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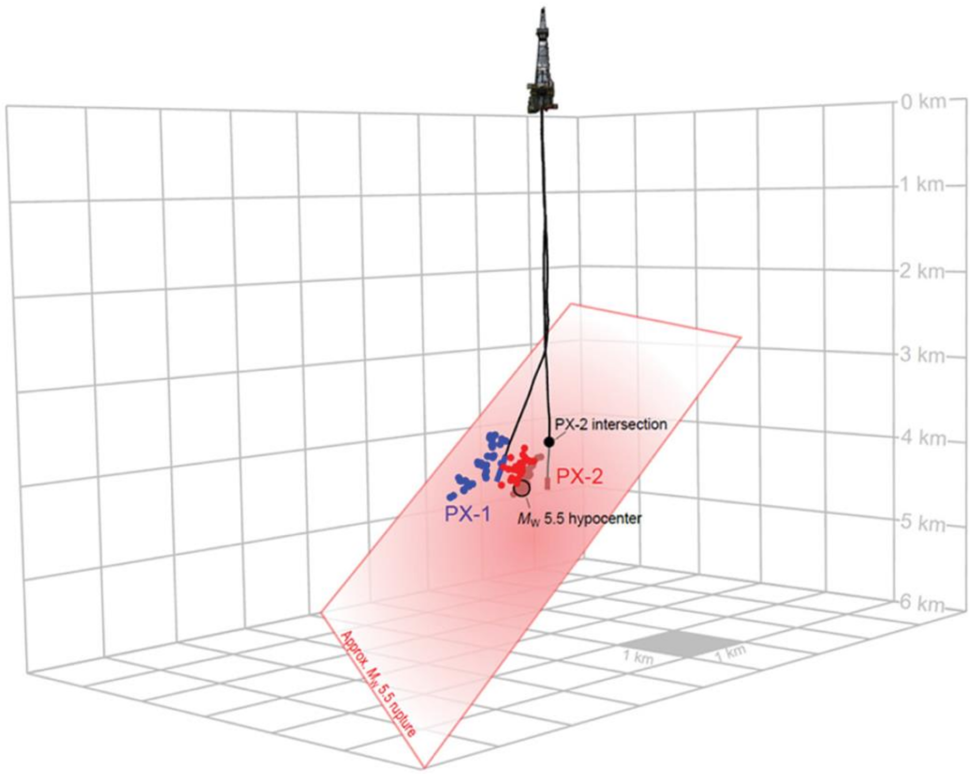
Swiss Seismological Service

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Evaluation of the seismic risk of the Haute-Sorne geothermal project in light of the Pohang (South Korea) earthquake

A report by the Swiss Seismological Service at ETH Zurich to the canton of Jura

18 October 2019



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Authors

Lead author: Prof. Stefan Wiemer
With contributions from: Dr. Philippe Roth, Dr. Marco Broccardo, Dr. Francesco Grigoli, Dr. Dimitrios Karvounis, Dr. Arnaud Mignan, Dr. Antonio Pio Rinaldi, Dr. Toni Kraft, and Michèle Marti.

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Cover picture
View of the induced seismicity induced during the stimulation of PX-1 and PX-2 beneath Pohang, and epicentre and fault plane of the magnitude 5.5 earthquake of Nov. 15 2017 (from Ellsworth et al. (2019).

Contents

1. Context

In 2013, the canton of Jura approached the Swiss Seismological Service (SED) at ETH Zurich to support the review of the seismic hazard and risk assessment for the proposed deep geothermal energy project in Haute-Sorne. The mandate covered the seismic risk related part of the permitting and environmental risk assessment process. The SED reviewed the seismic risk-related aspects of the permit application of Geo-Energie Suisse AG (GES). The reviews were documented in a series of reports and became part of the environmental risk assessment procedure and permitting process in the canton of Jura. In addition, the SED discussed with the cantonal authorities suitable seismic monitoring strategies and reflected acceptance criteria for permitting deep geothermal projects. Under consideration of these inputs, the canton of Jura issued the permit to GES with a series of obligations. Some of them, referring to seismic risk, have been contested in court.

In November 2017, a damaging earthquake of magnitude 5.5 occurred near the city of Pohang in South Korea. The event was immediately suspected to be related to nearby stimulation activities of a geothermal project (Grigoli et al., 2018). The earthquake injured 135 residents, displaced more than 1'700 people into emergency housing, and caused more than USD 75 million in direct damage to over 57,000 structures. According to the Bank of Korea, the total economic impact adds up to more than USD 300 million (Lee et al., 2019). GES informed the canton of Jura immediately about the magnitude 5.5 earthquake, its possible relation to the geothermal project, and GES's involvement in this project as part of the EC-project DESTRESS. In response to this information, the canton of Jura asked GES to analyse the Korean earthquake and geothermal project, and to comment if an update of their seismic risk study for the Haute-Sorne project was needed. Subsequent analysis of the events by the SED (Grigoli et al., 2018) and other groups (Kim et al., 2018) showed that the magnitude 5.5 mainshock and numerous aftershocks occurred within 1 to 2 kilometres of the geothermal project, making a causal link to the stimulation activities probable. The Pohang project shares a number of similarities with the Haute-Sorne plan in the Jura: it is also aimed at establishing an Enhanced Geothermal System (EGS) and targeted similar depths, temperature ranges, and injection volumes.

GES delivered a series of reports summarizing the findings to the canton of Jura in early 2019. In the following, the canton asked the SED in March 2019 to review the GES reports and their conclusions. In the meantime, the Korean government had commissioned an independent expert committee consisting of twelve local and five international experts to investigate the incident (the Overseas Research Advisory Committee, ORAC). The committee published its findings in March 2019 and a synopsis of the analysis and lessons learned was published by Lee et al. (2019). Based on an in-depth analysis of the data available, the commission concluded that the stimulation activities at the geothermal plant have triggered the magnitude 5.5 earthquake. Their main findings have also been summarized and published on the SED website (see news report "*Earthquakes and geothermal energy: lessons from Pohang*"). In consequence, the SED asked GES to additionally provide a comparison between their findings on the Pohang earthquake and the report of the expert commission. This comparison was delivered to the SED in June 2019.

The SED implemented a review team composed of nine scientists with extensive experience in all aspects related to induced seismicity, led by the director of the Swiss Seismological Service (SED) at ETH Zurich, Prof. Stefan Wiemer. The SED bases its assessment on available reports and scientific publications on Pohang and other induced seismicity cases, own analyses of the available Pohang data, experiences from other geothermal projects, and discussions with colleagues from around the world - including experts from the Pohang expert committee. Our review focuses solely on the seismic risk associated with EGS and specifically the Haute-Sorne project, with respect to acceptance criteria defined by the canton. Potential benefits of EGS technologies with respect to revenues or climate-change related aspect are not considered neither potential implications of or for public acceptance.

The original version of this report has been formulated in English, allowing the canton of Jura to submit it to other national or international experts if so desired. A translation into French is also provided.

2. Role of the Swiss Seismological Service at ETH Zurich in the framework of deep geothermal energy

2.1 Mandates of the SED

The Swiss Seismological Service (SED) at ETH Zurich is the federal agency responsible for monitoring earthquakes in Switzerland and its neighbouring countries. When an earthquake happens, the SED informs the public, authorities, and the media about the earthquake's location, magnitude, and possible consequences. The SED also has federal mandate to assess at a national level the seismic hazard and risk posed by natural earthquakes. The activities of the SED are integrated in the federal action plan for earthquake precaution. The role of the SED – to warn the population and inform the authorities – is 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 a core funding via a 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 programmes 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 hazard analyses or monitoring projects that are regulated and financed by specific mandates. Because of its expertise, the SED is also frequently requested to act as a participant for selected task (e.g., seismic monitoring) on certain projects in the private economic sector.

Currently, the SED has no explicit federal mandate related to induced seismicity in the context of geothermal or other geotechnical projects. However, since November 2010 the SED receives funding from the Federal Office of Energy to run the GEOBEST project. The project allows the SED to support and advise operators of geothermal projects with respect to the seismic monitoring and cantonal authorities in the review of seismic risk assessments. In both cases, the support of the SED has to be requested by the operator and/or the regulator and the details of the collaboration are defined in a contractual agreement. In the framework of GEOBEST, the SED has published a "Good Practice" Guide for Managing Induced Seismicity in Deep Geothermal Energy Projects in Switzerland".

Independently of the SED's existing or non-existing involvement in a geothermal project, the SED informs the public as soon as the national seismic monitoring network records potentially perceptible earthquakes. In addition, all seismic events – including smaller, not felt earthquakes - recorded by the national network are made available in real-time on the SED website.

2.2 Independence and transparency

The broad spectrum of 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. In an effort to avoid competition with private service providers, these specialized advisory services are limited to cases where the requested expertise is not available in the private sector. This wide range of functions is based on both roles of the SED as the official federal agency responsible for monitoring earthquakes and as the leading Swiss research institute in this field, and is consistent with the tradition and aims of ETH Zurich. However, besides advantages and synergies, these functions also involve the potential for conflicts of interests and can evoke complaints of bias. Both the SED and ETH Zurich have since 2014 implemented the following measures in order to avoid - or at least reduce - potential role conflicts wherever possible. These measures 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. We will also always involve several experts from within the SED in our reports; this report for example is authored by nine experts in the domain of induced seismicity, each with at least four years of relevant experience beyond their PhD.

Clear contracts: All collaborations with the industry or government offices exceeding 10k CHF are regulated by a contract that specifies the objectives, deliverables, timelines, responsibilities, IP rights including background and foregrounds, independence, public rights, etc. These contracts are reviewed by experts, including lawyers at ETH transfer, the technology transfer office of ETH Zurich. Contract exceeding 50k CHF will be signed by the Vice President of Research of ETH. Contracts can be made public on justified request.

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 ETH 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 consults 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).

No joint appointments, gifts, or financial compensations: To further avoid conflicts of interests, the SED does not employ staff jointly with industry. According to the ETH compliance guide, SED staff is not allowed to receive any personal compensations for working on projects that may create a potential conflict of interest (this includes all geothermal projects in Switzerland).

2.3 Past and current SED relevant involvements in deep geothermal projects

Over the last 15 years, the SED has been involved in several geothermal projects in Switzerland and around the world. Without exception, the SED had an advisory role and no right to take actionable decisions. To secure its independency, the SED has as part of the reimbursement for its advisory role never agreed to receive any share of profits or other benefits outside of access to data for scientific research as part of the reimbursement for its advisory role. Below we briefly describe our role in projects most relevant to Haut-Sorne. Other previous and upcoming projects as in Schlattingen, Geneva, Lavey or Bedretto are not reported in detail here.

2.3.1 Basel, Switzerland

The Basel Deep Heat mining project in 2006 was the first deep geothermal project the SED accompanied. The SED was essentially responsible for independently monitoring the relevant – i.e., potentially felt - seismic activity during the stimulation process; the results have been published in the ECOS database and on maps on the project website. The SED was also tasked to inform the authorities whenever a recorded earthquake had a local magnitude of 2.0 or more. The SED was not involved in the permitting and the review of the seismic hazard and risk assessment.

After the damaging magnitude 3.4 earthquake in December 2006, the SED provided the authorities of the canton of Basel-Stadt with expert advice on the earthquake risk of the Deep Heat Mining project (SERIANEX study[1]). The scientific analysis of the Basel injection related data resulted in more than twenty publications by the SED in international peer-reviewed journals.

Since April 2012, the SED has officially taken over the seismic monitoring of the deep borehole in Basel. For this purpose, two of the operator's borehole seismometers were included in the SED network. An increase in the seismicity at the Basel site initiated at about the same time and reached magnitudes of up to magnitude 1.9 until 2017. The canton of Basel-Stadt commissioned the SED to investigate the reason for the increase of seismicity. The investigation came to the result that the closure of the well in April 2011 led to an increase of the fluid pressure in the reservoir, that subsequently triggered the seismicity[2,3]. Following these results, the canton ordered an opening of the borehole in 2017 and asked the SED to monitor the operation. The SED implemented a highly sensitive pattern recognition technique to monitor the site and implemented an alarming system for the canton and the operator. These activities were funded by Industrielle Werke Basel (IWB), the owner of the deep well in Basel.

The SED continues to monitor the seismic activity in the immediate vicinity of the borehole in Basel. On behalf of the canton, the SED supported IWB in developing a long-term strategy for the seismic monitoring and is enhancing its seismic network in the area. Detailed information about the Basel project can be accessed here: www.seismo.ethz.ch/earthquakes/monitoring/geothermal-energy-basel/Project-Description/

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[1] Baisch S, Carbon D, Dannwolf U, Delacou B, Devaux M, Dunand F, et al.: Deep Heat Mining Basel: Seismic risk analysis. . In: SERIANEX: Report from Department fürWirtschaft, Soziales und Umwelt des Kanton Basel-Stadt. Amt für Umwelt und Energie (2009)

[2] www.seismo.ethz.ch/export/sites/sedsite/home/.galleries/pdf_home/Induzierte-Erdbeben-im-Nachgang-des-eingestellen-Geothermieprojekts-in-Basel.pdf

[3] http://www.seismo.ethz.ch/export/sites/sedsite/home/.galleries/pdf_home/2017_03_29_MM-Oeffnung-Bohrloch_final.pdf

2.3.2 St. Gallen, Switzerland

Commissioned by the St. Galler Stadtwerke (sgsw) and as part of the GEOBEST-CH research project, the SED has been carrying out the seismological monitoring of the geothermal project of the city of St. Gallen since spring 2012. To this aim, six, and later up to twelve, dedicated seismological stations have been installed and maintained. The SED also reviewed the seismic risk study and mitigation planning submitted by the operator to the canton and provided advice to the canton after the occurrence of the magnitude 3.5 earthquake. The SED has informed the public on its website on the observed seismicity and interpretation[4] along with background information. Since 2013, the SED has been publishing a number of articles on the induced seismicity and its relation to the geological structures and the gas kick. sgsw has commissioned to SED to continue monitoring the St.Gallen area with a reduced network of four stations until September 2020. These activities were funded by sgsw through the EC project S4CE.

Detailed information about the St. Gallen project can be accessed here: www.seismo.ethz.ch/earthquakes/monitoring/geothermal-energy-st.gallen/project-description/

2.3.3 Pohang, South Korea

The SED is part of the consortium of the DESTRESS project funded by the European Commission in the framework of the Horizon 2020 programme (see also 2.4). The operators developing the site in Pohang (NexGeo Incorporated) have offered the Pohang EGS project as one of several testing and demonstration sites collaborating within the DESTRESS project. Initially, and as written in the DESTRESS proposal, it was foreseen that the SED would contribute to the seismic monitoring of the Pohang geothermal site as well as to the implementation and testing of an adaptive traffic light system. However, after initial discussions within the DESTRESS consortium and with the Pohang project operators, the SED decided to withdraw from the proposed engagement at the Pohang site in the fall of 2016. In addition to communication and language problems, the primary reason for this withdrawal was the perceived lack of a rigorous seismic risk assessment approach followed by the Pohang operators. No risk study was available to the SED or the DESTRESS consortium, the seismic network installed by the operator and local academic partners appeared to be sub-standard, and the procedures for risk assessment and risk mitigation from the Korean side were not clear and accessible. The SED lent a borehole seismometer and cable to GES, also a partner in DESTRESS, that GES subsequently installed and operated in Pohang starting in December 2016. A few months after the damaging earthquake, and in order to make sure that the lessons learned from Pohang would be publicly known, the SED pushed in early 2018 for a high-profile publication of the Pohang preliminary results (Grigoli et al., 2018), using publicly available data and the recordings of the deep borehole seismometer installed near the injection site.

2.4 Existing collaboration with GES

As stated above, ETH Zurich and the SED are promoting knowledge transfer from academia to industry. With this intention, the SED has in the past, and still is, collaborating with GES in various research projects. The SED is aware that such collaborations can hold a potential for conflicts of interests. As specified above, binding legal agreements and additional rules for independence and transparency shall assure SED's scientific freedom and allow it to fulfil its mandate as a reliable federal institution. In addition, due to SED's practice to publish its work in scientific journals, its findings are reviewed by other experts and accessible publicly. In the light of transparency, past and current research collaborations with GES are listed below:

[4] www.seismo.ethz.ch/earthquakes/monitoring/geothermal-energy-st.gallen/earthquake-chronology-geothermal-energy-project-in-st.-gallen/

- **CTI (now Innosuisse) funded project RT-RAMSIS** started in 2015 and terminated in July 2019. RT-RAMSIS is geared at developing approaches to manage induced seismicity hazard and risk in real-time. The SED initiated the development of the first Adaptive Traffic Light Systems (ATLS). The concept of ATLS has been introduced already in the obligations of the canton to the Haute-Sorne project (No. 51, Système de feux de signalisation prédictif (ATLS)). Software developed at SED for ATLS will be available for GES to implement at the Haute-Sorne project.

- **GEOTHERMICA project COSEIMIQ:** This research, innovation, and demonstration project brings together a small team of geothermal operators and scientists from Switzerland, Ireland, Germany, and Iceland. They are working on improving and validating the advanced technologies for monitoring and controlling induced seismicity that have been developed and coded in the past three years in the RT-RAMSIS project. These technologies will be tested in Iceland as a data-driven, adaptive decision support tool during industrial applications, the core objective of COSEISMIQ. COSEIMIQ will demonstrate the technology (Technology Readiness Level 6+) as part of a commercial, multi-well application in Iceland, a country with many successful geothermal projects and common induced seismicity.

- SED and GES are both partners in the **DESTRESS consortium,** a project funded by the European Commission in the framework of the Horizon 2020 programme and led by GFZ Potsdam. In DESTRESS 16 partners form research and industry in Europe and South Korea are collaborating. The focus of the SED is again on improving seismic monitoring and risk assessment procedures, while GES focuses on demonstrating zonal isolation as well as on multi-stage stimulation procedures. Haute-Sorne was foreseen as a DESTRESS demonstration site; it has been replaced 2018 by Geldinganes in Iceland (for SED) and Bedretto (for GES).

- **SCCER-SoE:** the SED and GES are among the 30+ partners of SCCER-SoE from academia and industry, with a strong focus in the past two years on risk assessment methodologies and scaled experiments (in the Grimsel and Bedretto laboratories).

- **DEEP Geothermica:** The SED is leading a proposal submitted to the second round of the EC cofound programme GEOTHERMICA in 2019 (nine partners from five countries including GES). The proposed project focuses on developing and testing novel, machine learning based seismic processing and novel forecasting methods for adaptive traffic light systems. The demonstration site chosen for this project is located in Utah. FORGE is a dedicated underground field laboratory sponsored by the US Department of Energy (DOE) for developing, testing, and accelerating breakthroughs in EGS technologies. Knowledge transfer to other sites, including Haute-Sorne, is a specific target of the project.

3. The Pohang earthquake

3.1 The Pohang event and its current understanding

The magnitude 5.5 earthquake in Pohang was, when it occurred on November 15 2017, a great surprise to the operators and the Korean public. While the series of injections had created many earthquakes of up to magnitude 3.2, the population was largely unaware of the geothermal project and the associated risk. After the magnitude 5.5 earthquake, there was an initial reflex by the operators and some of the involved agencies to deny a causal link to the geothermal operations, in parts due the fact that a larger, tectonic earthquake had occurred in September 2016 about 40 km south of Pohang (Figure 1). There was also a considerable debate in the scientific community whether the event shall be called 'induced' or 'triggered'. However, this technical distinction is likely irrelevant both to the people affected and for establishing responsibilities in a legal sense. Because no clearly defined, universally accepted and determinable distinction exists between 'triggered' and 'induced' seismicity, we will use in this report the two terms interchangeably.

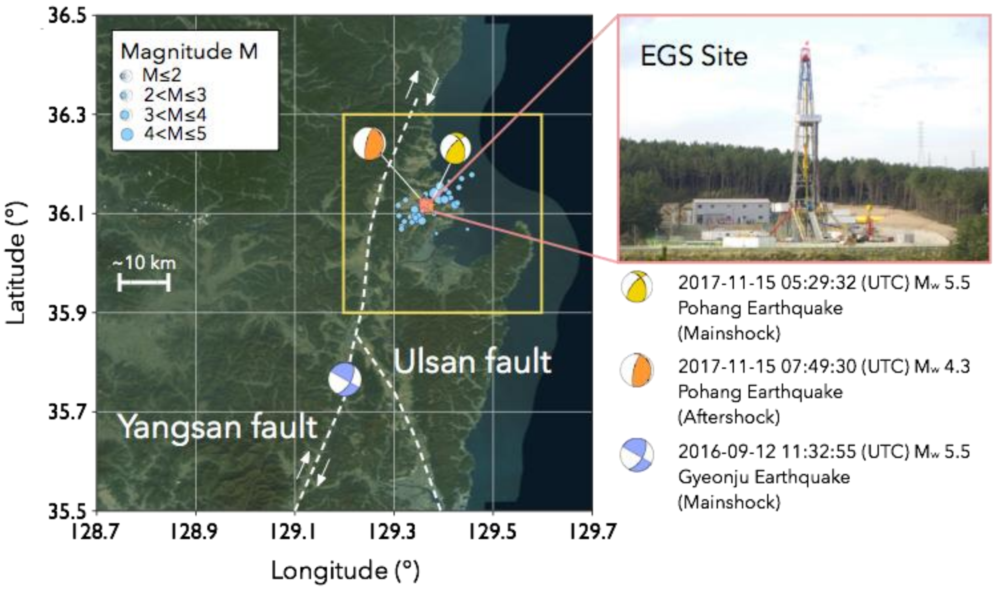

Figure 1: *Map of the region of Pohang, South Korea; shown are the location of the drill site, the known major faults (white lines), the mainshock of Nov. 15 2017 (yellow 'beach ball') and the Sept. 2016 Gyeonju magnitude 5.5 earthquake.*

Below we provide a brief summary of the sequence of injections and the related seismicity, excerpted from Ellsworth et al. (2019):

> *"Over the course of approximately four years from 2012 to 2016, two exploratory wells named PX-1 and PX-2 were drilled into the granitic basement to develop the EGS. PX-1 had a designed depth of 4'127 m, but the drill pipe became stuck after crossing 4'000 m, and the hole was lost below a depth of 2'485 m. PX-1 was later side-tracked and extended in the west-northwest direction to a depth of 4'215 m with a measured depth (MD) of 4'362 m. PX-2 was drilled to a depth of 4'340 m. PX-1 and PX-2 are 6 m apart from each other in the north– south direction on the ground surface and are ~600 m apart at the bottom. Both wells are cased along their length except for the bottom 313 m in PX-1 and 140 m in PX-2. These bottom intervals are open for fluid injection and flow back.*
>
> *Five hydraulic stimulations were conducted between 29 January 2016 and 18 September 2017. The first, third, and fifth stimulations were conducted in PX-2 and the second and fourth in PX-1. Each hydraulic stimulation involved multiple cycles of injection of water*

under high pressure followed by shut-in or flow back. The Pohang magnitude 5.5 earthquake occurred when PX-1 was shut-in and PX-2 was open after the fifth stimulation. Figure 2 shows the injection rates and the net injection volume over the entire period of five stimulations. The volumes of water injected into and flowed back from PX-1 are 5'663 m3 and 3'968 m^3, respectively. The volumes of water injected into and flowed back from PX-2 are 7'135 m3 and 2'989 m^3, respectively. Thus, a net volume of 5'841 m^3 of injected water remained in the subsurface following the stimulations.

In PX-2, the maximum wellhead pressure and injection rate reached 89.2 MPa and 46 l/s during the first stimulation. In PX-1, the maximum wellhead pressure and injection rate reached 27.7 MPa and 19 l/s during the second stimulation. Injection pressures were higher overall for PX-2 than for PX-1 at similar injection rates. Seismicity accompanied each stimulation and for injection into PX-2 continued for up to several months (Figure 2)."

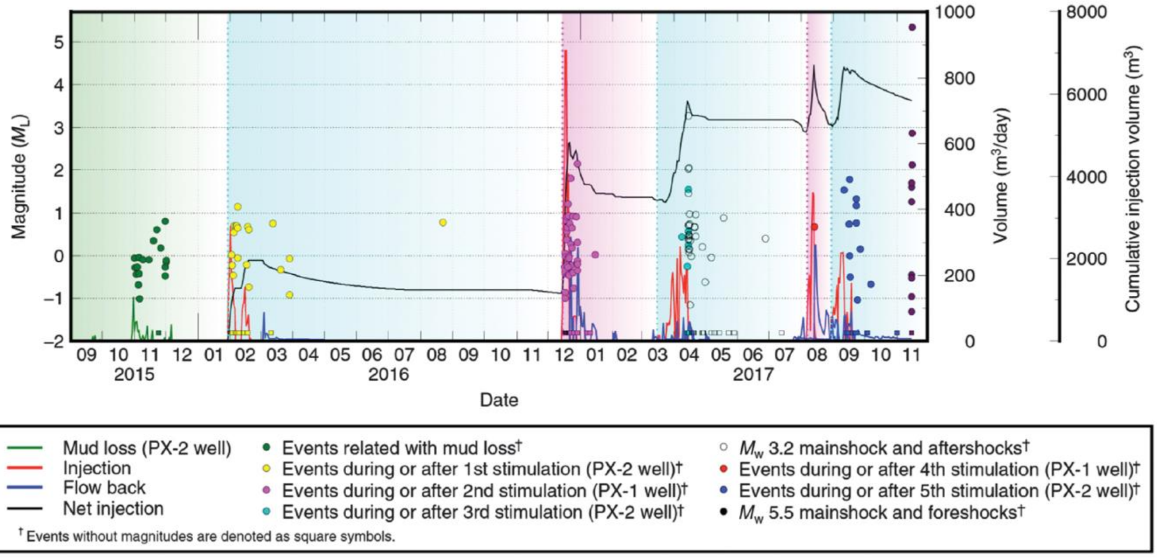

Figure 2: *Timeline of injections and seismicity in the wells PX1 and PX2 (from Ellsworth et al., 2019).*

The subsequent analyses of the mainshock, its aftershocks, and the re-analysis of the injection sequences by several independent groups have led to currently about 20-30 peer-reviewed publications in addition to the report published by the Korean investigation team and to the report delivered to the canton by GES. These research contributions have by now revealed a largely consistent picture with few remaining inconsistencies. Broadly speaking the analysis presented by GES is well in line with the available interpretations to date; details are commented on in subsequent sections. However, the various studies on Pohang, including the ones by GES, also reveal in our opinion the limits in the ability of scientists and engineers to understand and ultimately forecast the detailed evolution and timing of induced earthquakes. For example, the fact that the mainshock occurred roughly two months after the end of the hydraulic stimulations (Lee et al., 2019) is not really well understood: Did fluid or overpressure continue to migrate along the later activated fault, did earthquake-earthquake interaction play a role (Ellsworth et al., 2019) or did the fault weaken because of chemical alteration (Westway & Burnside, 2019)? What is the role of tectonic stresses and in particular of the static and dynamic stress changes from the 2011 Tohoku and 2016 Gyeonju earthquakes in pre-conditioning the faults (Hong et al., 2018)? What is the contribution of each of the individual injections to the ultimate failure?

Many of these open questions will probably remain unanswered forever, since no observation exists to answer them. However, the relevant basic facts in Pohang have been established and documented in Lee et al. (2019) as well as Ellsworth et al. (2019): there findings confirm and strengthen the initial assessment by Grigoli et al. (2018) and by Kim et al. (2018) and can be summarised as:

The magnitude 5.5 Pohang earthquake was triggered by the EGS stimulations at the geothermal site, likely primarily by the ones in the PX-2 well. Seismicity induced by injection, injection-related stress changes, or possibly chemical alteration re-activated and weakened a major pre-existing fault zone. A rupture occurring on this fault grew to a magnitude 5.5 earthquake through the release of tectonically accrued strain.

3.2 Shortcomings in the risk governance of the Pohang project

The analysis of the Pohang stimulation and mainshock performed so far by GES, the SED, and other research groups as well as the work of the ORAC committee all have pointed a number of major shortcomings of the Pohang monitoring, risk management, and risk governance approaches[5]. The SED does not have a full overview of all steps and procedures applied, and it is not our role or responsibility to assess responsibilities. It is also always easy to identify shortcomings in the benefit of hindsight. Therefore, the statements below serve to identify the lessons the SED considers important to be learned from the Pohang project when considering the Haute-Sorne project:

1. The a-priori risk considerations by the operators were in our assessment not adequate for the values at risk and the type of project. Given the limited empirical data and experience from EGS worldwide and given the considerable exposure and vulnerability of parts of the building stock, a much more comprehensive hazard and risk assessment that systematically considers uncertainties and alternative opinions should have been performed. Procedures for such analyses are common in other risk assessments, e.g. for natural earthquakes and have been established in the wake of the Basel EGS project also for induced seismicity (SERIANEX, 2009; Bachmann et al., 2011; Mignan et al. 2015). Giardini (2009) as well as Kraft et al. (2009) have concluded that the risk from EGS projects must be taken seriously, but many of these lessons and procedures learned from past projects were not implemented in the Pohang project.
2. The chance of severely damaging earthquakes was - to our knowledge - excluded from the risk considerations; it was also excluded from the communication about the project. No adequate insurance solution or pre-arranged ways to reach compensation was - to our knowledge - in place, and the possibility of damaging, low probability-high consequence event was not discussed with the regulators. There was possibly too much trust put in the earthquake-size-limiting effect of the maximum injected volume (McGarr limit) despite ample evidence that the McGarr limit is not a fixed limit (van der Elst et al., 2016, Gischig and Wiemer, 2013, Atkinson et al., 2017). The awareness that run-away ruptures are possible was lacking among the operators, as was the awareness that such ruptures can be triggered with minimal overpressures. The later was for example illustrated for the case of basement faults beneath wastewater injection sites in the eastern US.
3. The seismotectonic context, the local soil amplification and the presence of major faults were not considered with a sufficient level of concern nor integrated into the project plan; the presence of a major fault zone penetrated during drilling and oriented optimally to be potentially

[5] As stated in section 1, some of these shortcomings were apparent at early stages of the project, as a consequence of which the SED had withdrawn in the fall of 2016 from participating in the project.

reactivated in the contemporary stress field was not interpreted with a risk and safety focus in mind.

4. The seismic monitoring network and analysis procedures were grossly inadequate for appropriate risk governance. The hardware and software for data acquisition and data processing were, with respect to critical aspects, below the state of the art. In addition, the staff was insufficiently trained to interpret the seismic data. The selected sites for the deployment of seismic monitoring stations were inappropriate with noise conditions at many sites being poor. The combined effect of these shortcomings is that the available microseismic data was highly insufficient for risk management and process understanding. It is unfortunate that even after numerous person-months of distributed efforts by several research groups worldwide, the quality of the available seismic (and other) data remains much below the required level and it will be impossible to be improved substantially in retrospective. The detection and location capability of the Pohang seismic system was one to two order of magnitudes poorer than the one of similar systems in other EGS projects (Basel, Soultz, Ritterhofen, Helsinki, Cooper Basin). This translates to one to two order of magnitudes more uncertainty regarding the seismic response from the stimulation.

5. The setup for processing seismic data was not able to provide the required information for real-time analysis and mitigation beyond a basic, classical traffic light system. There was no attempt to implement simple or advanced adaptive hazard and risk assessment strategies that have been proposed in the literature (e.g., Gischig and Wiemer, 2013; Hirschberg et al., 2015; Trutnevyte and Wiemer, 2017; Mignan et al., 2017). An appropriate analysis of the productivity data and size distribution of the induced earthquakes, if done in real-time, should have raised an alarm (see section 2.3). The magnitude 3.2 earthquake that occurred in April 2017, should have triggered an in-depth analysis of the induced seismicity related to the past injections, including a detailed seismic hazard and risk analysis.

6. The operators appeared to be lacking the awareness and culture for health and safety requirements with respect to seismic risk related issues; potential warning signs were ignored in the all-dominating effort to create an economically viable reservoir. Datasets collected were not analysed in a timely fashion for their risk related implications. The regulatory oversight of the project likewise was poorly established. There was no culture of critical reflection and questioning, and also the occurrence of the natural magnitude 5.5 Gyeonju earthquake in September 2016 did not lead to a change in risk culture.

7. International experts involved in the projects, specifically in the DESTRESS consortium, lacked courage and did not vocally enough raise concerns, despite the fact that they realised many of the shortcomings in the risk management. Experts were likely too concerned about getting involved in Korean internal processes. Cultural differences may have played a role but there was also a certain degree of 'wishful thinking' and vested interest in seeing the project succeed. In addition, from what is known, the procedures of the Korean operator were not violating national regulations, additionally explaining the reluctances of international experts. However, as stated above, the procedures applied were clearly not in line with established best practices in the field. Clear opposition was neither raised by GES who had an active role as consultant during some of the stimulations; it also applies to a somewhat lesser extend to the SED. In hindsight, the SED should not only have withdrawn from the Pohang project in 2016 but also expressed its concern more clearly to Korean colleagues and maybe even regulators.

8. Access by outside groups to the data collected during drilling and stimulation, including the experts collaborating within the DESTRESS project, was limited. This situation worsened after the occurrence of the magnitude 5.5, when the SED asked, without success, access to the data of the local seismic network. Foreign experts also perceive a lack of communication and transparency on procedures and next steps. This prohibited a wider review, discussions and feedback that may have led to a better understanding and external warnings.

We summarise these shortcomings and their implications as follows:

To our knowledge, there was not a single mistake or oversight that would explain the occurrence of the magnitude 5.5 earthquake, nor a single measure that would have definitely prohibited it. As commonly observed in many accidents, the ultimate event is the consequence of a chain of multiple decisions and processes. It is likely, although by no means certain, that without these substantial shortcomings in the approaches to seismic monitoring and risk management, the magnitude 5.5 mainshock could have been avoided.

3.3 Was the Pohang earthquake an extreme event?

We like to point out one aspect of the Pohang event that in our view has so far been less investigated nor quantified: the question whether the observed seismicity during stimulation already suggested at a higher than acceptable chance of a larger event to come. In the Basel EGS systems, for example, it has been shown in retrospective analyses and documented in a number of publications (Bachmann et al., 2011; Goertz-Allmann and Wiemer, 2012; Gischig and Wiemer, 2013; Mignan et al., 2015, 2017; Broccardo et al., 2017) that when using the seismicity measured during the first three days of the Basel stimulation, and considering the injection plan for the next 10 days, a magnitude 3 or larger event was likely to occur. This is relevant, because it suggests that the smaller events occurring initially are already an important key to understanding the future.

The seismic record and earthquake catalogue for Pohang project is unfortunately very poor even today, two years after the event. Earthquake locations and reliably computed magnitudes (in the M_w scale) for only about 100 micro-earthquakes are available (Ellsworth et al., 2019)[6]. We use this data set for a preliminary basic analysis and hazard/risk assessment: the analysis of the productivity (often called seismogenic index) and the size distribution of observed induced micro-earthquakes. This limited data set shows an unusually low b-value of b=0.65 (Figure 3), computed from induced earthquakes before the magnitude 5.5 earthquake. This b-value is to our knowledge the lowest ever recorded for an EGS project (Mignan et al., 2017). A low b-value indicates a higher proportion of larger events when compared to small ones, and thus a much higher chance of a large event to occur. Low b-values also have been associated with high differential stresses (e.g., Scholtz, 2015). In Figure 4, we compare the observed a- and b-values translated into the expected maximum event from Pohang (red) to those of other stimulations. This plot illustrates that, given only the extrapolation of the observed seismicity - a conservative Null hypothesis - a magnitude 2.5 to 4.0 event was the expected maximum magnitude to be observed. A magnitude greater or equal to Mw=5.5 was possible with a chance of about 3.5 %.

[6] For comparison, the Basel real-time dataset of just one stimulation contained more than 3000 events well located and with reliable magnitudes, post-processing using modern tools now can detect as many as 280'000 events (Hermann et al, 2019)

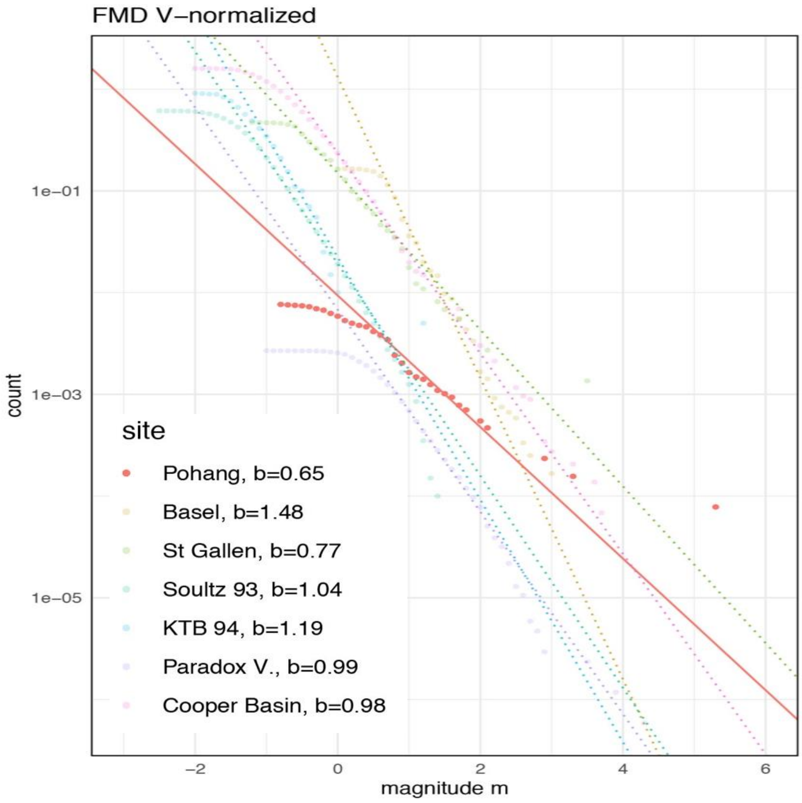

Figure 3: *Comparison of observed number of events as a function of magnitude, normalised by injected volume.*

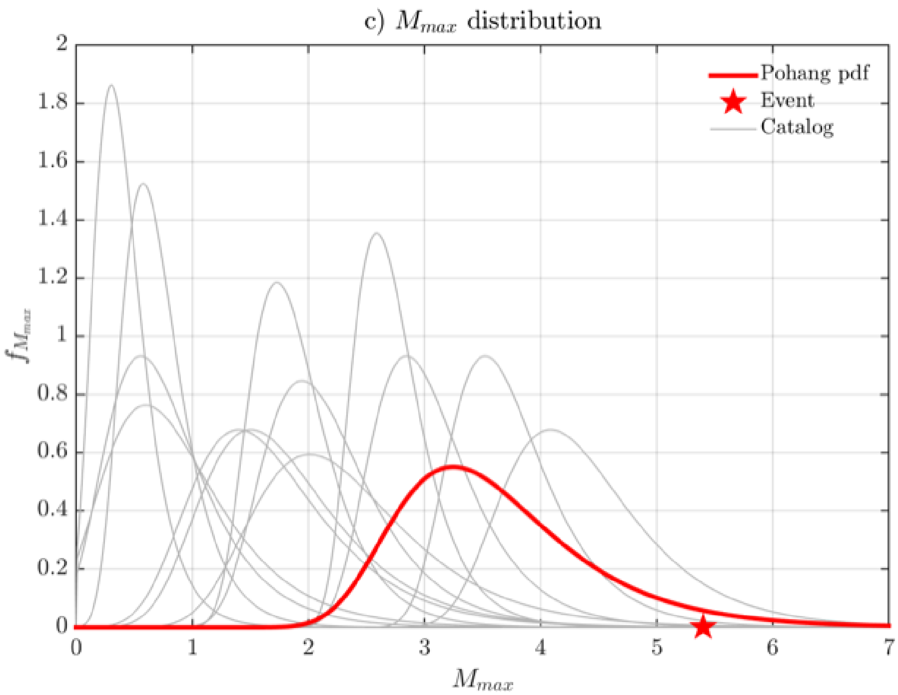

Figure 4: *Comparison of the maximum expected earthquake for different EGS projects, based on observed a- and b-values (see review in Mignan et al., 2019a). The Pohang project (red curve) has an expected value of 3.2, but a magnitude 4 or larger has a probability of more than 30%.*

We convert this observed seismogenic response in Pohang (in terms of the b-value and a-values) into individual risk (i.e., the probability of a person dying in a given building type). We use the GMPE (ground motion prediction equations) for the Haute-Sorne region but Pohang seismicity parameters

(Figure 5). The resulting mean risk (red horizontal lines) is well within the red shaded area for all building types, the risk posed by the seismicity is therefore judged to be too high to be acceptable. Our analysis supports the conclusion by GES that if regulations as specified for Haut-Sorne would have been in place in Pohang, they would have stopped the project substantially earlier. It can also be seen as encouraging for induced seismicity risk mitigation: The observed seismicity indicates at least in some cases early on that the underground response is unsafe.

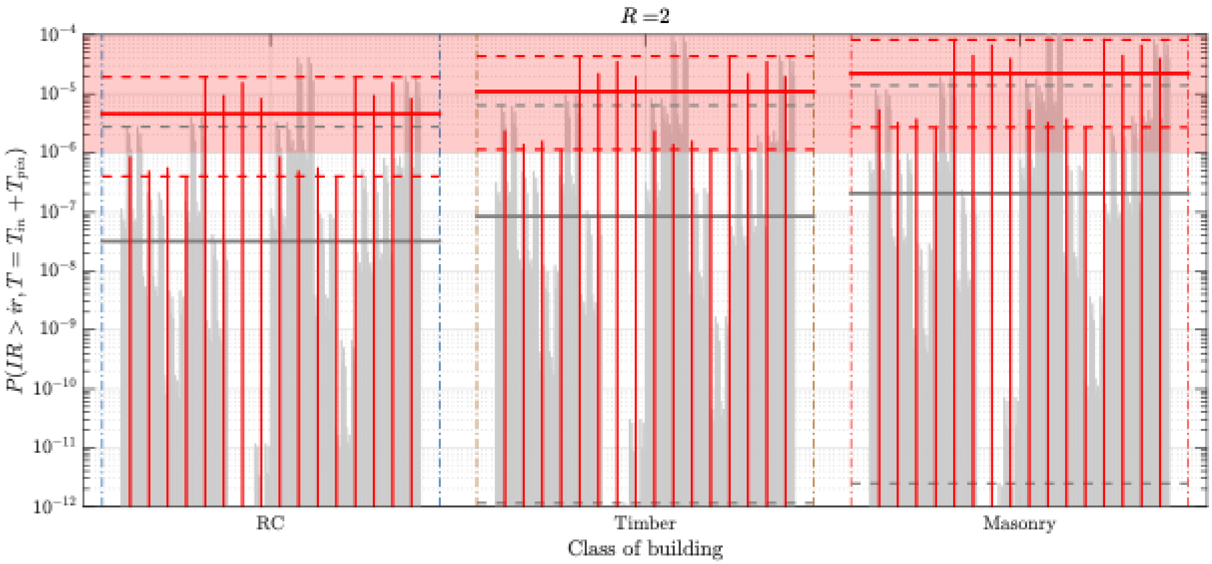

Figure 5: *Individual risk for three building types (Reinforced Concreted, RC; Timber and Masonry) at an assumed 2 kilometre distance computed when assuming the observed Pohang seimogenic response but Haute GMPE and site response.*

3.4 Other relevant EGS projects since 2014

When considering the need to update the seismic risk related part of the environmental impact statement from Haute-Sorne dated from 2014, it is in our opinion also important to consider other pilot projects, and the general progress in understanding and managing induced seismicity. This broader evaluation is in line with the cantonal requirements to update the risk assessment if significant new findings emerge. We focus here on EGS projects and important future developments, and purposefully also mention success stories for EGS technology in order to present a balanced outlook.

3.4.1 Helsinki, Finland (summary modified from Kwiatek et al., 2019)

This commercial pilot project is located in the Helsinki metropolitan area, on the urban campus of Aalto University, and represents with 6.4 km depth the deepest EGS system worldwide. It is also one of the first to apply a multi-stage stimulation concept similar to the one foreseen in Haute-Sorne. The aim of the project is to produce a sustainable baseload for the campus area's district heating network, with development costs being offset by saving in imported fuel and reduced CO_2 emissions. A 6.4 km measured depth (MD) stimulation well, OTN-3, and a 3.3 km observation well, OTN-2, were drilled mostly not only with down-the-hole air and water hammer methods but also with rotary methods for steering purposes. Both wells are entirely located in crystalline Precambrian Svecofennian basement rocks consisting of granites, pegmatites, gneisses, and amphibolites. The last 1'000 m of OTN-3 were drilled inclined at 42° to the northeast (NE), left uncased, and completed with a five-stage stimulation assembly.

In June and July 2018, a total of 18'160 m^3 of water was pumped into the rock formation at true vertical depths of 5.7 to 6.1 km over a period of 49 days. This included moving injection intervals and stoppages of a few days at various points during the stimulation. The stimulation was injection rate–controlled, with flow rates varying at discrete levels between 400 and 800 litres/min (typically just above the technical lower limit of 400 litres/s). This resulted in measured well-head pressures ranging from 60 to 90 MPa and below an upper safety limit for the pumps at 95 MPa. Induced seismicity was monitored by a three-tier seismic network, all telemetered to the project site. The local authorities set the desired maximum for an earthquake to occur due to the stimulation activities at this depth at a magnitude of 2.0. This limit was based on the expected peak ground velocity (PGV) at the surface from such an earthquake. A traffic light system was in place to control seismicity. The largest event observed was indeed a magnitude 1.9, but more than 40'000 micro-earthquakes were observed (Figure 6), and the operator is considering the stimulation a success. Many of the induced earthquake were felt and heart as bangs or rumbling, causing some concern in the local population. Observed b-values range between 1.2 and 1.6. The second well and second stimulation is planned. We have no information on the enhancement in transmissivity achieved by the stimulation.

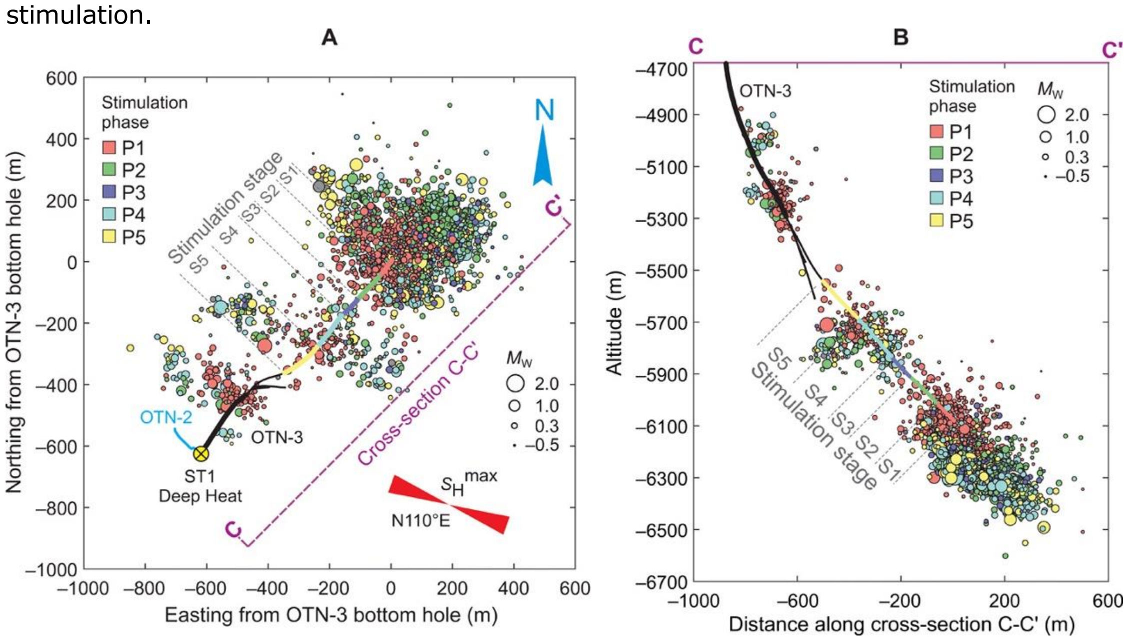

Figure 6: *Map view (left) and cross-sectional view of the Helsinki stimulation (source Kwiatek et al., 2019).*

The Helsinki project can be considered a closer analogue to the Haute-Sorne project and it demonstrated (so far) that EGS can be successfully deployed beneath an urban area. The project specifically demonstrated the effectiveness of zonal isolation, the ability to monitor very small micro-earthquakes using borehole seismometer chains, the effectiveness of real-time monitoring, and the ability to control seismicity below the pre-agree threshold.

3.4.2 Rittershoffen, France

The ECOGI joint venture (Electricité de Strasbourg group, Roquette Frères, and Caisse des Dépôts et de Consignation) is in charge of the development and the exploitation of the Rittershoffen EGS plant located 6 km east of Soultz-sous-Forêts, in Northern Alsace, France. This EGS reservoir is one of the very few currently under development in Europe and is designed to produce 24 MWth (170 °C, 70 l/s).

The first well of the doublet (GRT1) was completed end of 2012 and reaches, at 2'580 m depth, the crystalline fractured basement which constitutes the reservoir formation together with the overlaying Buntsandstein sandstones. A reservoir development strategy was defined, and first consisted in enhancing the connections between GRT1 and the fractured reservoir. These operations were applied in two sequences, in April 2013 and in June 2013 respectively. The stimulation operations were successful, providing the expected enhancement of the hydraulic properties of the reservoir. Induced seismicity was observed but did not exceed magnitude 1.6. The second well, GRT-2, was drilled from March to August 2014. No stimulation was necessary; the maximum observed seismicity during operation was a magnitude 1.3. The plant has been operating since 2016, producing about 25 MWth thermal power.

3.4.3 FORGE, USA

The FORGE geothermal site and underground field laboratory in Utah (US) is funded by the US department of Energy with ultimately more than USD 150 million. FORGE's mission is to enable cutting-edge research, drilling and technology testing, as well as to allow scientists to identify a replicable, commercial pathway to EGS. FORGE is located near the town of Milford in Beaver County (Figure 7), Utah, on the western flank of the Mineral Mountains. Investigations will commence in 2020 as the facility is being constructed and continue through 2024. Competitive funding rounds will be open for public application to attract outstanding programmes of innovative research and development in geothermal engineering and science. Near term goals are aimed at perfecting drilling, stimulation, injection-production, and subsurface imaging technologies required to establish and sustain continuous fluid flow and energy transfer from an EGS reservoir.

FORGE could potentially deliver import insight into successful EGS stimulation and risk management strategies that would also be available to Haute-Sorne.

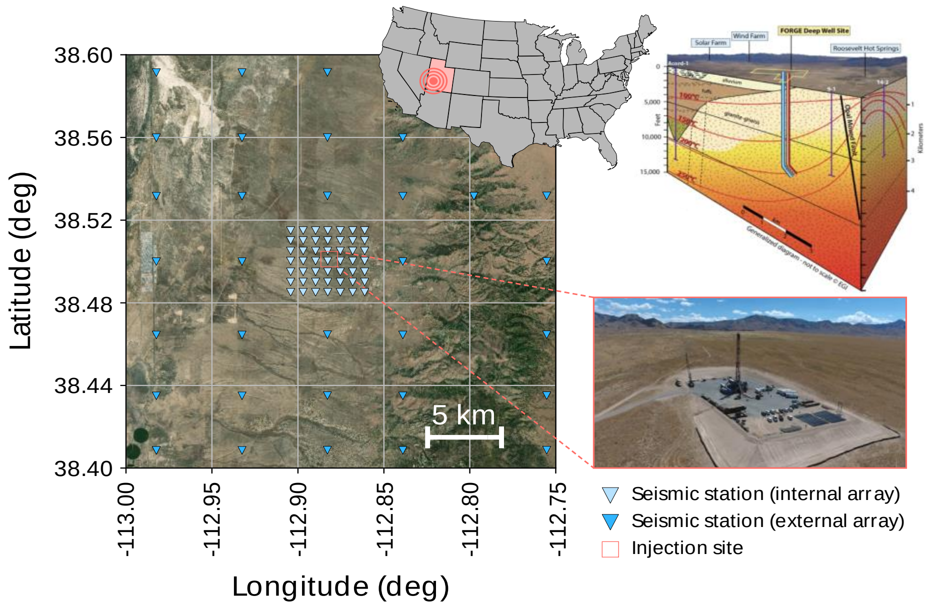

Figure 7: *Location of the FORGE geothermal site in Utah and generalized project layout (source: K. Pankow, Utah Univ).*

3.5 Evaluation of the GES reports on Pohang

We find the reports presented by GES overall comprehensive, in most parts well balanced and generally in line with the findings of other research groups. GES has invested a substantial effort in the understanding of the Pohang event and its potential implications for Haute-Sorne. No other geothermal operator worldwide has attempted as comprehensive a review of Pohang as GES did. Some differences in interpretations between GES, the OCRA report, and the emerging literature exist, and the numerous ongoing studies will likely reveal additional details. However, these are in our assessment not critical for evaluating the implications of the Pohang incident for the Haute-Sorne project.

GES presents in our assessment convincing arguments that the Pohang event would not have occurred if the different safety layers foreseen in the Haute-Sorne project had been applied. This assessment can never be proven with absolute certainty, but it is clear that the project plan proposed by GES and the additional requirements imposed by the canton would have effectively prohibited all of the shortcomings listed in section 3.2 and 3.3. Most of the lessons learnt from Pohang have already been addressed in GES's risk assessment and project strategy provided to the canton. Below we provide some specific feedback to the main conclusions:

Chapter2: Active Faulting (Page 5): We agree with GES that active faults have been searched for and not been identified in the vicinity of Haute-Sorne. However, as pointed out in our recommendation 6 in chapter 4, additional evidence on major faults near Haute-Sorne could be obtained using 3D seismic imaging.

Chapter2, 4, 5: Seismicity (Page 6, 15 and 21): The risk study of Haute-Sorne has indeed considered historical and instrument seismicity, and no major earthquakes are known to have occurred in the vicinity of Haut-Sorne. However, the Jura and the Haute-Sorne region are seismically active, and in the assessment of the SED, larger earthquakes of magnitude 6+ are in principle possible everywhere in the alpine region, to which the Jura belongs as well geologically. The recurrence period of such earthquakes is in many regions very long, so they would often not be known from the historical or instrumental record. We also agree that a naturally occurring magnitude 5.5 within 30-40 kilometres of Haute-Sorne would clearly need to trigger a re-evaluation of the seismic risk.

Chapter2 & 3: State of Stress (Page 7 and 14): GES has considered the stress field in the Haute-Sorne region as a critical parameter for reservoir development and for seismic safety; they also recognise the need to characterise the stress field in-situ once the exploration drilling is completed, and consider this information for an update of the risk study. As pointed out in our recommendation 3, we consider this stepwise approach to risk assessment, with a specific break point after the exploration phase, a critical component for ensuring a safe project.

Chapter3: Site selection and concept (Page 9): We agree that the multi-stage stimulation project away from major fracture zones, as proposed by GES, is different from the one applied in Pohang and offers in principle conceptual advantages with respect to seismic safety and risk management. Because the GES concept on purpose avoids major fault zones, it is especially critical to ensure as much as possible that no major faults are located nearby (see our recommendation 6 and 7). It is also a fact that faults and fault zones exist in all sizes, the concept of GES relates to stimulating 'minor' fracture zones but avoid major fault zones, but these terms have to our knowledge never been clearly defined nor quantified. Defining the semantics of fault zones with respect to their sizes and geological expressions as well as seismic potential clearly would be welcome for future updates of the Haute-Sorne risk study.

Chapter3: Petrographic analysis of fault zones (Page 10, 11): It is in our assessment unclear at this point (but not relevant for Haute-Sorne) to what extend the Pohang operators were aware of the fault that they crossed while drilling, to what extend this was interpreted correctly and considered as a safety risk, or actually seen as a positive sign for permeability. creation. Important for Haute-Sorne is only that also information obtained during the drilling is considered during operation and in the in the update of the seismic risk study, actions that GES has foreseen.

Chapter 4: Seismicity near the EGS site prior to stimulation (Page 15): A key requirement of Haute-Sorne imposed by the regulator is that monitoring must be in place six months prior to stimulation, so that the background seismicity characterisation can be improved. Beyond that it is of course important to also consider regional changes in seismicity patterns and their potential links to periods of heightened risk, but in our assessment the empirical and scientific basis for understanding such regional changes is very thin at best, even more so when trying to relate it to the risk potential of a stimulation. Expert opinion is the only viable option to consider such input.

Chapter 4: Seismicity and mud losses (Page 16): We agree that the drilling must be monitored in detail in order to detect seismicity related to drilling, and this is foreseen in Haute-Sorne. We also consider the information that mud losses triggered seismicity relevant for risk assessment but like to caution that these are likely quite frequent observation in some locations (i.e., Iceland) without them being a major risk concern. In Basel, cementing also caused seismicity, which has not yet been explored for its risk management potential. Especially when deploying highly sensitive net-works, such drilling induced seismicity will be even more common, and it is non-trivial to include the information in risk assessments

Chapter 4: Seismicity locations (Page 17 and 18): We agree with GES that accurate location in near-real time are a key requirement and that they are foreseen. Differences between the ORAC report and the GES study in the Pohang earthquake location exists in, which is expected because of different data used and different methodologies, but these differences are not relevant for the overall interpretation or implication for Haute-Sorne. We consider the ORAC location as published by Lee et al. (2019) and Ellsworth et al. (2019) the best available ones today. Our recommendations on seis-mic monitoring are summarised in recommendation 4.

Chapter 4: b-values (Page 19): The b-value is a critical parameter as we also point out in section 3.3. It is ensured that the Haute-Sorne project will take this into consideration.

Chapter 4: Velocity model (Page 19): A suitable velocity model is a critical need for understand-ing the ongoing seismicity. While for Haute-Sorne the overall principles are established, a more detailed planning that explicitly targets the updating strategy when new data is arriving, needs to be developed by GES (see our recommendation 4).

Chapter 5: Hydrogeologic analysis of fluid pressure perturbations (Page 21-25): We con-sider the discussion on modelling the triggering mechanisms as important but still ongoing. As ex-plained in section 3.1, there will likely never be a unique and generally accepted model that explain the occurrence of the M5.5 event. These inherent uncertainties in understanding induced seismicity, given the available (and lack of) data on the location of faults and their stress state, mandated probabilistic approaches that explicitly consider these uncertainties (see our recommendation 1 and 2), they also mandate that safety is considered a process that build an a number of layers, or barriers (see recommendation 5). Finally, these uncertainties mandate a stepwise, adaptive and data driven approach to risk assessment (recommendation 3).

Chapter 6: Mainshock (Page 26-27): The mainshock rupture plane and its location to the bore-holes is well understood by now and GES is correct that the delay in triggering is feasible based on existing models (although, again the actual mechanisms is argued). It is also clear that the actual mainshock released pre-accrued tectonic stresses and extends much beyond scaling relationships that relate injection volume or area affected by the induced seismicity with the actual upper mag-nitude of the event (the 'McGarr limit'). We lack in the review of GES a discussion if the probability of run-away ruptures is adequately addressed in the current Haute-Sorne risk study, given also studies such as the one by van der Elst et al. (2016). One branch of the risk model logic tree caps the maximum magnitude ('McGarr limit', see our discussion in section 4.2.3), which is a concept that is re-iterated in the GES report on section 3.5 (page 44). In our understanding, this branch should in a re-evaluation of the seismic risk be down weighted or eliminated (see our recommen-dation 3).

In our assessment, GES present a fair, detailed and highly competent analysis of the Pohang project. This analysis is useful for the scientific debate and the understanding of what went wrong in Pohang, and we encourage GES to publish or make available their analyses as much as feasible. An important side-benefit of the analysis performed by GES is also that it allowed GES build up knowledge, experience and capacity, and to reflect on the Haute-Sorne concept and consider improvements. We agree also with the assessment of GES that the Haute-Sorne project plan and oversight are much more advanced and appropriate, with a strong focus on safety. We disagree with GES in their conclusion that no changes are need to the Haute-Sorne project plan, and we summarize our recommendations in section 4.

4. Assessment of the implications of Pohang for Haute-Sorne and recommendations by the SED

4.1 Introduction

The Pohang event has highlighted one more time the challenges related to seismic risk when exploiting underground resources. These challenges are not limited to EGS systems, they also exist in mining, conventional and non-conventional hydrocarbon production, tunnelling, hydro-dam impoundment, hydrothermal-type geothermal systems, etc. (Figure 8), due to a range of physical mechanisms. There is currently no pathway to reduce the risks related to induced seismicity to zero in EGS projects, with the obvious exception of not doing a project in the first place. The fundamental question in light of the Pohang earthquake is therefore: can induced seismicity related risks be reliably assessed and quantified, can risk mitigation and safety layers be designed such that the risks are reduced to an acceptable level[7]?

Below, we summarise the recommendations of the SED for the Haute-Sorne Project in the light of the Pohang earthquake and other recent developments in the domain of induced seismicity risk that we commented on in section 3.

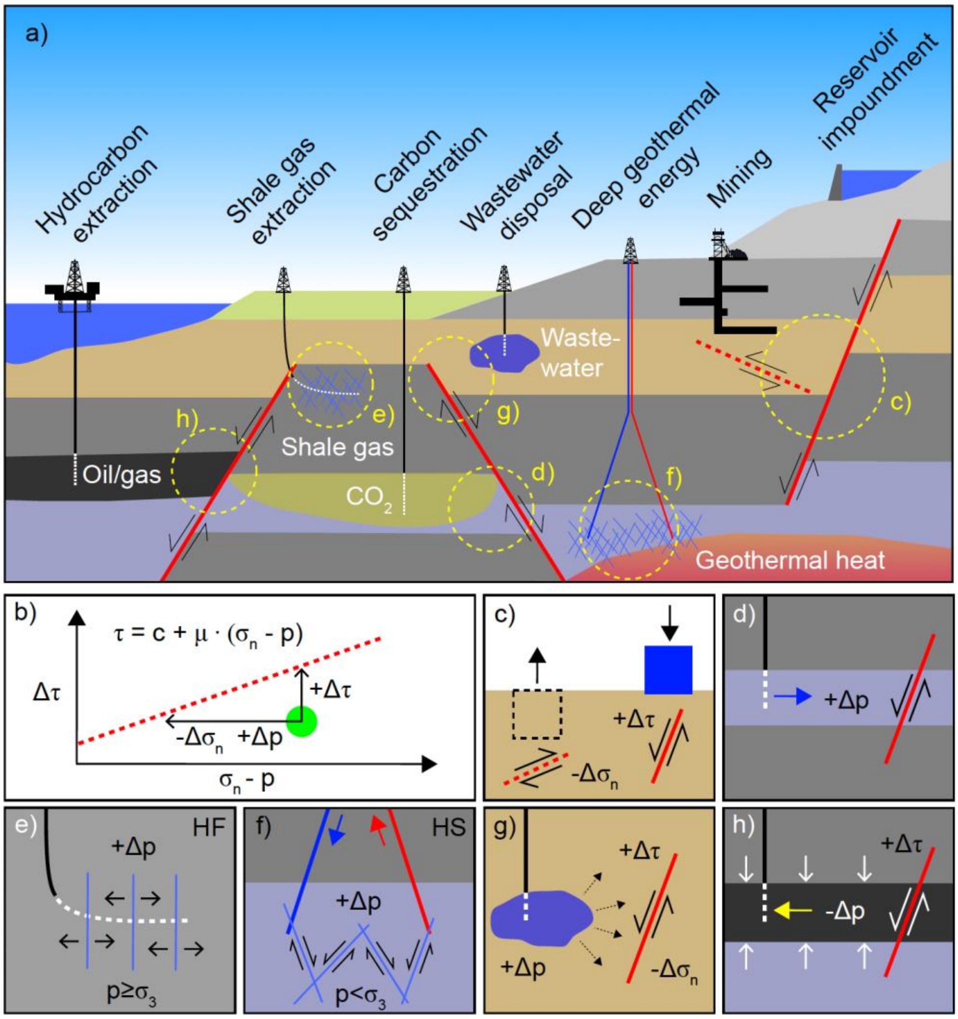

Figure 8: *Industrial activities and physical mechanisms inducing seismicity (From Zbinden, 2019; modified after Grigoli et al., 2017): conventional (oil and gas) and unconventional (e.g., shale gas) hydrocarbon extraction, carbon sequestration, wastewater disposal, deep geothermal energy extraction.*

[7] Different kinds of acceptance exist: regulatory acceptance, but also public acceptance. Our report is largely targeted at regulatory acceptance levels, as defined in the environmental impact assessment presented by GES.

4.2 Assessment and recommendations

4.2.1 Validity of the overall risk assessment and acceptance framework for Haute-Sorne

The first overarching question we address here is if the overall framework chosen by the canton for the seismic risk related parts of the permit of Haute-Sorne has been invalidated by the unexpected occurrence of the Pohang earthquake. The permitting process is based on Probabilistic Seismic Hazard (PSHA) and Risk Assessment (PSRA) compared to acceptance criteria in terms of individual risk and insurance needs, defined by the canton.

In our assessment, the Pohang earthquake, while being a sobering reminder of the risk posed by induced seismicity, is neither unexplainable nor a total surprise. Induced earthquakes of similar size and larger have occurred in other geotechnical contexts and the physical, hydrological, geo-mechanical, and seismotectonic framework to understand run-away ruptures exists. In their assessment, GES follows the concept of Probabilistic Hazard/Risk Assessment (PSHA/PSRA) with the small chance of a run-away rupture included in the probabilistic part of the Haute-Sorne seismic risk study, which contributes to the individual risk and insurance risk calculations. Such an event was also considered in the monitoring strategy and, in the risk mitigation plan. PSHA/PSRA is a widely used framework commonly applied to seismic hazard and risk assessment for natural earthquakes as well as other perils. It provides a well-established structured analysis pathway for quantitative analyses and integrates uncertainties in a formal way by the means of a logic tree. It also has been applied increasingly for induced seismicity hazard and risk assessment (e.g., Bommer et al., 2017). The strength of PSHA/PSRA are that:

- All existing knowledge is integrated in a transparent and reproducible way into the assessment.
- Uncertainties are expressed and considered in a formal way.
- Different expert opinions can be considered such that the overall study reflects the 'centre, body, and range of the informed technical community'.
- PSHA and PSRA reflect the current state of the art. Advances in understanding can be readily integrated in a pragmatic way.

Lee et al. (2019)'s key message from the lessons learned from Pohang reads as:

> "*Best practice involves a formal process of risk assessment, with input from competent authorities, and the updating of this assessment as knowledge of the potential hazard evolves*"

We consider the Haute-Sorne project, its a-priori risk assessment and approach to update the risk as in line with these recommendations. Many of the main lessons learned from Pohang have in fact been anticipated in the Haute-Sorne risk study by GES: the need to quantify uncertainties and consider alternative views, the need to perform a risk-based assessment that considers site amplification and buildings at risk in a quantitative way, as well as the need to update risk studies as new data becomes available and also in near-real time. In this sense, we consider that the Haute-Sorne risk study submitted by GES still meets the state of the art, and we expect that other projects will follow a similar probabilistic and risk-based approach in the future, in line with the recommendations by Lee et al. (2019).

Likewise, the acceptance criteria defined by the canton of Jura for the Haute-Sorne project in terms of individual risk and insurance value risk are in our assessment the right metrics to base decisions on. Acceptance is based on a probabilistic estimate of individual risk and insured values. It has been suggested that the main reason for GES for selecting the Haute-Sorne location was the lower population density as compared to Basel, which could be interpreted as being 'unfair' for residents in Haute-Sorne. This statement is in our assessment misleading: the acceptance criteria applied by the canton is *individual risk for a 1 in 1'000'000 case*, which is the same metric applied for other technologies or natural perils. In essence, every single individual is considered equal and has the same right to be protected. Therefore, there is no difference in acceptance if a project is built beneath a single house or beneath a large city. There is, however, a difference for the operator in the second acceptance criteria applied: the need to carry insurance for a 1 in 10'000 event. The cost of such an insurance is substantially higher in a densely populated area, and in one with more vulnerable buildings on soft soil. Nevertheless, the individual risk level is thereby not concerned.

Recommendation 1: The overall framework for risk assessment, risk mitigation, and acceptance criteria defined by the canton has not been invalidated by the Pohang earthquake. The underlying principles have in fact been reinforced by the lessons learned from the Pohang project and they are now more accepted by the informed technical community. We recommend to the canton that this framework should continue to be used as the basis for permitting.

4.2.2 Can induced seismicity risk be assessed and controlled?

Induced seismicity is an inherent possibility of every deep geothermal project, and it is a certainty in EGS projects. In the EGS concept, small seismic events (often called micro-seismicity) are needed to create and maintain a reservoir for water circulation in the basement rock. Induced seismicity additionally allows monitoring the reservoir's condition and evolution. Since micro-seismicity is needed to create an EGS, the EGS concept thus critically depends on the ability to control induced seismicity to an acceptable level, and thus also to balance economical outcome and safety (e.g., Mignan et al., 2019a; 2019b).

The Pohang accident raises the important question to what extend EGS related induced seismicity can be managed and controlled. After the project failures due to induced seismicity in Basel, St. Gallen and now Pohang, the degree of predictability of the underground response to human induced activities clearly is limited and needs to be reflected on. Is there a causal link between action and reaction, or are induced earthquakes as unpredictable and uncontrollable as natural ones? In the assessment of the SED, managing and controlling induced seismicity is possible, albeit with varying degree of uncertainty throughout the different project phases.

The phenomenon of induced seismicity is not new, not limited to EGS technology, and not limited to injection into basement rock (Figure 8). Mining related induced seismicity and its management have been around for more than 100 years in some areas. Reservoir impoundment has likely caused earthquakes of magnitude 3 to 4 in Switzerland in the 1960's and 1970's. Wastewater reinjection related induced seismicity observed in the Eastern US, but also in Canada and China, can exceed magnitude 5.0. Often the economic benefits outweigh the risks and projects adapt and continue. In other cases, they ceased the operations. A recent example is the project in Groningen (The Netherlands), where the Dutch government decided to stop natural gas extraction in early 2022 because of induced seismicity risk. Gas worth several billions of Euros will not be produced since no pathway could be found to sufficiently reduce this risk.

Risk assessment and risk management for induced seismicity in an EGS context relies in essence on two fundamental principles:

– **The seismic response of the underground is highly variable but to a first order a site-specific constant.** A-priori, this constant is not known but it can be at least roughly estimated early during the injection or through a test-injection. Once this factor is approximately known, it can be used for quantifying and limiting the seismic risk, but changes with time can occur.

– **The seismic response of the underground scales to a first order with the volume of rock that is significantly perturbed**. This is almost a trivial statement but important: the more faults are exposed to stress increases, the more likely some of them can be activated, so the higher the seismicity rate and the maximum expected event size. Because the volume affected can be computed and is a direct consequence of the injection volumes and injection strategy, risk mitigation is in principle feasible: Tiny injection volumes (i.e., 1 m^3) are virtually always safe, larger volumes may be problematic if the seismogenic response is high.

An almost perfect example of these two principles is the Basel injection: If one plots the cumulative number of events as a function of time, normalised by volume (Figure 9; Broccardo et al., 2017), the distribution follows a straight line within the expected randomness (of a stationary Poisson process). Such a behaviour is predictable and hence controllable to a certain degree and currently successful EGS projects in Soulz, Ritterhofen, or Helsinki have exploited these principles effectively. Vice versa, the Pohang project did not explore them (see section 3.3).

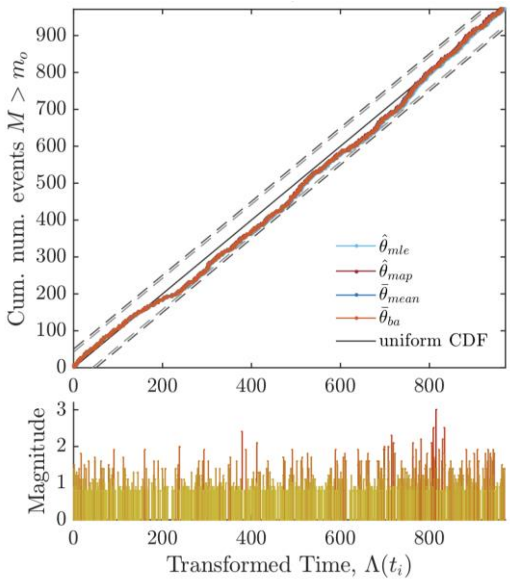

Figure 9: *The cumulative number of events observed during the Basel injection plotted as a function of time, normalised by volume (i.e.: transformed time). The straight line indicates that the seismic response of the underground to injection is a constant.*

These two basic principles are at the core of risk mitigation through traffic light systems or advanced traffic light systems. More complex models for forecasting seismic activity couple seismic data with hydro-mechanical processes exist and should be used increasingly. However, even when just applying these two principles, risk assessment and risk mitigation is possible.

The Basel EGS project of 2006 can be considered a failure of controlling induced seismicity, because the project was terminated after a strongly felt earthquake also causing damage. An alternative view, however, is to consider it a success for the management of induced seismicity: The seismic monitoring and traffic light system in place made sure that mitigation actions were initiated early enough to prevent potential severe damage and injuries. A subsequent risk study showed that the Basel site given the concept of a massive stimulation poses non-acceptable seismic risks, so the project was terminated. It is plausible that a continuation of the injection would have led to a Pohang-like earthquake; alternatively, terminating the injection at day 3 or 4 instead of day 6 would likely have avoided the magnitude 3.4 event in Basel. The case of induced seismicity at the St. Gallen hydrothermal system is more complex: the traffic light in place was on yellow and then red, and the operators were advised to stop the injection, but this advice was not implemented because fighting the gas kick was the first priority. A lesson learned from St. Gallen is therefore that mitigation on seismicity and gas kicks needs to be considered as coupled processes, which is implemented for Haute-Sorne.

However, it is also clear that seismic risk management and mitigation have limitations, and Pohang has re-iterated these limitations: The response of the underground can vary with time and as pressure diffuses, the largest events can by chance also happen early in a sequence, or very late, additional physical processes may be critically important in some instances, etc. Surprises can therefore happen; however, we believe that induced seismicity risk assessment and risk mitigation is feasible and effective in reducing the overall project risk. The most critical element for successful risk mitigation is awareness of what is actually going on. The failure of Pohang to apply risk mitigation is in our interpretation more a failure in the situation awareness during the project (section 32,) rather than a failure of principles that risk mitigation strategies rely on.

Recommendation 2: The seismic response of the underground to injection can be in principle understood and forecasted using empirical experience, data assimilation and numerical modelling. Therefore, we consider risk assessment and measures to control seismicity feasible strategies for permitting and real-time risk reduction, but they must be done well and consider the limitations and uncertainties.

4.2.3 The need to update the specific choices made in the risk assessment

The computation of probabilistic seismic hazard and risk for natural or induced earthquakes depends on the available empirical data, computational models, and to a certain extend on expert choices (the same is true for other risks). With time, the state of the art (and state of practise) evolves as new data or new models become available and expert knowledge also evolves. Today, a new hazard and risk assessment done for Haute-Sorne would likely result in different values from the ones done 5 years ago, just like any other risk assessment study repeated five years later. This is especially true in the domain of induced seismicity risk that is relatively new field and evolving rapidly. Updating the risk study once a *significant* change in the state of the art demands it a requirement by the canton posed to GES (no. 55) – but what exactly amounts to a significant change is difficult to assess and not clearly regulated. It is also neither practical nor fair to an operator that the baseline for the acceptance of a project changes every time a new publication comes out.

In our assessment, there are a few areas where the Haute-Sorne Risk study can and should eventually be updated, based on recent developments and new data:

- The ground motion prediction models applied, published in Edwards et al. (2016), should be adopted to be in line with the ones used in the national seismic hazard model, released in late 2015.

- The variability in underground response to fluid injection, both in terms of a-value and b-value, should be more explicitly considered in the risk study, based on studies by Mignan et al. (2017; 2019a) and Broccardo et al. (2017). The computational framework to consider these uncertainties explicitly now exists and has been used for example for the Bedretto and Geldinganes projects.

– The Haute-Sorne risk model contains one model branch where the maximum possible magnitude is limited (i.e., truncated) based on the injected fluid volume or area of seismicity. This truncation is still a plausible scenario in certain circumstances when and where run-away ruptures are impossible, because of a lack of mature faults or the stress state (e.g., fracking in weak sediments). However, there is now convincing evidence that the so called 'McGarr limit' is in most instances a statistical effect and not a fixed boundary (van der Elst et al., 2016). We anticipate that in a re-evaluation of the probabilistic hazard for Haute-Sorne, the weight of the 'truncated' branch should be reduced, or that this branch should be removed. This would add additional weight in the risk analysis to the probability of run-away ruptures, emphasising the important of Pohang-like scenarios.

– There are now improved models available or emerging for forecasting the response of the underground given a certain injection strategy, and better approaches to quantify the risk limiting effect of classical or adaptive traffic light systems. These can be introduced in risk assessment.

– Improved datasets in local site amplification, building stock and vulnerability of Swiss buildings are becoming available as part of the national earthquake risk models (2017 – 2022). These new and improved databases may be available for an improved risk-based assessment.

It is not obvious in which direction the risk assessment would evolve if these changes were to be applied in an updated Haute-Sorne hazard and risk study, and the effort in implementing these amendments is nontrivial. It would then also always be possible for an operator, such as GES, to reduce the risk to acceptable levels by adopting a more conservative traffic light threshold, or by adopting a dynamically adapting threshold. This approach has been described by Mignan et al. (2017).

While an update to the Haute-Sorne Risk study given the aforementioned advances of the state of the art and available data in the past five years is needed, we suggest to not implement it today but to integrate it with the exploration stage of the Haute-Sorne project proposed by GES.

The key lesson from past induced seismicity risk studies, and a key lesson also from Pohang is that an a priori assessment of seismic risk is possible, but that the outcome has very large uncertainties. The most recent risk study conducted by the SED for the Geldinganes project in Iceland illustrates this nicely. For this project, the a-priori risk is assessed to be acceptable with an individual risk well below 10^{-7} per year. However, the most remarkable feature about the risk assessment is the very wide uncertainty band, covering five orders of magnitude. This state of deep uncertainty reflects on parts the fact that the response of the underground to injection cannot be modelled accurately before the in-situ conditions are better known, based on test stimulations and at-depth (i.e., in-situ) site characterisation. We anticipate that, as data on the local conditions becomes available, the mean value of the risk assessment might change; most of all, however, the uncertainties should be substantially reduced. While expecting this uncertainty reduction is rational and it has been shown in off-line, retrospective analysis, it has not yet been demonstrated in a geothermal project. The SED will conduct a first real-time test of the usefulness of such adaptive risk assessment approaches for risk reduction in Geldinganes (Iceland) in the fall of 2019.

In our assessment, updating the Haute-Sorne risk study is indeed needed, but the most-meaningful update that will reduce the inherent uncertainties is only possible once new data is collected in-situ, at reservoir depth. Once a first drill hole is established, important data for calibrating the risk model to local conditions will be collected through a volume-and-seismicity limited test stimulation (including assessment of the state of stress, fracture distribution, etc.), which will permit to reduce the uncertainties and allow to take much more informed decisions. Therefore, a test stimulation with limited volumes of fluid under moderate pressures is needed to allow for a substantial update of the risk study. This procedure is already foreseen by GES and is part of the permit issues and it remain in our opinion the single most important measure for ensuring a safe stimualtion. It also will allow GES to better decide if developing a commercially viable reservoir is possible, given the local conditions and constrains posed by keeping the seismic risk at an acceptable level. The drilling of the exploration borehole itself, the characterisation tests, as well as a first test stimulation with reduced volumes will only carry a fraction of the risk of the overall reservoir stimulation, a risk that has been demonstrated in the GES risk study to be well below the acceptance criteria defined by the canton.

Recommendation 3: The SED recommends that a full update to the risk study is mandated by the canton only after the drilling and characterisation of the first exploration well are completed. An update conducted today will not result in substantial insights beyond the existing risk study. Only once the in-situ conditions are better known can the inherent uncertainties in seismic risk assessment be substantially reduced. The permitting for the full stimulation of the reservoir should be strictly conditioned on demonstrating acceptable risk conditions, based on in-situ conditions measured through the exploratory well and the refined reservoir development plan. This updated version of the risk study should also be reviewed by the canton and external reviewers before a stimulation permit is issued. The updated risk study serves then also the blueprint for implementing adaptive traffic light approaches.

4.2.4 The need to update strategies for seismic monitoring & mitigation strategies

The Pohang project is in many aspects a prime example on how to not conduct seismic monitoring and analysis workflows for EGS projects, making it also difficult to draw conclusions on the usefulness of seismic risk management strategies from this project. Evaluating the seismological metadata of the Pohang monitoring network installed by the operator indicates for example that a conceptual error led to the limited resolution of the system. High-sensitive weak-motion seismometers were installed at mostly noisy surface sites, whereas low-sensitive strong-motion accelerometers were installed in shallow boreholes. Consequently, the detection level for seismic signals was in the first case limited by the high anthropogenic seismic noise level and in the latter case by the limited resolution of the acceleration sensors. For all seismic monitoring systems, it should be carefully evaluated if the chosen equipment can resolve the expected or desired seismic signal levels and if the noise conditions at the sites are sufficiently low for the foreseen monitoring task. Textbooks (NMSOP-2: doi.org/10.2312/GFZ.NMSOP-2; Havscov, 2010: doi.org/10.1007/978-3-319-21314-9) and scientific publications exist (e.g., Kraft et al., 2013; Plenkers et al, 2015) that describe this evaluation procedures for micro-seismic monitoring in detail.

Several seismic networks were operated at the Pohang site without thorough coordination and mainly without real-time data access for the operator or for seismic services. To our knowledge, earthquake location and magnitudes where therefore only available with a considerable delay. In addition, earthquake locations and magnitudes had a poor accuracy and no relative earthquake locations were calculated by any participant of the Pohang project in reasonable time. To our knowledge the first reliable relative locations were calculated by Kim et al. (2018) using data from an independently installed network. Equally unfortunate, no reliable magnitudes were available for a very period of the stimulation phase of the project.

Current state-of-the-art: As outlined above, induced micro-seismicity at the beginning of the hydraulic stimulation holds critically information on the likely seismic response of the subsurface to this operation. In our assessment is therefore that in all phases of a geothermal project, changes in the spatio-temporal behaviour of the induced microseismicity might indicate potentially problematic developments in seismic hazard. It is therefore essential to deploy and professionally operate a highly sensitive, real-time seismic monitoring system that can provide automatically accurate earthquake locations and magnitudes, including relative relocations. Results of the monitoring must be feed into algorithms that will provide a forecast of the upcoming seismicity, and they must be available in real-time to the drilling operators and to the regulator. Changes in the induced seismicity patterns, such as the appearance of lineaments that may be indicative of the reactivation of a major faults, should be noticed in near-real time by the analysts, and should trigger a re-evaluation of the seismic hazard at the level of a local expert group that may decide to put operations on hold an re-evaluate the hazard and risk more thoroughly. Authorities must take care that mitigation concepts are developed by the operators and reviewed by experienced, independent experts. Last but not least, it also takes trained and capable staff to perform seismic monitoring and analysis well.

Beyond the state-of-the-art: Seismic monitoring and processing techniques are evolving rapidly and new kinds of sensors (e.g., fibre-optics based seismometers and distribute acoustic sensing) and machine-learning based automated processing offer a lot of potential to detect and located micro-earthquake much more complete, rapid and reliable (see for example Herrmann et al., 2019). These methods have the potential to provide additional improvements to the safety of EGS reservoir stimulations, since problematic developments can be sensed earlier on and process understanding is enhanced.

Recommendation 4: GES was in our assessment well on track with respect to seismic monitoring requirements, and the Pohang earthquakes does only reinforce the need take monitoring and analyst in real-time extremely seriously. GES has a solid plan to address the state-of-the-art monitoring and analysis requirements outlined above, and these are also mandated in the stipulations by the canton. GES is also investing into understanding the potential of new technologies beyond the current state-of-the-art and exploring how these can be used to enhance the safety of the Haute-Sorne project, and is investing into the build-up of capable staff. We encourage GES to continue along these directions. Missing is, however, a detailed monitoring and analysis planning, including plans on how to determine and improve the velocity model, a quantitative assessment of the performance to be expected and the responsibilities of the stakeholders (GES staff, external companies, SED staff, regulator) as well as a plan how this information will be used in near-real-time, for example as part of adaptive traffic light systems or for expert analysis. This plan should be given to the canton and approved well before the exploration drill (phase 1) is started.

4.2.5 The need for multiple safety layers and a forward-looking safety culture

A key finding from the Pohang project is, in our assessment, that not a single mistake or oversight led to the catastrophic failure but a combination and chain of events over the entire project duration, possibly combined with a certain degree of 'bad luck' (section 3.2). The lessons to be learned are in principle well known in risk, safety, and security assessments: Safety is not achieved with a single measure and one-time assessment, but through an ongoing process that involves **numerous safety layers** (also called safety barriers) combined with a good safety culture as part of the organisational structure and regulatory oversight. A good progressive safety culture also requires knowledgeable and well-trained staff, and openness to internal and external criticism.

The GES reports on Pohang outlines credibly how the different safety layers regulated as part of the Haute-Sorne project would likely have prohibited the occurrence of a run-away rupture. These layers are based on site selection, project execution, monitoring procedures, and quantitative risk assessment (see the discussion in Chapter 3). Additional safety layers could in our assessment be added (such as 3D seismic imaging, see below). The seriousness and urgency that GES has shown in addressing the Pohang earthquake, and the dedication of the Haute-Sorne project plan to safety layers, are, in our assessment, positive and important steps towards ensuring the safe implementation of the Haute-Sorne project.

It is also important to realise that at least in the case of EGS, enhancing the safety of the project will not only cost money (i.e., enhance seismic monitoring), but also may have a strong impact on the ultimate economic output of the project (i.e., a more conservative traffic light system will decrease the chance of creating an economical viable heat exchanger; Mignan et al., 2019a). Because of the limited experience with EGS systems in Switzerland and worldwide, we believe that the Haute-Sorne pilot project should put safety first and foremost, economic constraints and financial considerations second. The substantial funding availed from the Swiss Federal Office of Energy for the execution of Haute-Sorne project must in this respect be recognised by the operator as an important contribution to safety.

Recommendation 5: We encourage GES to maintain and further strengthen a proactive and progressive safety culture with respect to the management of induced seismicity. This includes maintaining and extending capacities and expertise within the organisation with respect to the risk management of induced seismicity risk, dedicated training, and possibly organisational changes that encourage safety. We suggest that the cantonal authorities explicitly consider also a good organisational safety culture as an important criterion for review and permitting.

4.2.6 The need for better fault characterisation using seismic reflection data

The presence of potential faults in the volume of rocks affected by the operations in geothermal projects has been known for a long time to be an important factor, but Pohang has further strengthened the critical character of this factor. Faults can often be recognized when and if the borehole trajectory crosses them, although the 'San Andreas Fault Drilling' project has highlighted that even major faults can be hard to locate exactly even while drilling through them. To identify faults that are close to the well trajectory but do not cut it, or to identify faults before drilling starts, reflection seismic data along 2D profiles or in form of 3D surveys, as routinely acquired around the world on a daily basis, are a viable option. The option to collect additional reflection seismic data was considered during the permitting process of the Haute-Sorne project, but seismic imaging capabilities in the crystalline basement are limited due to the lack of prominent reflectors. Ultimately the canton decided in 2015, based on input from different experts, that there is too little added information with respect to seismic risk to warrant demanding a costly 3D seismic imaging campaign. We believe that in light of a fresh look at recent seismic data collected in the field that illustrate the importance of knowing major faults and of correctly characterising the seismotectonic context in the region (Figure 10) but also in light of the Pohang mainshock, this decision should be reviewed.

The currently available seismic data set in the western Delémont basin consists of three 2D profiles acquired and processed for the hydrocarbon exploration of the approx. 1.3 km thick Mesozoic sediment package in the early 1970s. One profile runs essentially through the drilling site. The quality of the imaging resulting from the acquisition and processing of this early data is fair to poor. Acquiring additional reflection seismic data has been considered in the past by GES but was always rejected based on the argument that the reservoir area at depth is located within the crystalline basement, a geological environment in which the density and seismic velocity contrasts on which the reflection seismic method relies are essentially missing.

This is partly a valid argument, even when one takes into account the great progress made by the industry in the acquisition and processing of reflection seismic data. This progress can be convincingly illustrated by looking at the different generations of seismic data available to Nagra in a very similar geological environment, in the eastern Jura. The comparison between the (2D) seismic data of the 1970s and the data acquired recently along (nearly) the same profiles is spectacular with a much higher resolution power, far less artefacts and, as a consequence, a much sharper delineation of faults (Figure 10). This is true for the Mesozoic sediment cover and – where available – for the underlying Permocarboniferous troughs. 3D data surveys obviously represent yet another improvement in the imaging of the subsoil and have proven to be the critical piece of information for unravelling the St. Gallen hydrothermal system and induced seismicity (Diehl et al., 2017). This data also helps as an input for locating induced earthquakes accurately (

The Permocarboniferous troughs, although very old structures, are important for the project as their bordering faults are considered to be reactivable in the present stress field by many geologists. Indeed, in Sundgau, the adjacent, southernmost part of Alsace (F), such reactivation has been shown to exist (Ustaszewski, 2005). Based on (intrinsically low-resolution) gravimetric data, GES has concluded that no such Permocarboniferous sediments exist below the Haute-Sorne site (Meier & Zingg, 2013). They assume that the southern limit of the trough runs in east-west direction in the north of their site. Nagra's recent interpretation of their new 2D and 3D data shows, however, that these troughs are typically not delimited by a single fault on both sides but by a series of parallel faults, with a step-like distribution of the Permocarboniferous sediments.

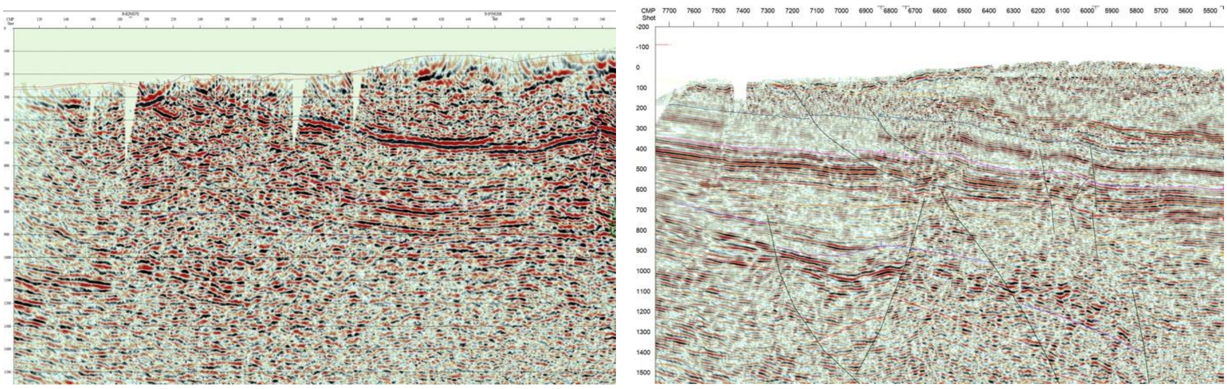

Figure 10: *N-S profiles in the Argovian Jura from 1980 (left) and 2011 (right), demonstrating the advances in seismic imagining capabilities. Courtesy Nagra, 2014.*

Recommendation 6: The lack of modern 3D seismic imaging of the vicinity of the reservoir is a long-standing criticism to the Haute-Sorne project raised in the informed technical community. Given the open questions on the location and expression of Permocarboniferous troughs, given the heightened importance of characterising faults in light of the Pohang earthquake, and given the progress made in seismic imaging capabilities, we recommend that a state of the art 3D seismic survey and subsequent seismotectonic interpretation should be conducted before the full stimulation. This imaging should targets faults roughly within 2 to 3 kilometres surrounding the drilling site. Seismic imaging will add one additional safety layer to the project and help to reduce uncertainties in the project planning. If GES can demonstrate that sufficient resolution is possible with several 2D lines, this may be considered as an alternative. Seismic imaging is not a core expertise of the SED and the project planning should be conducted together with experts in this domain. The seismic interpretation should then be used also as input in the update of the seismic risk study before the full stimulation.

4.2.7 The need for better fault characterisation using downhole data

An additional safety layer related to the presence or absence of major fault zones could potentially be devised by conducting borehole-centred imaging for major fault zones and then integrating this data in the risk assessment and risk mitigation strategies. This is most easily done using cross-hole seismic techniques, which require two or more boreholes and in the case of Haute-Sorne will offer only a limited potential because only two deep boreholes will be drilled and very close to each other in the top kilometres. It should be considered to apply cross-hole imaging techniques of the volume between the two boreholes at depth before the full reservoir stimulation (stage 7 in the GES plan, Figure 11), in order to detect major faults in-between the two wells and thus in the centre of the area to be stimulated.

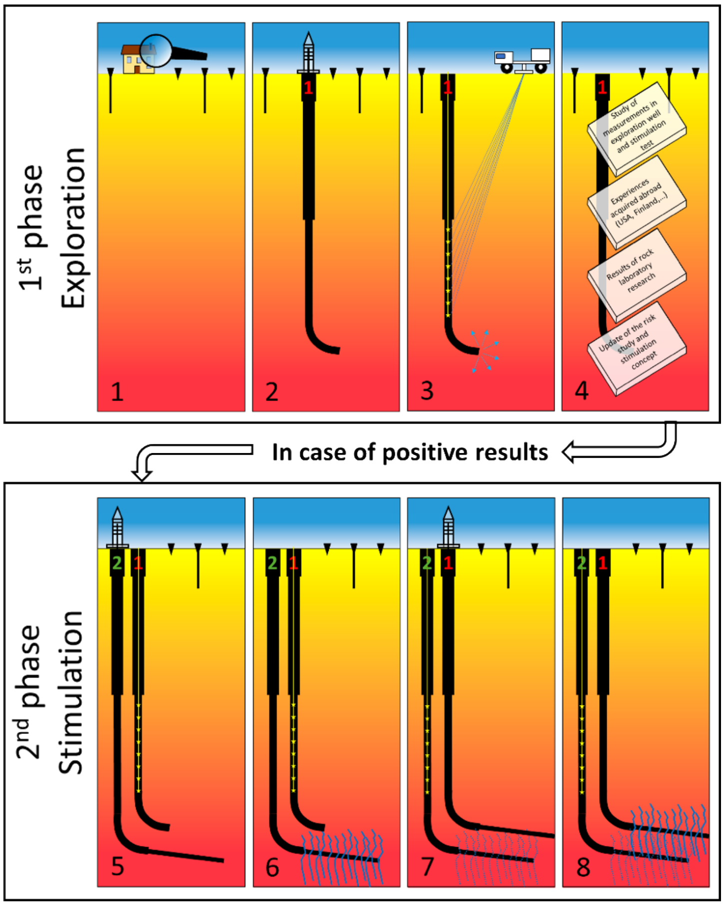

Figure 11: *Staging of the Haute-Sorne project as proposed by GES.*

In addition, it may also be feasible to detect major faults from a single borehole, using seismic reflections, Vertical Seismic Profiling (VSP) measurements from the surface, radar imaging, or magneto-telluric methods. Technologies are rapidly evolving and new sensors, such as distributed acoustic sensing using fibre-optic cables may offer new opportunities. The exploration borehole drilled by GES thus can also offer opportunities for characterising faults and fractures within 1 to 2 kilometres from the borehole. GES is foreseeing such activities, but the work has in our opinion yet to be planned in detail and it should be included formally in the risk re-assessment and permitting process for the full stimulation. This is not the core expertise of the SED so advise from experts in seismic imaging should be considered. It is for example possibly useful to conduct the 3D imaging only after the exploration borehole has been drilled, in order to position sensors in the well during the imaging campaign.

Recommendation 7: We recommend that GES develops a detailed plan on detecting faults from the exploratory borehole and in-between boreholes 1 and 2 as an additional safety layer. Fault characterisation from borehole-based measurements should be integrated in the update of the risk study. Knowledge transfer from other projects from around the world, and collaboration with experts in this domain should be integrated.

4.3 Summary of recommendations

In our assessment, the overall concept for the seismic risk assessment and risk management for the Haute-Sorne EGS project, as presented by GES and given the conditions imposed by the canton of Jura, is sound and does not need to be fundamentally changed in light of the Pohang earthquake. However, we propose a number of additional steps and measures that can further enhance the safety of the project in light of the lesson learned from Pohang. The most fundamental and costliest recommendation in this respect is our suggestion to the canton to require a state-of-the-art 3D seismic imaging campaign to be conducted before the full stimulation is permitted.

In our assessment, the most important safety layer of the Haute-Sorne project relates to the use of the exploration phase to collect relevant data in-situ, such as the fracture distribution, the stress distribution, and the seismogenic response to injections. This first phase foreseen by GES (Figure 11) poses in our assessment only a minimal seismic risk during the test stimulation, a risk that is substantially below the acceptance criteria defined by the canton. This risk assessment has not changed in light of the Pohang earthquake. Therefore, we suggest that GES should be allowed to execute the exploration phase. This exploration phase must be exploited to acquire as much data as possible from in-situ measurements that are critical to reduce the a-priori uncertainties of the seismic risk assessment. The data and analyses must then be used to design in detail a safe reservoir stimulation strategy, to calibrate the numerical modelling and adaptive risk assessment procedures, to calibrate and test the seismic monitoring, and to search for unknown nearby major fault systems. In our assessment, an update of the seismic risk study is not needed before the execution of the exploration phase, but it is critically important and also much more meaningful once the exploration phase is concluded. Many deep geothermal projects in the past have moved on rapidly after the drilling phase to the execution of the stimulation, since every day of the drilling rig on site costs 50k CHF or more. Taking time here to carefully re-analyse the data without the drill rig in place is very sensible given the existing uncertainties and limited experience with EGS technology in Switzerland and worldwide.

Permitting for the second phase of the project, the actual reservoir stimulation should then be based on an updated seismic risk assessment including mitigation plan that considers the data collected in the exploration phase but also takes into account the progresses in understanding EGS systems and induced seismicity overall and the experiences gained in other projects (e.g.the ongoing experiments in the BedrettoLab, the second stimulation of the Helsinki project (2020), and the Utah FORGE project). Likewise, new findings on the triggering mechanisms behind the Pohang earthquake, if any, could be integrated in the update of the risk assessment. Additional data such as 3D seismic imaging campaign results should likewise be integrated in the update.

The formal separation of the Haute-Sorne project into two stages, each preceded by a risk study and assessed by the canton, can greatly improve the quality and robustness of the risk assessment and the safety of the project overall. This concept is already indirectly foreseen in general in the project plan handed to the canton by GES for the Haute-Sorne project in condition 56 and 57 by the canton:

> *56. The individual risk of death must not exceed an annual probability of 1/1,000,000. This risk must be recalculated when acquiring any new data that may significantly change it. The calculation method, described in the GHG report of 9 March 2015 (Assessment of the seismic risk induced by the geothermal project of Haute-Sorne), must be updated if necessary if it no longer corresponds to the recommendations of the Federal Office for the Environment in this respect.*
>
> *57. The seismic risk analysis will be updated whenever new data or knowledge (technical or scientific) is acquired that is likely to significantly change the level of risk or its management.*

We propose to define and formalise this updating procedure and we suggest to the canton to require a full update to the Haute-Sorne seismic risk assessment after the exploration phase and before the stimulation phase. This update should be independently reviewed and approved by the canton before a full reservoir stimulation can start.

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