Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Lessons Learned from Basel: New EGS Projects in Switzerland Using Multistage Stimulation and a Probabilistic Traffic Light System for the Reduction of Seismic Risk

Peter M. Meier, Andrés Alcolea Rodríguez and Falko Bethmann

Geo-Energie Suisse AG, Reitergasse 11, CH 8004 Zürich, Switzerland

p.meier@geo-energie.ch

Keywords: EGS, petrothermal, hydraulic stimulation, multi-stage stimulation, control of induced seismicity, risk studies

ABSTRACT

In Switzerland the large geothermal potential for electrical power production can only be used if Enhanced Geothermal Systems (EGS) will be technically feasible because 90% of the deep underground consist of low permeable crystalline rocks. Based on the data of the Deep Heat Mining Project Basel a new multi-stage stimulation concept has been developed which reduces the risks of induced seismicity and promises a better return of energy. The mitigation plan for induced seismicity includes three major points. First, induced seismicity will be reduced by limiting the areas of the hydraulically stimulated fracture planes. This can only be achieved with a borehole completion allowing the hydraulic isolation of up to 30 individual borehole sections within the reservoir. Secondly, the site selection criteria lead to avoid densely populated areas, areas with high natural seismic activity and placing the geothermal reservoir at a safety distance of at least one kilometer from regional or major fault zones. Third, in addition to deterministic risk studies we have applied a probabilistic approach recently developed by the Swiss Seismological Service to show that the multistage stimulation of smaller fracture zones has a better risk profile than the massive stimulation concept of the Basel project.

1. INTRODUCTION

In Switzerland the large geothermal potential for electrical power production can only be used if Enhanced Geothermal Systems (EGS) will be technically feasible. Based on the data of the Deep Heat Mining Project Basel a new concept has been developed which reduces the risks of induced seismicity and promises a better return of energy. In addition the acceptance by the local population and the authorities play an important role. Geo-Energie Suisse Ltd. the following organization of Geopower Basel Ltd. has started permitting procedures for EGS pilot projects at five sites in Switzerland in order to create a portfolio of projects sites. The sites are located in the communities of Haute-Sorne (Canton Jura), Avenches (Canton Vaud), Etzwilen (Cantons Thurgau and Zurich), Pfaffnau and Triengen (both canton Luzern).

Hydrothermal systems for an electricity production from deep geothermal energy in a larger extent are in Switzerland exceptional areas like fault zones and permeable aquifers in depth of 4000 to 5000 m. A large-scale extension of such systems like in the Munich region could not be proven up to now. In Switzerland for sedimentary systems in greater depths, whose temperatures also allow an electricity production, only a small zone in the foreland of the Alps can be taken into account. Additionally the situation complicates, as the very good aquifers in the Bavarian Molasse Basin become to the West less permeable with lower flow rates of the groundwater.

Based on these considerations the Geo-Energie Suisse Ltd. decided to focus their activities on the development of EGS-pilot-projects (petrothermal systems) because the great potential for electrical power production lies within the crystalline basement (Fig. 1). If it is possible to install in the crystalline rocks of the basement an artificial heat-exchanger, that technology can be used nearly everywhere in Switzerland. For the first time such a big permeable system could be created in the well Basel-1 in 5000 m depth, however, the unrequested side effect of induced seismicity occurred.

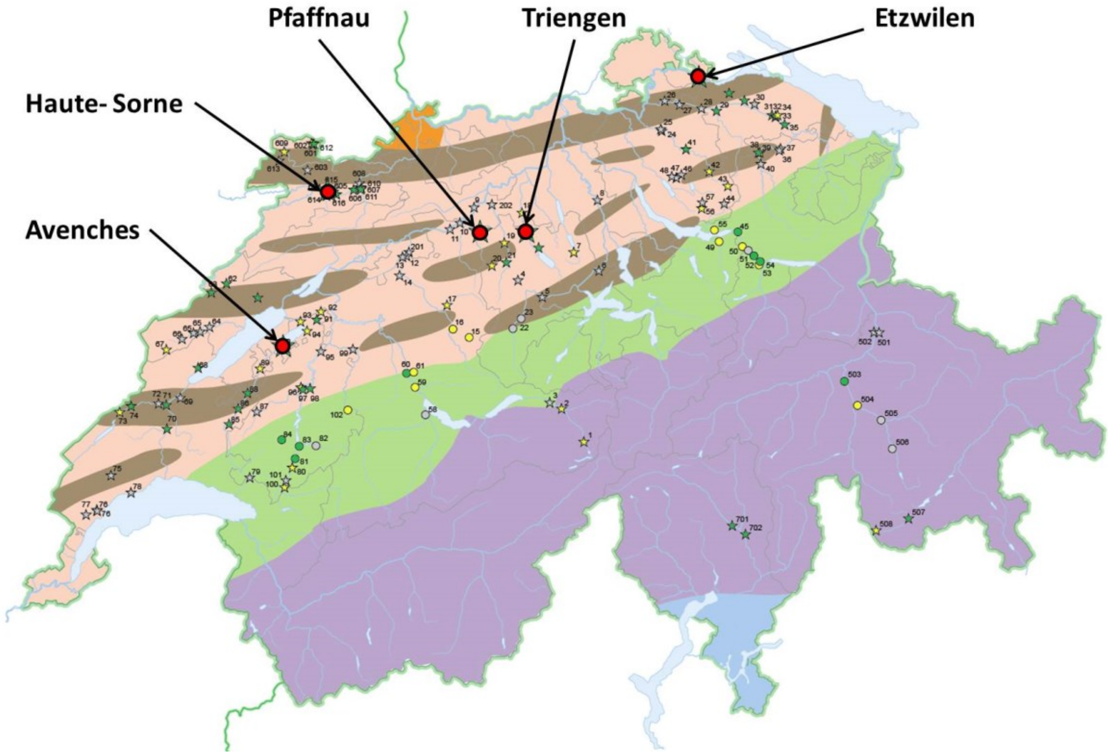

Figure 1: Portfolio of sites for EGS-pilot projects and schematic representation of the main geologic units in Switzerland at a depth of 5 km, where the temperatures are expected to lie between 150 and 200°C, enough for the production of electrical power. At this depth there exist sedimentary rocks only in the Pre-Alps (green area), where one could expect in principle similar favorable conditions for hydrothermal projects within large karst aquifers like in the Munich area. However, until today no regional aquifers have been found in Switzerland. Therefore the geothermal development of Switzerland focuses on the development of petrothermal systems within the crystalline and metamorphic basement (light brown: Molasse basin; violet: Alps). For the moment no projects are planned in the permo-carboniferous (dark brown). Five sites where chosen for pilot projects out of a portfolio of over 120 possibilities.

The Basel results and the ongoing research and development show that the magnitude of such seismic events can be controlled by a series of measures. Therefore, especially the approved techniques from the oil and gas industry shall be included, like the combination of horizontal well with a multitude of stimulated zones.

The stimulation of an Enhanced Geothermal System (EGS) involves the injection of a fluid at high pressure, which induces seismicity and enhances permeability. Although to date there is no recorded instance of a significant danger or damage associated with induced seismicity related to geothermal energy production, induced seismicity is an important topic that needs to be coped with because the occurrence of a large magnitude event causing structural damages cannot be fully excluded.

This presentation reports on the tasks undertaken by Geo-Energie Suisse. It will be shown that the three key-points for the reduction of seismic risk based on the lessons learnt from the Basel data are:

(1) the stimulated area must not exceed a certain threshold surface which lead to the development of a quasi-horizontal multistage stimulation system at a depth of about 4500 m,

2) the site selection by avoiding areas that are densely populated, that show an increased natural seismicity and that are located within or next to regional fault zones

(3) the application of a probabilistic traffic light system, e.g., the injection is stopped if the exceeding probability of a certain magnitude is high. Such an Advanced Traffic Light System (ATLS) has been developed by the Swiss Seismological Service and has been calibrated using the data from the Basel project and adapted to our multistage stimulation system.

2. QUASI HORIZONTAL MULTIFRAC SYSTEM FOR STIMULATION OF SMALLER FRACTURE SURFACES

The Basel project used a vertical borehole that intersected a sub-vertical fracture system below the casing shoe at a depth of about 4400 m. The hydraulic stimulation lead to a large disk shaped reservoir (Fig. 2) with a vertical and horizontal extend of about 1 km each and a thickness of about 50 to 100 m (Häring et al, 2008). This disk is oriented more or less in the direction of the largest horizontal stress in agreement with geo-mechanical theories.

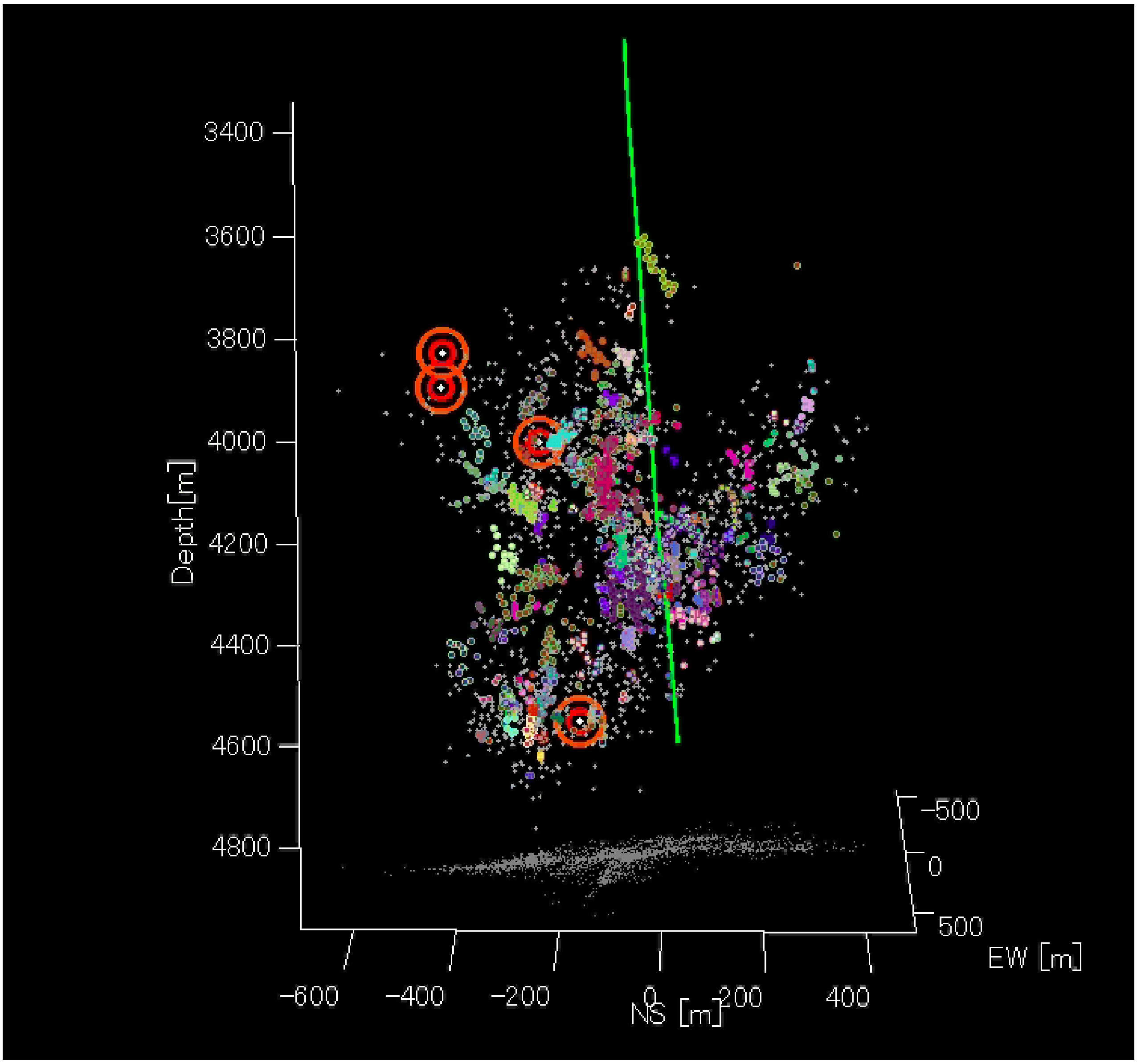

Figure 2: Basel reservoir size: cloud of measured seismicity as an estimate for the reservoir extension; side view in EW direction. The projections of the seismic cloud on the horizontal ground plane show that the reservoir is disk shaped with an lateral extend of about 1000 by 1000 meters and a thickness in EW of 50 to 150 m. The red points mark the four seismic events with magnitudes over 3.0, which occurred after stopping 6 days of water injection with high pressures.

Like in Basel the stress regime in most of the Swiss Molasse basin is believed to be strike-slip with the largest and smallest stresses being horizontal and the intermediate stress being vertical. Therefore hydraulic stimulation will lead to shearing of natural fractures which are approximately vertical and oriented within a sector of around +/- 30° from the direction of the largest horizontal stress. This stress regime implies drilling boreholes at great depth horizontally oblique to the direction of the natural fracture set that can be stimulated hydraulically. The aim is to intersect as many as possible of these vertical natural fractures. For operational reasons the boreholes will be deviated only to approximately 55° from the vertical in order to use wire-line systems for borehole logging and other operations.

The lowest sections of the boreholes will be completed with open-hole packer systems allowing a zonal isolation of up to 30 stimulation intervals. Such systems are available from the oil and gas service industry for temperatures up to approximately 175°C, the expected temperature at the targeted vertical depth of 4500 to 5000 m. The multistage zonal isolation is crucial for both reservoir creation and control of seismic risks. Control of seismic risk can be achieved by limiting the radius of each of the stimulated fracture surfaces to a few hundred meters. The fundamental consideration leading to this approach is based on observed data from many projects all over the world showing a clear correlation between the stimulated fracture plane areas and the seismic magnitudes (Fig. 3). This correlation was also confirmed by detailed numerical modeling studies.

A schematic representation of the massive hydraulic stimulation approach used in Basel compared to the planned multistage stimulation system is shown in Figure 4. The planned borehole completion of the sub-horizontal wells allows control of pressures and flow rates within individual stages during hydraulic stimulation as well as during operation. This ability to control is believed to be crucial for the creation of an economic EGS reservoir and to control induced seismicity.

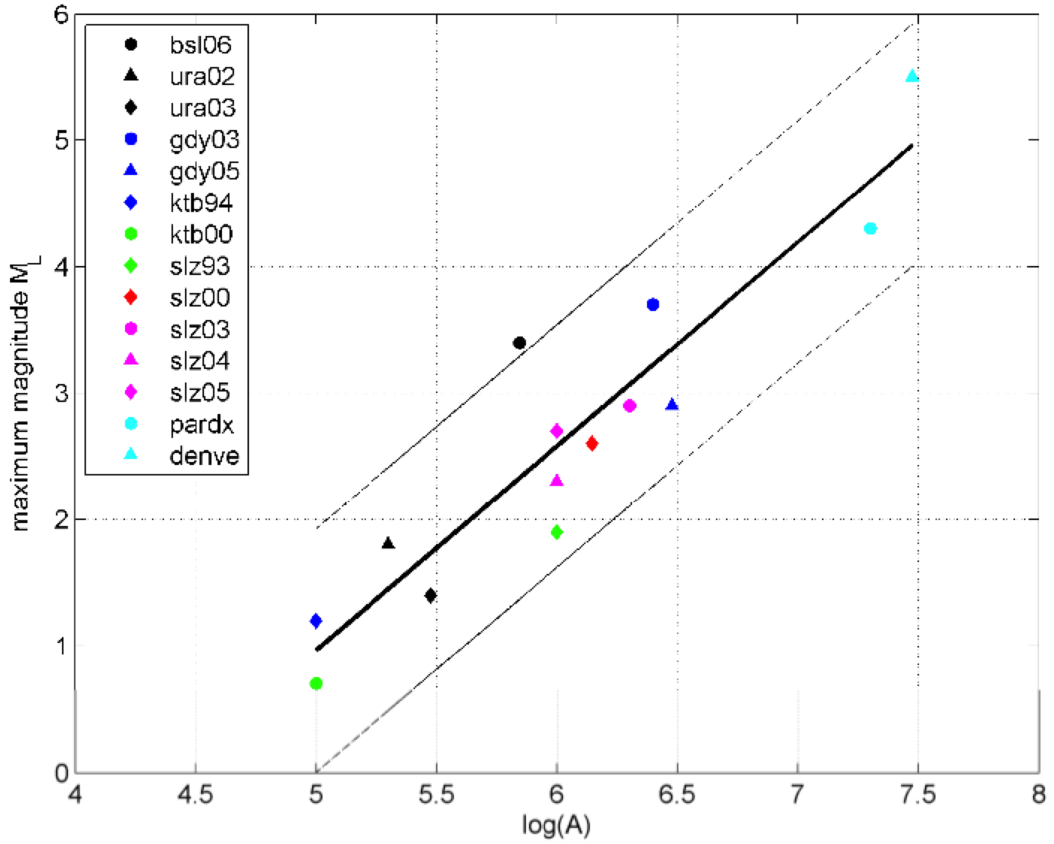

Figure 3: Maximum magnitude (M_L) as a function of the logarithm of the seismically active area for the injection experiments (Figure from Serianex risk study (Baisch et al., 2009); bsl: Basel, ura: Bad Urach, gdy: Australia, ktb: Germany, slz: Soultz-sous-forêts, pardx: paradox valley, denv: Denver)

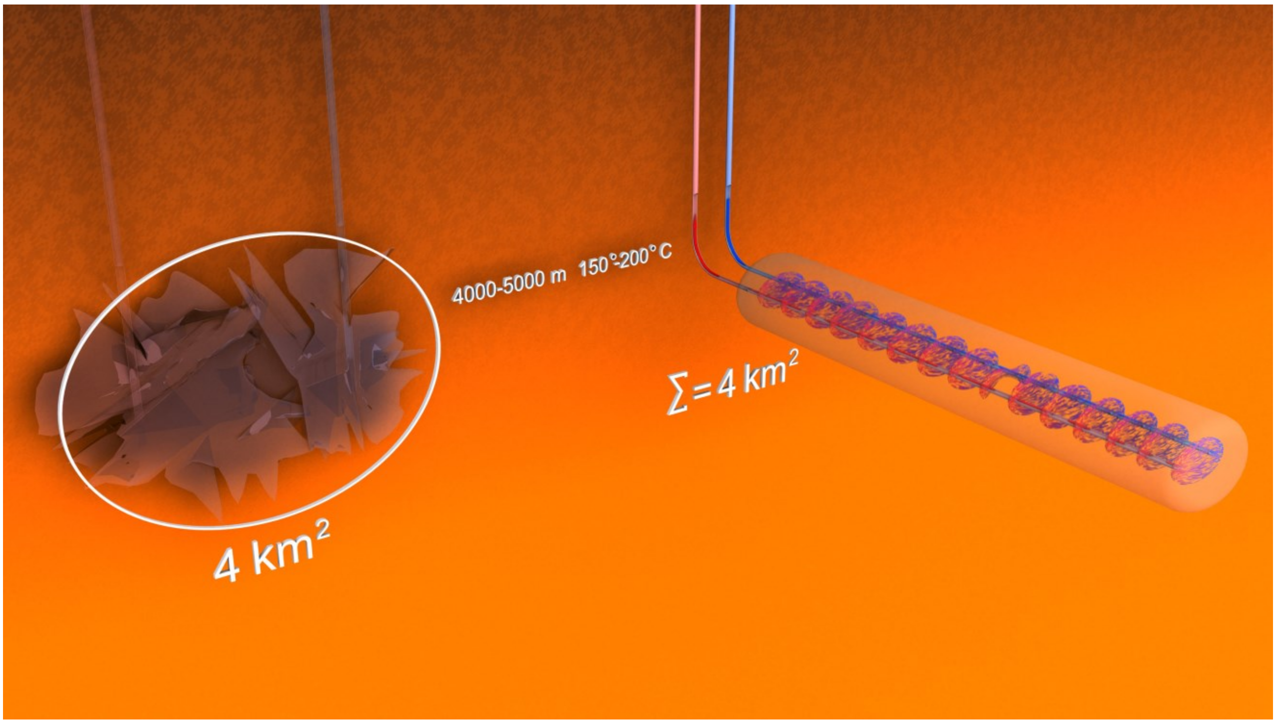

Figure 4: Schematic representation of the massive hydraulic stimulation concept like in Basel (left) in comparison to the multistage stimulation concept planned for future EGS projects in Switzerland (right)

3. THREE SITE SELECTION CRITERIAS TO AVOID SEISMIC RISKS

For the site selection of the pilot projects we followed three underling premises for the reduction of seismic risks. First the site shall be located in an area with a relative small population density. Second the natural seismicity shall not be elevated. And third the reservoir shall A) not intersect a large fault zone following the recommendations of Zoback (2012) and B) not lie closer than one kilometer to major fault zones thus avoiding possible thermal induced geo-mechanical instabilities on these large fault planes during the operational phase of the power plant due to cooling the surrounding rock mass around the reservoir.

For the screening of possible locations we used a risk map of Switzerland (Fig. 5) showing the exposure to natural seismic risks thus taking into account the criteria of small population density and low natural seismicity. Within the suitable areas (greenish) major fault zones were identified based on existing geophysical and geological data to keep the necessary safety distance of at least one kilometer to the reservoir.

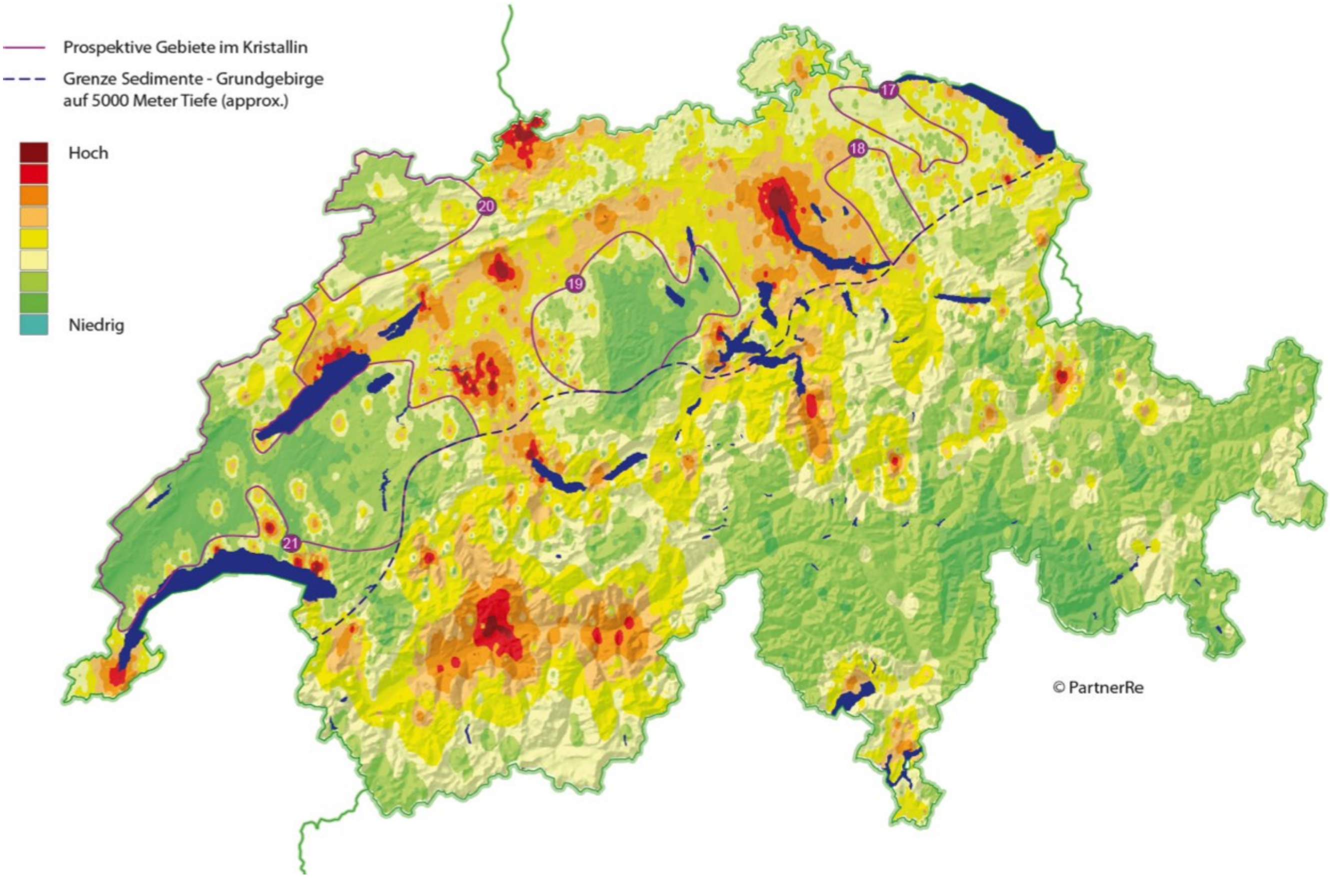

Figure 5: Map showing the exposure to natural seismic risks. The screening for adequate sites concentrated on the greenish and light yellowish areas of the Molasse basin.

4. ADVANCED PROBABILISTIC TRAFFIC LIGHT SYSTEM

The stimulation of an Enhanced Geothermal System (EGS) involves the injection of a fluid at high pressure, which induces seismicity and enhances permeability. Although to date there is no recorded instance of a significant danger or damage associated with induced seismicity related to geothermal energy production, induced seismicity is an important topic that needs to be coped with because the occurrence of a large magnitude event causing damages cannot be fully excluded. Two pillars for the reduction of seismic hazard are (1) the real-time monitoring of induced seismicity and (2) the application of reactive systems to cease the injection as a response to seismicity, termed "traffic light systems" or simply TLS. Generally, TLS are reactive and deterministic, e.g., the injection is stopped if a pre-defined threshold magnitude is exceeded. Rarely, TLS are probabilistic, e.g., the injection is stopped if the exceeding probability of a certain magnitude is high. Adding such criteria confers the TLS with forecasting capabilities, thus becoming an Advanced Traffic Light System, or ATLS. Such a system has been developed by the Swiss Seismological Service and has been calibrated using the data from the Basel project (Goertz-Allman and Wiemer, 2013; Gischig and Wiemer, 2013, Mena et. al. 2013).

In this work, we assume rock properties of the crystalline basement of the DHM project in Basel because (1) no available data exist for Haute-Sorne, (2) other available data sets in granitic formations are scarce and most often not publically available and, more importantly, (3) the Basel granite defines an extreme scenario regarding the strength of induced seismicity (Baisch et al., 2009). Therefore, the calculations presented here are considered conservative with respect to seismic hazard. It is also assumed that the multi-frac stimulation of parallel fractures is a succession of independent stimulations of individual fractures (i.e., individual hazards are multiplied). This approach leads to an overestimation of seismic hazard, as the stimulation of a fracture alters the stress field at the surroundings, theoretically leading to (a) smaller shear stresses, (b) smaller differential stresses and (c) higher effective stresses. These three effects reduce both the frequency and magnitudes of induced seismicity at neighboring fractures.

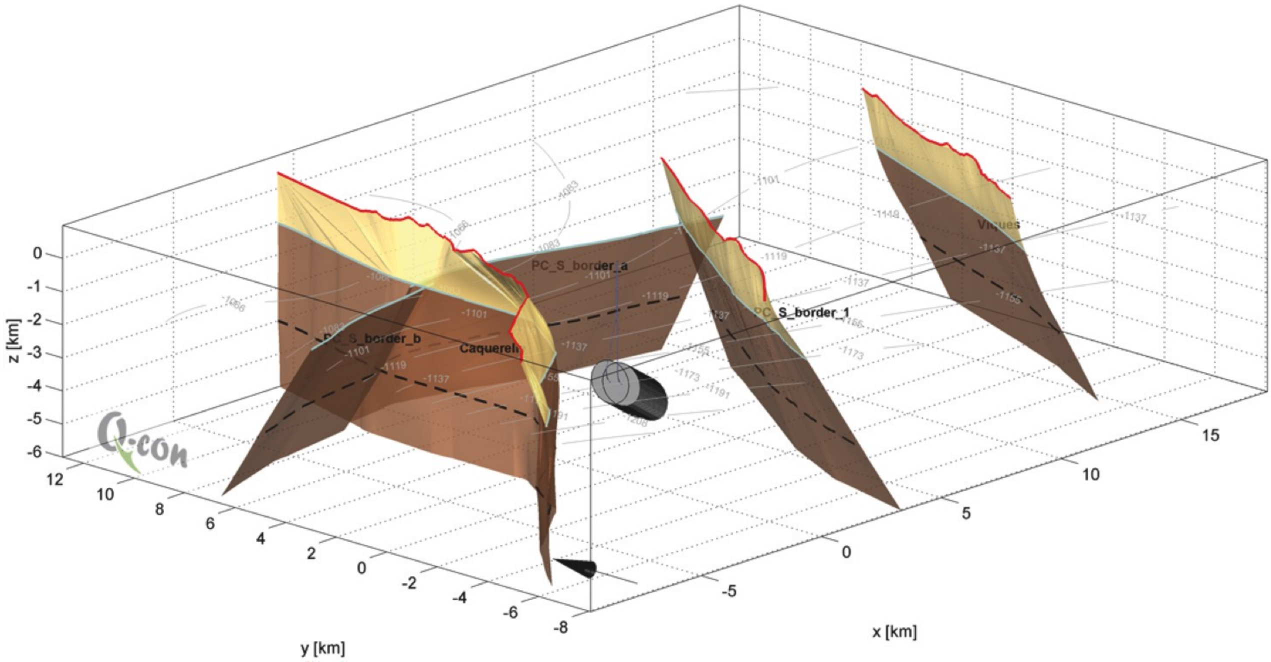

Figure 6: 3D-representation of major fault zones at the community of Haute-Sorne. The reservoir (grey area in the center) keeps a safety distance of over one kilometer from these fault zones.

In this study we explore the role of the different stopping criteria defining the traffic light system during hydraulic stimulation. To that end, we evaluate the seismic hazard associated with the stimulation of a single fracture at a depth of 4500m. Four stopping criteria involving increasingly stricter criteria are evaluated:

(1) Basel injection history, implying the occurrence of a magnitude M_L= 2.8 event, that lead to a shut-in after approx. 6 days of injection. The equivalent stimulation radius results in ~ 700 m.

(2) Design criteria Geo-Energie Suisse Ltd.: The injection is stopped if an equivalent radius R = 300 m is reached. The target is reached within 3-4 days. This is a simple engineering criterion that defines an economically viable heat exchanger.

(3) Adding TLS: The injection is stopped if: (a) an equivalent radius R = 300 m is reached or (b) the maximum observed magnitude exceeds a threshold value M = 2. This threshold magnitude defines the deterministic traffic light system (TLS).

(4) Adding ATLS: The injection is stopped if: (a) an equivalent radius R = 300 m is reached or (b) the maximum calculated magnitude exceeds a threshold value M = 2 or (c) the exceeding probability of a magnitude 2.6 is larger or equal than 5%. The latter defines an Advanced Traffic Light System (ATLS). Such a combination of criteria is deterministic (the injection is stopped if "something happens", i.e., M = 2) and probabilistic (the probability that "something will happen" exceeds a threshold value). Shut-in occurs after ~ 3 days.

A set of 1000 simulations was carried out for each case. The same seed fields were used regardless of the stopping criteria. It was found that the statistics of the calculated induced seismicity (e.g., quantiles of M_{max}) did not vary after approximately 500 simulations. Only the frequency-magnitude distribution of the catalogues is more stable at high magnitudes because these magnitudes are sampled with more frequency. Results are displayed in Figure 7.

The first observation that becomes apparent is the strong effect of area reduction (comparison between black and red curves). The role of stricter criteria defining the traffic light system is observed in the progressive and considerable reduction of hazard (black to red, red to blue and blue to green curves). The magnitude of the event that occurs with a probability of 100% is reduced from 2.8 (no traffic light system) to 2.0 with the strictest criteria (i.e., the simple ATLS presented here). The probability of exceeding the minimum damage threshold in Haute-Sorne (i.e., M = 2.6) drops from 100% (actually 2 to 3 events with $M \geq 2.6$ are to be expected in the absence of traffic light system) to a 12% only. Thus the implementation of a probabilistic traffic light system reduces considerably the seismic hazard. The stricter the ATLS criteria are, the greater the risk reduction is.

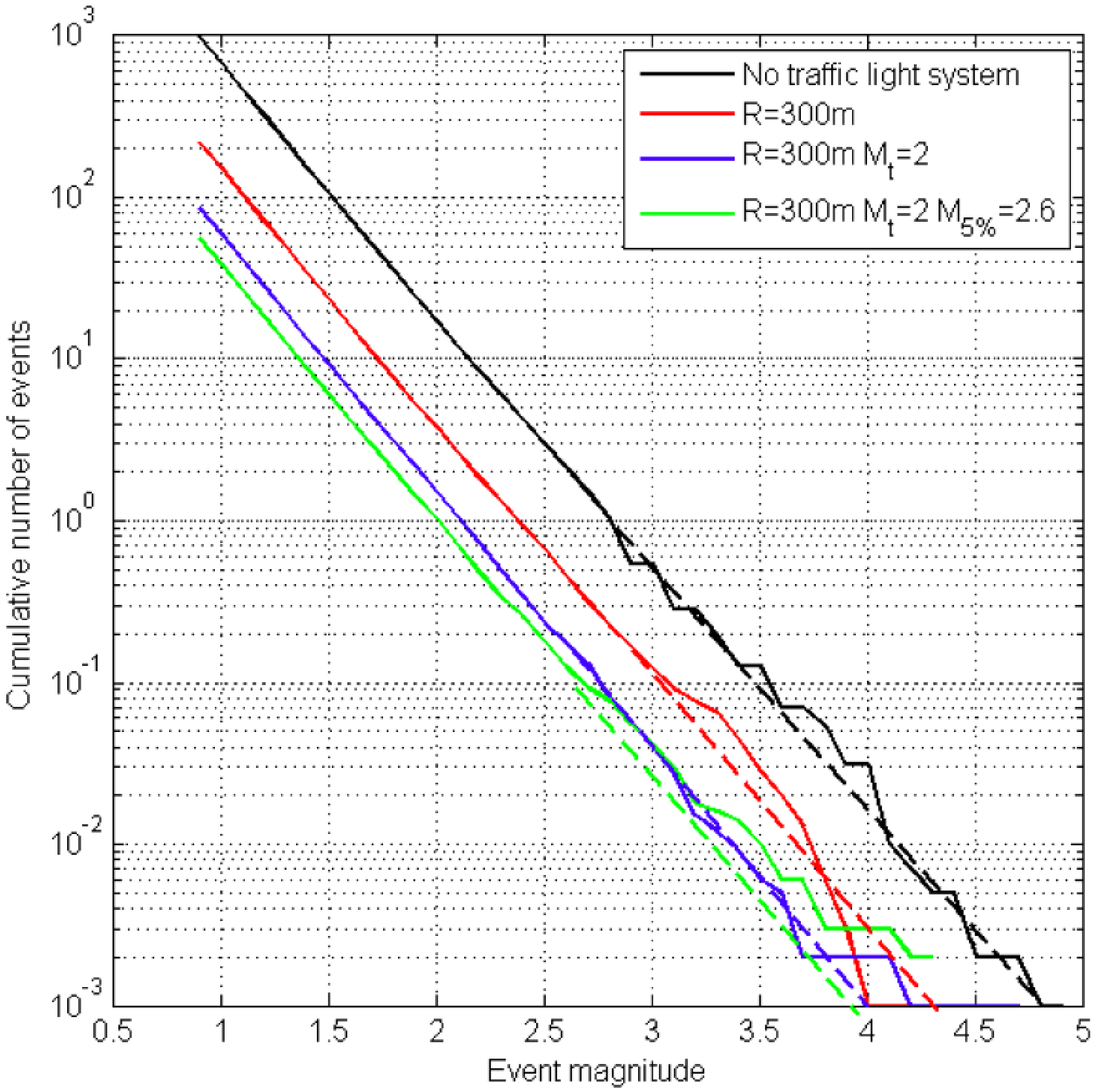

Figure 7: Median frequency-magnitude distributions of 1000 catalogues corresponding to the stimulation of a single fracture at a depth of 4500m. Four distributions involving different traffic light systems are displayed. Dashed lines depict the maximum likelihood extrapolation of the corresponding event sequence. These lines are used to estimate exceeding probabilities of magnitudes larger than 3.0. Beyond this value, the frequency-magnitude distribution deviates from its expected logarithmic behavior, related to the rare sampling of higher magnitude events (statistical effect).

5. CONCLUSIONS

The lessons learnt from the Basel project are significant. Taking into account the risks of induced seismicity in the design and planning of EGS reservoir creation, in the site selection and during reservoir stimulation and operation is mandatory for the development of EGS-projects in Switzerland, which is a densely populated country. Only a combination of a series of measures will lead to effective mitigation of risks of induced seismicity as a prerequisite for obtaining trust of authorities, investors, insurances and hopefully public acceptance.

REFERENCES

Baisch, S., Carbon, D., Dannwolf, U., Delacou, B., Devaux, M., Dunand, F., Jung, R., Koller, M., Martin, C., Sartori, M., Secanell, R., Vörös, R.: Deep Heat Mining Basel - Seismic Risk Analysis. SERIANEX study prepared for the Departement für Wirtschaft, Soziales und Umwelt des Kantons Basel-Stadt, Amt für Umwelt und Energie, http://www.wsu.bs.ch/geothermie, 553 pages. (2009).

Häring, M.O., Schanz, U., Ladner, F., Dyer B.C.: Characterisation of the Basel 1 enhanced geothermal system. *Geothermics*,(2008), doi:10.1016/j.geothermics.2008.06.002.

Mena, B., Wiemer, S., Bachmann, C.: Building robust models to forecast the induced seismicity related to geothermal reservoir enhancement. Bulletin of the Seismological Society of America, 103(1), pp. 383, (2013) doi: 10.1785/0120120.

Gischig, V. S., Wiemer, S.: A stochastic model for induced seismicity based on non-linear pressure diffusion and irreversible permeability enhancement. Geophysical Journal International, (2013) doi:10.1093/gji/ggt164.

Goertz-Allmann, B.P., Wiemer, S.: Geomechanical modeling of induced seismicity source parameters and implications for seismic hazard assessment. Geophysics, 78(1), (2013) KS25–KS39.

Zoback, M.D.: Managing the seismic risk posed by waste water disposal, *Earth,* (2012) pp. 38-43