a better understanding of possible induced earthquakes. Here, we only take the latter benefit into account.

GRID Category 0: Analysis of reflection seismic data is not necessary.

GRID Category I: As it is considered very unlikely that these projects will cause induced earthquakes, interpretation of reflection seismic data is not necessary.

GRID Category II: As typical projects in this category are hydrothermal projects in existing aquifers with depths of more than a few kilometres, possibly near known fault systems, a review of the existing reflection seismic data is highly advisable to characterize the fault system in terms of its orientation and potential for (re-)activation. Where the available data is insufficient, the acquisition and interpretation of a few 2D profiles or even of a 3D survey may be considered. This is true even if such a Category II project is not planned to perform

[22] The seismic impedance is the product of seismic velocity and rock density.

substantial stimulation and the pore pressure and stress field perturbations are not expected to extend outside of the immediate vicinity of the well.

GRID Category III: Even if seismicity in such projects is a tool required to enhance permeability and even if it would be desirable to 'see' along which structural elements such a seismicity develops, this is not a field for seismic reflection as projects in this category are commonly petrothermal projects typically designed in seismically transparent basement rocks. However, reflection seismic data might be of benefit to those projects located close to the sediment–basement interface and concerned about avoiding faults. Should the project alternatively be located in the sediment package, the acquisition of reflection, preferably 3D seismic data or the incorporation of possibly existing high-quality data is very much appropriate and highly recommended.

11. Mitigation and resilience strategies for induced seismicity

11.1 General considerations

As noted first by Bommer et al. (2006), innovative risk reduction strategies are possible in the scope of induced seismicity since one can manage the risk through control of the hazard, in contrast with standard seismic risk mitigation where only an intervention on vulnerability and/or exposure is feasible. Traffic-light systems have been proposed to determine when the risk associated to induced seismicity reaches an unacceptable level and thus when the EGS operations must be modified or stopped (e.g., Bommer et al., 2006; Häring et al., 2008; Giardini, 2009; Convertito et al., 2012, Bommer et al., 2015; Mignan et al., 2015). Note that traffic lights also can return to green (or yellow) after some time. It is therefore just as important that criteria are formulated as to whether and when operations can be restarted.

Predefined mitigation measures are important elements of risk assessment and risk reduction. The future evolution of induced seismicity can, to a certain degree, be controlled through adequate mitigation steps. Reducing injection or depletion rates, potentially interrupting operations, will lead to a strong reduction of seismicity with time, although the delay times can be ranging from hours to weeks.

Conservatively tuned traffic-light systems are thus a highly effective way to reduce the risk. By agreeing beforehand to a certain threshold, the project risk can be greatly reduced. A simplified example is given here: The operators of a site where no seismicity is expected during an acidification test agree to stop the injection if, notwithstanding, seismicity of $M_L \geq 1.0$ occurs. In the hazard assessment it can then be roughly assumed that the probability of a $M_L = 2.0$ event is around 10% and the probability of a potentially damaging event of magnitude 3.0 is 1% or less. This is a result of the universal observation that earthquakes scale following a power-law distribution (the so called Gutenberg-Richter law) and without site-specific knowledge, a slope of 1.0 can be assumed. In this case, there are 10 times more earthquakes at magnitude M than at magnitude M+1. Setting the same traffic light at magnitude 2.0 rather than at magnitude 1.0 will result in a seismic hazard that is roughly 10 times larger.

Projects where induced seismicity is not just an unwanted by-product but a tool to create the enhanced permeability of the reservoir itself (e.g., petrothermal projects), are faced with a more difficult problem: the need to balance safety and the economic success in terms of heat output. Gischig et al. (2014) reflected on this problem in detail. The choice of the threshold for mitigation measures, therefore, is directly coupled to the economic success rate of the project.

Please note also that just like for natural earthquakes, insurance against induced-earthquake damage is an important element of recovery and resilience. While approaches to define insurance policies are outside of the SED expertise, we do like to point out that the existence of adequate insurance policies has been a major factor influencing public acceptance.

11.2 Traditional traffic-light systems

The most widely used tools so far for hazard and risk management and mitigation, and an integral part of 'protocols' or good practice recommendations (e.g., Majer et al., 2012; Ellsworth, 2013; Grigoli et al., 2017) are so called traffic-light systems, first proposed by Bommer et al. (2006) for the 'Berlín' geothermal project in El Salvador. This approach was also adopted by the EGS project in Basel (Häring et al., 2008) and 2013, during the St. Gallen hydrothermal project (Diehl et al., 2017b). In both cases, the operators were well aware of the possibility of inducing earthquakes, strong enough to be felt. To monitor earthquake activity and to be prepared for hazard mitigation actions, they adapted the traffic-light system to be based on three components:

- Public response,
- observed local magnitude and
- peak ground velocity (PGV; see Häring et al., 2008 for details).

In a four-stage action plan, the injection of fluids in Basel would either be:

- continued as planned (green),
- continued but not increased (yellow),
- stopped (orange) or
- stopped and a "bleed-off" initiated (red), where bleed-off means the active release of fluids out of the borehole.

The traffic-light system threshold levels were defined somewhat ad-hoc and primarily based on expert judgment. The pressure reduction and eventual bleed-off of the system in Basel during the critical days around December 8, 2006 were consistent with the actions stipulated in the traffic-light system. However, the ultimate failure of the Basel EGS project suggests that the standard traffic-light system, as defined, was not a sufficient monitoring and alerting approach (see Bachmann et al., 2011). In the case of St. Gallen, the situation was somewhat different: Here, the yellow threshold of the traffic light was reached, but the intended action of stopping the injection for at least six hours was not taken because of the concern about the gas pressure in the well.

11.3 Adaptive traffic-light systems (ATLS)

A new generation of '*Adaptive Traffic-Light Systems*' (ATLS) has been developed and tested by scientists at ETH Zurich, forming the seismicity-related safety components of future hazard assessment and control systems for a hydraulic stimulation and long term operations (Gischig et al., 2014; Karvounis et al., 2014; Király-Proag et al., 2016; 2017; Mignan et al., 2017). Figure 31 shows the concept of ATL. Key ingredients are:

Forward looking: Rather than being reactive schemes (i.e., a certain observed magnitude/intensity triggers a certain action), ATL systems are centred on robust, forward-looking models that make probabilistic forecasts on the expected future seismicity based on a range of key parameters (current seismicity, current and planned pressures, permeability, static Coulomb stress changes etc.). Such forward-looking systems anticipate for example, that the probability of inducing the largest events in the hours after shut-in is substantial (e.g., Bachmann et al., 2012; Goertz-Allmann and Wiemer, 2013). The most advanced systems will not only limit the hazard and risk to acceptable levels, but also jointly optimize seismicity and reservoir creation (Gischig et al., 2014).

Probabilistic: Forecasts are made within a fully probabilistic framework that considers:

- the epistemic uncertainties stemming from our limited understanding of the physical processes acting during the stimulation and long-term operations.
- the aleatory variabilities of the processes themselves.

Such a probabilistic framework integrates also the view of the broader informed community by representing the centre, body and range of knowledge. A technical approach to this is to integrate model alternatives in a logic tree structure to characterize the uncertainties arising from our limited knowledge numerically (Mignan et al., 2015). Induced seismicity hazard and risk assessment is thus elevated to the quantitative analysis level that is common to most critical infrastructures. By integrating the forecasted rates of events for all magnitudes in the hazard and risk space, it also allows considering highly unlikely but extreme events, without letting them become 'show-stoppers'.

Adaptive: The forecasted seismicity and resulting risk are updated – automatically as much as possible - on the fly as new data becomes available. All data is integrated using Bayesian principles, meaning that 'prior' knowledge is combined with newly acquired data, depending on the degree of confidence in the data and its past performance in forecasting. Therefore, models need to be updated on the fly as new information is collected. The updating strategy in terms of parameters to be estimated, time window and magnitude ranges to fit them to, is critical and an intrinsic component of each model. Updating too many parameters, or fitting data to time windows of insufficient length, may lead to less robust models. Mena et al. (2013) and Király-Proag et al. (2017) show that such an optimally on-the-fly combined, ensemble model performs better than individual models. It is also smoother in its earthquake rate forecasts and subsequent hazard estimates.

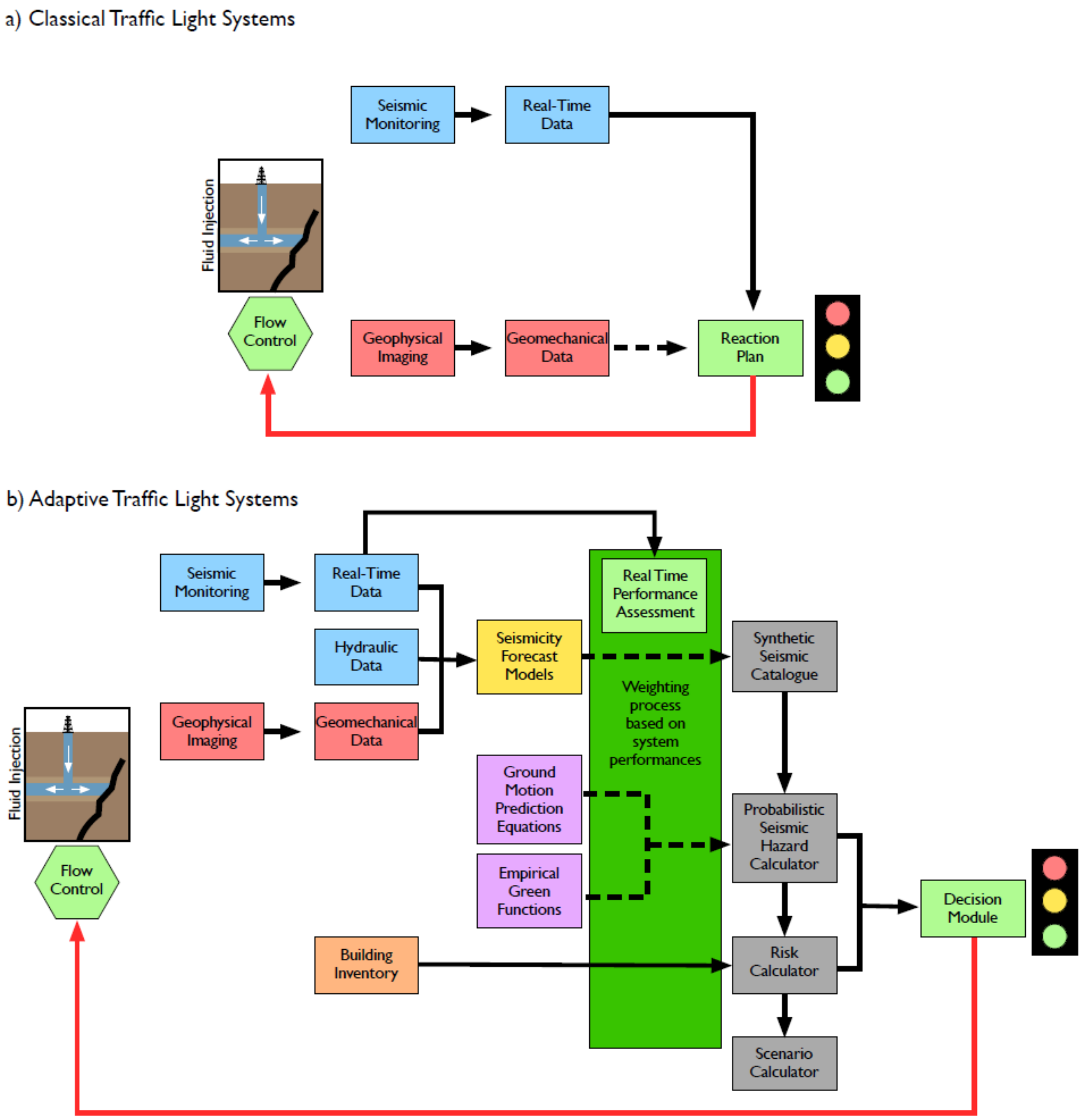

Figure 31: a) Classical Traffic Light System. Decisions are based on observed magnitudes and ground motions. Thresholds are defined in a static manner taking geotechnical information into account to the extent possible. b) Proposed Advanced Traffic Light System. Decisions are based on a forward looking, probabilistic and adaptive framework. Models are assessed in near real time and weighted accordingly. After Grigoli et al. (2017).

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Appendix A

Independence and transparency of the SED

The Swiss Seismological Service (SED) at ETH Zurich is the official federal agency for monitoring earthquake activity in Switzerland and its neighboring countries and for assessing Switzerland's seismic hazard. The role of the SED – to warn the population and inform the authorities – was defined in the context of both the Federal Council ruling on the optimization of early warning and alerting of natural hazards (OWARNA) and the revised ordinance on issuing warnings and raising the alarm (Alarm Ordinance).

In order to perform these fundamental national tasks, ETH Zurich receives financing via the federal financing contribution, pursuant to Article 34b of the FIT Act. The SED regularly applies for funding from promotion agencies such as the Swiss National Science Foundation or the EU framework programs in order to carry out scientific research projects. In addition to this, the SED also acts as a partner to various public bodies (federal offices, cantonal and local authorities) in conducting seismic risk analysis and monitoring projects that are partly regulated and financed by specific mandates. The SED's expertise means it is also frequently requested to act as a partner on certain projects in the private economic sector.

The broad spectrum of the SED's activities includes services to society, academic teaching and research, transfer of knowledge, and specialized advisory services for authorities and the private economic sector. This wide range of functions is based on both the SED's role as the official federal agency responsible for monitoring earthquakes and as the leading research institute in this field, and is consistent with the tradition and aims of ETH Zurich. However, as well as advantages and synergies, this also involves the potential for conflicts of interest and accusations of bias. Both the SED and ETH Zurich have implemented the following measures in order to avoid any potential role conflicts wherever possible. These are aimed at defining and, where appropriate, limiting mandates clearly, presenting these transparently, and communicating them openly.

Transparency: The SED provides information about all its mandates, and the understanding of its role in these mandates, in a transparent manner. All data acquired is made available for public access. The SED provides extensive information, proactively and without limitation, in the event of any potentially perceptible seismic event, and also provides background information.

Peer review: Relevant findings are published in scientific journals and as such are subject to a peer review process. This means that all statements made by the SED are based on published and scientifically accountable findings as far as possible.

Supervision: The SED is a non-departmental entity according to Article 61 of the Organization Ordinance of ETH Zurich (RSETHZ 201.021) and reports directly to the ETH Vice President Research and Corporate Relations (VPFW). An advisory board made up of carefully selected professors supports the VPFW in determining the strategic focus of the SED.

Mandate selection: The SED primarily gives support to the national, cantonal, and local supervisory authorities. Services are only provided to the industrial sector if these do not impact the independence of the SED in any way. If in doubt, the director of the SED will consult the VPFW and the SED advisory board. The director of the SED is an appointed full professor of ETH Zurich; the director and his/her employees are subject to the regulations of ETH Zurich regarding integrity and ethics in study and research – in particular, the Guidelines for Research Integrity and Good Scientific Practice at ETH Zurich (RSETHZ 414).