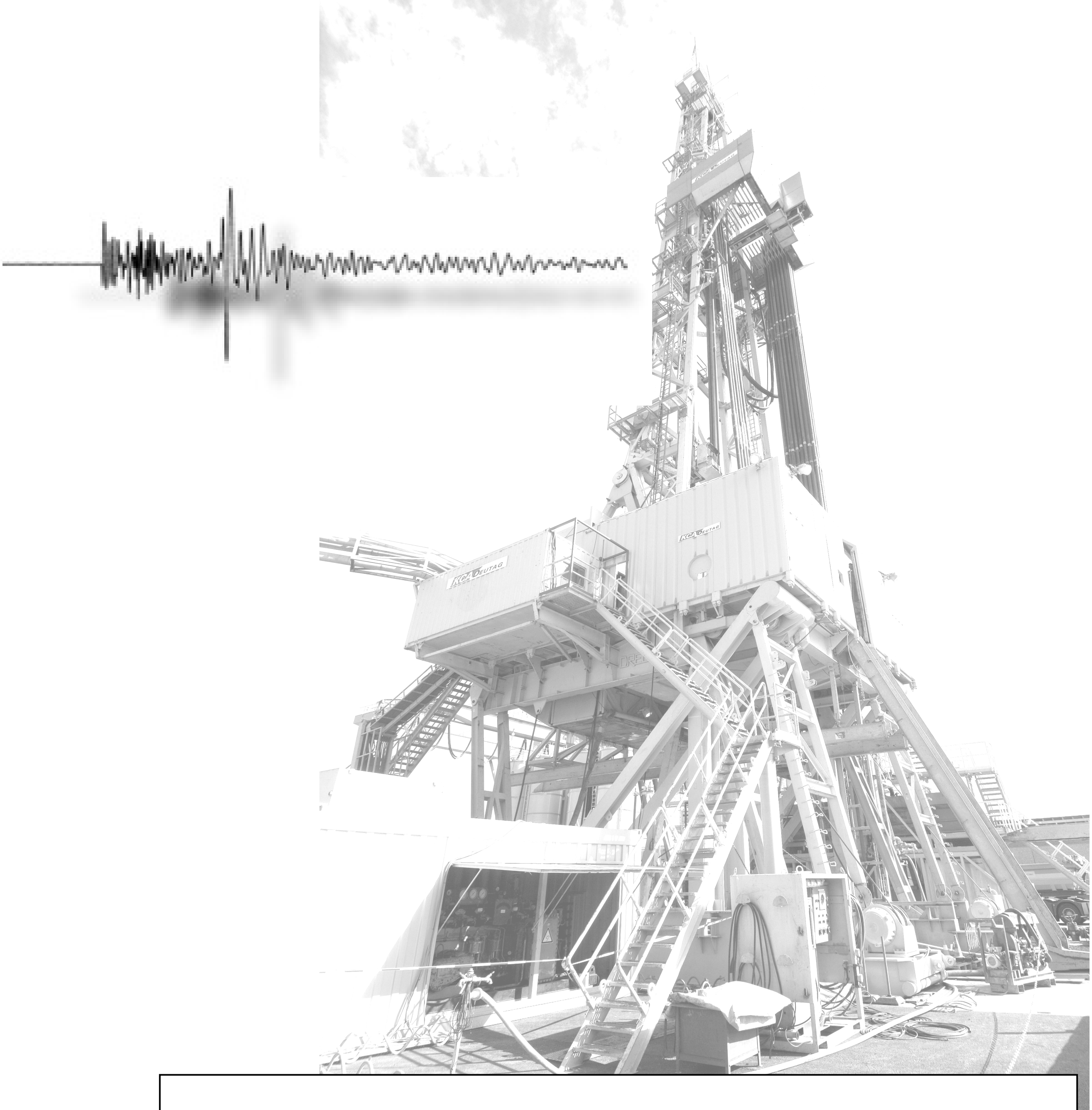

Deep Heat Mining Basel

Seismic Risk Analysis

SERIANEX

Title:	**Deep Heat Mining Basel -** **Seismic Risk Analysis**
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Q-con GmbH	Marktstr. 39 76887 Bad Bergzabern Germany	AP 1000 - Project Management AP 3000 - Induced Seismicity AP 4000 - Triggered Seismicity AP 7000 - Recommendations AP 8000 - Documentation
Bureau d'Etudes Géologiques SA (BEG)	Rue de la Printse 2 1994 Aproz Switzerland	AP 2000 Geological Model
JUNG-GEOTHERM	Gottfried-Buhr-Weg 19 30916 Isernhagen Germany	AP 3000 - Appendix 3 Hydraulic Analysis
GEOTER S.A.S	Pôle Géoenvironnement 3, rue Jean Monnet 34830 Clapiers France	AP 5000 Probabilistic Risk Analysis
RÉSONANCE Ingénieurs-Conseils SA	21 rue Jacques Grosselin 1224 CAROUGE (Genève) Switzerland	AP 5000 - Appendix 2 Assessment of Property Stock
RiskCom	Friedrich-Naumann Weg 38 75180 Pforzheim Germany	AP 6000 Risk Assessment & Communication

CONTENTS

SUMMARY

In the course of the development of an enhanced geothermal reservoir at a depth of about 5 km underneath the city of Basel, a felt earthquake of magnitude M_L = 3.4 was triggered on December 8th, 2006. The operator's insurance paid out property damages of about 7 million CHF, which were attributed to the earthquake. The geothermal project has been suspended since. In the current study, commissioned by the Kanton Basel-Stadt and supported by the Swiss federal government, we assess the seismic risk resulting from continued development and subsequent operation of the geothermal system.

Besides seismicity triggered directly by the geothermal project, the study also considers the impact of the geothermal reservoir on natural seismic activity in the Basel region. The principal issue is to what extent the geothermal project may affect the occurrence of a large earthquake. Such an earthquake caused large damage to the city of Basel in the year 1356.

To analyse the issue, we developed a 3-dimensional geologic model of the subsurface of the Basel region. In the wider vicinity of the geothermal reservoir, eight relevant, natural fault zones were identified, each of them large enough to produce large earthquakes. We estimated the seismic activity of these faults, i.e. the time intervals when large earthquakes could be expected to occur on these faults. We found that the geothermal reservoir can have an impact on the recurrence time of these natural earthquakes by modifying subsurface stresses. But, numerical simulations demonstrate that these variations are very small and represent a negligible risk.

In addition, the development and operation of the project is expected to result in seismic activity in the immediate vicinity of the geothermal reservoir. We developed a numerical model to capture these processes, ran computational simulations and used empirical relations to investigate how future seismic activity might evolve. Given the local conditions, there is a high probability that earthquakes exceeding the strength of previous activity will occur during continued development and operation of the geothermal facility. We expect the biggest event magnitude in the order of M_L=4.5. Further, we anticipate up to 30 felt earthquakes in the development phase, 9 of which might reach or exceed the intensity of the earthquake of December 8th, 2006. Within the operational period of 30 years, we expect 14 to 170 felt earthquakes.

To estimate the associated property damage, we recorded the building stock within a radius of 12 km around the facility. Using probabilistic modelling of the seismic risk we classified buildings according to their vulnerability. Based on expert judgement, we expect no relevant property damages to infrastructural facilities resulting from the induced earthquakes. However, in all likelihood property damage of 40 million CHF is to be expected in case of continued development of the geothermal reservoir. This comprises minor structural damages, which we expect to occur in large numbers due to the high population density. There is a 15% probability, that damages will even exceed 600 million CHF in an extreme case. During the projected facility's operational period of 30 years, the most probable property damage is set at 6 million CHF per year.

While the risk of the geothermal project to cause bodily harm is low, the property damage may be deemed as unacceptable according to risk criteria of the Swiss ordinance on major accidents. We reach the same conclusion also by comparing other technical risks in Switzerland, where in some cases potential cumulative damages are less.

In light of the considerable property damage risk in Basel, we evaluated alternative concepts for developing the geothermal reservoir at its current location. We conclude that none of the concepts considered will completely rule out the occurrence of earthquakes. Therefore, alternative utilization concepts at this location will require a separate risk assessment.

From a seismic risk perspective, the location of Basel is unfavourable for the exploitation of a deep geothermal reservoir in the crystalline basement. Other locations in Switzerland may offer a significantly lower seismic risk. A thorough evaluation of site-specific seismic risk should be required for future geothermal project developments in Switzerland. The findings of this Basel study constitute an important data point for future risk assessments. After analyses of the data acquired from the suspended project and after comparison with experiences made in other geothermal projects, we consider the Basel earthquakes caused by the geothermal project to have been exceptionally strong.

OVERVIEW

Background

An earthquake of magnitude $M_L = 3.4$ was triggered on December 8th, 2006, in the course of the development of a geothermal reservoir at a depth of around 5 km underneath the city of Basel. This earthquake was clearly felt in the city and was also associated with a loud bang. The operator's insurance subsequently paid out property damages of about 7 million CHF.

After the earthquake of December 8th, 2006, the further development of the geothermal system was initially suspended and this risk study was commissioned by the Kanton Basel-Stadt.

Objective

In this study we assess the seismic risk resulting from continued development and subsequent operation of the geothermal system. The objective of the study is to provide a scientific basis for the appraisal of the acceptability of risks related to the geothermal facility.

We have distinguished two types of seismic risk. On the one hand, we consider earthquakes within the reservoir that are directly related to continual development and the subsequent operation of the geothermal facility (induced seismicity). On the other hand, we investigate to what extent the operation of the geothermal facility affects natural seismic activity in the Basel region (triggered seismicity). In particular, we analyse the impact on the recurrence time of large earthquakes, such as the Basel earthquake of 1356. The resulting seismic risks are quantified in terms of damage to persons and property damage. We list recommendations on how to proceed with the Basel geothermal project based upon a comparative risk assessment.

Outline

This study comprises six work packages, each of which contains a final report that is appended to this summary document. Here, we summarize the key findings of the work packages.

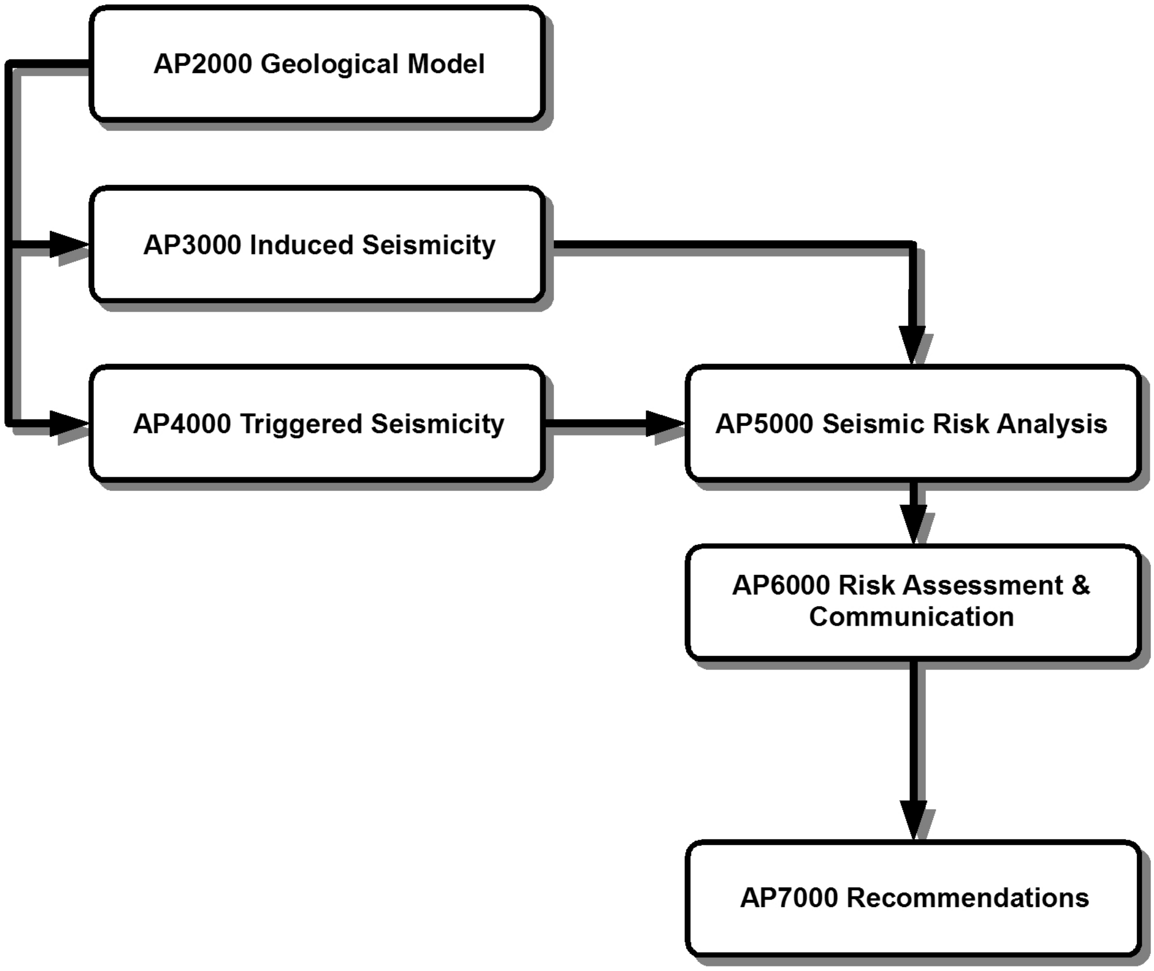


Figure 1: Schematic outline of the study.

SEISMIC RISK STUDY - ABSTRACT

To assess the seismic risk resulting from further development and subsequent operation of the geothermal facility it is essential to understand the natural processes causing changes in the subsurface. Seismic risk, associated with the geothermal facility, can be fully understood only by considering interactions with such natural processes.

Natural deformations within the Earth's crust (plate tectonics) generally result in the accumulation of stresses in the subsurface over time. Stresses are usually relieved by an earthquake when a critical threshold value is exceeded. Subsequently, stresses again accumulate, thereby completing a cycle of recurring earthquakes and continued deformation processes.

Earthquakes occur along zones of weakness, so-called faults. In these zones, adjacent blocks of rock are dislocated relative to each other during an earthquake. The strength of an earthquake (magnitude) increases with the size of the affected zone. Therefore, it is necessary to identify large, natural fault zones surrounding the geothermal facility and evaluate the natural stress accumulation on those faults.

We have summarized the current state of knowledge regarding local geology and natural fault zones based on numerous publications of data from previous studies. The state of knowledge is characterised by the fact that the existence, extent and orientation of the faults are mostly based on assumptions. Some faults do crop out at the surface and can therefore be mapped and investigated. Their extent with depth, however, is often interpreted with uncertainty. For example, the fault which caused the large earthquake of 1356, resulting in serious damage to the city of Basel, has not yet been identified, in spite of extensive research.

Taking these uncertainties into account, we have compiled a model of natural seismic activity for the Basel region by considering all known fault zones in the vicinity of the geothermal location a potential source for large earthquakes. Figure 2 depicts the position of the eight most important faults identified in this respect, with the largest fault extending over a distance of about 40 km. Of the eight fault zones depicted in Figure 2, six are sufficiently large enough to host significant earthquakes similar in magnitude to the event of 1356.

Due to poor constraints on the depth of the fault zones in Figure 2, we have estimated a maximum depth for each fault zone utilizing existing records of earthquakes. Frequently occurring, smaller earthquakes define the maximum depth at which the rock can still accumulate sufficient stresses. At the same time, earthquake records suggest the orientation and rate of natural deformation processes in the subsurface.

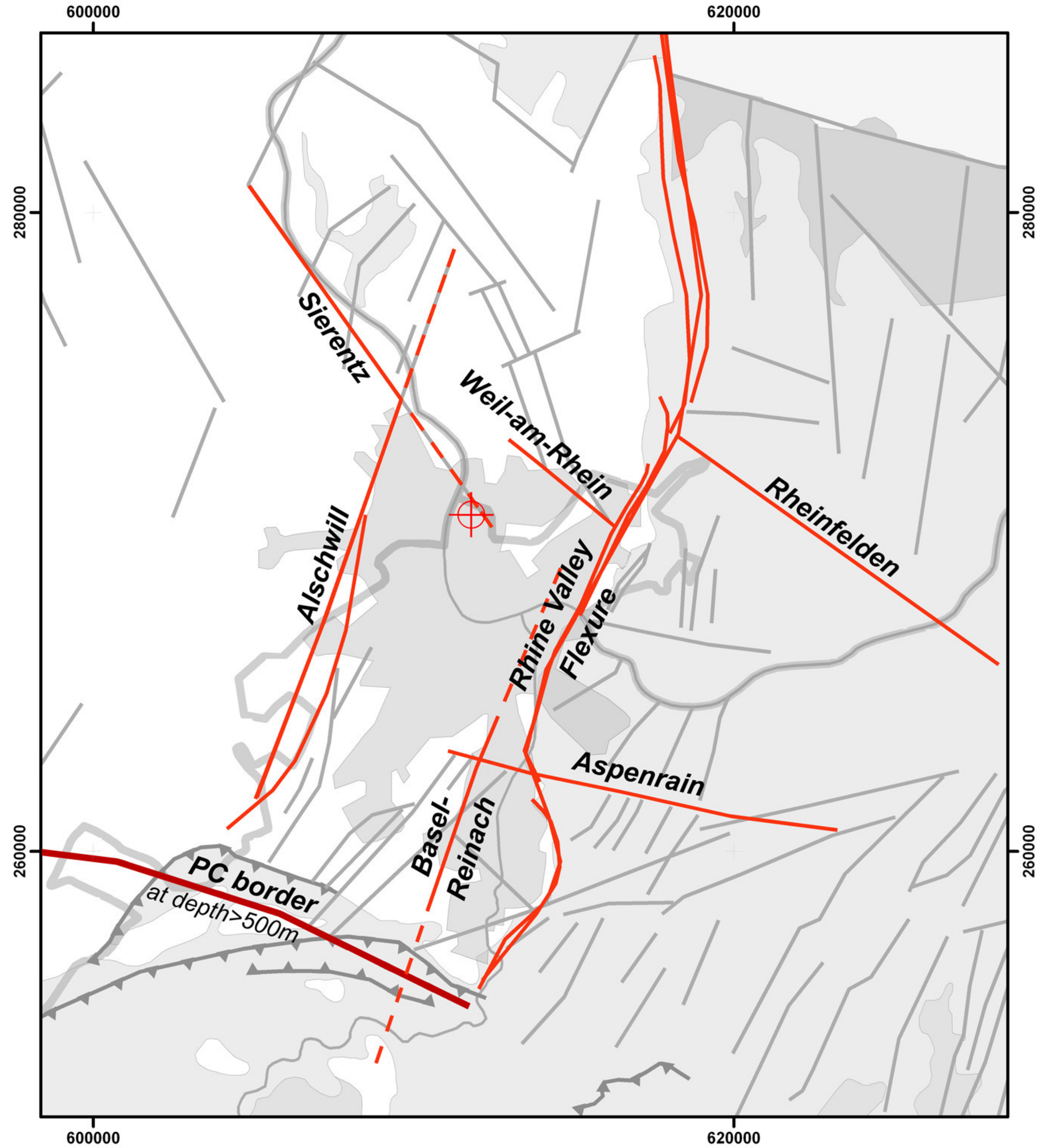


Figure 2: Map of the eight most important, natural fault zones in the vicinity of the geothermal location. The geothermal location itself is marked by cross lines. See Appendix 2000 for further details.

In addition to the model for natural seismic activity, we also developed a model to predict those earthquakes that are potentially generated by the geothermal system (induced seismicity). During the fluid injection of December 2006, the additional hydraulic pressure produced local stress changes in the subsurface that in turn triggered a large number of small earthquakes. The deformational processes associated with these earthquakes caused an increase in hydraulic conductivity. Thus, defining the locations of the small earthquakes traces the dominating water flow paths in the subsurface.

We derived a geometrical model of the artificially generated geothermal reservoir based on the 3-dimensional localization of these earthquakes. This model consists of a small number of larger fractures with increased hydraulic conductivity. In an extreme case, these can be combined within data accuracy to a single fracture with a surface area of about 0.75 km^2. Data, acquired during fluid injection, indicate that the activated fracture(s) already existed as a zone of weakness of natural origin and their conductivity was increased by several magnitudes due to the fluid injection of December 2006. In contrast, the adjacent rock matrix exhibits no significant hydraulic conductivity.

Based on these observations, we developed a computer model to simulate the propagation of hydraulic pressure and the associated seismic activity. The computer model relies on fundamental physical processes and was deliberately kept simple. Despite its simplicity, the model successfully reproduces the relevant observations during the fluid injection of December 2006. In particular, the largest magnitude earthquakes occur only immediately after fluid injection, and seismic activity continues over several months.

Further development and subsequent operation of the geothermal system was also simulated based upon this computer model. For example, Figure 3 depicts a model of such a system with a production well for the extraction of hot water, and an injection well where the cooled water is returned into the geothermal reservoir.

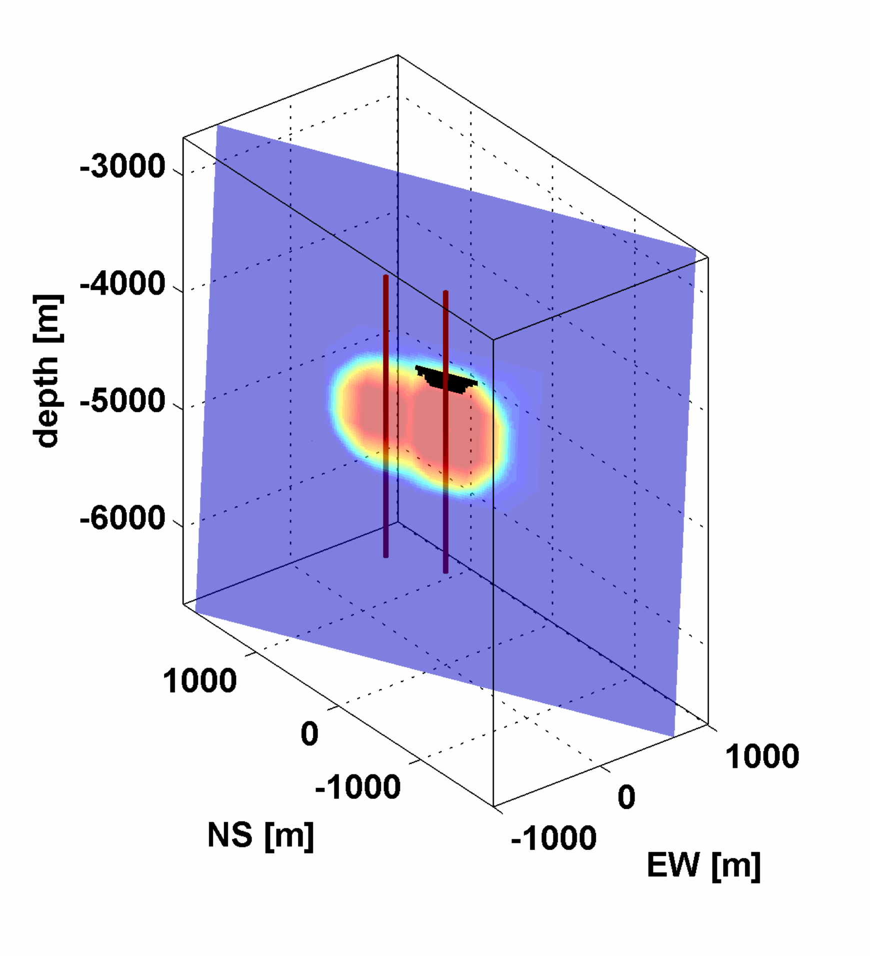


Figure 3: Computer simulation of the extension of the geothermal system. Warm colours indicate areas with increased hydraulic conductivity. In addition to the existing well (vertical line to the right), a second hypothetical well was placed at a distance of 500 m (vertical line to the left). The area marked in black indicates the region where the computer simulation of the water injection of 2006 produced the largest magnitude earthquake. See Appendix AP3000 for details.

The computer simulations predict a high probability for the occurrence of earthquakes when the geothermal system is further developed and operated. The strength of these earthquakes may exceed the already observed seismic activity, and we expect the maximum event magnitude to be in the order of M_L=4.5. Furthermore, we anticipate up to 30 felt earthquakes in the development phase, 9 of which with a similar or even greater strength compared to the December 2006 induced earthquake. In addition, during the operational period of 30 years, we predict 14 to 170 felt earthquakes.

In order to conduct an independent assessment of future seismic activity, we additionally looked into the data of comparable geothermal projects. From this data we derived an empirical correlation between the size of a geothermal reservoir and the maximum strength of associated earthquakes. In accordance with the results of the computer simulations, this relation also suggests comparatively strong earthquakes in the development phase. The upper limit of magnitude in this empirical model, however, is slightly lower (between M_L=4 and M_L=4.5).

Notably, both independent analyses result in a similar strength of predicted earthquakes. There is, however, a large discrepancy between the two analyses with respect to the frequency of occurrence of stronger earthquakes during the operational phase. According to computer simulations, the strength of seismic activity depends largely on whether fluid pressure is decreased at the outer boundaries of the reservoir during long-term operation. The strength of seismic activity decreases with increasing depressurization, and there is a high probability for the occurrence of pressure release within the Basel geothermal system. It was not possible, however, to sufficiently quantify depressurization within the relatively small observation period in December 2006. Therefore, we decided to run the computer simulations without accounting for pressure releases. This means that the results in the simulations tend to overestimate seismic activity. On the contrary, the empirical relations tend to underestimate seismic activity due to the underlying assumption that the reservoir does not grow during the operational phase. Such an assumption is not generally realistic as reservoir growth cannot necessarily be prevented. As a result, one can expect an actual seismic activity in between the range specified by the two independent methods, and we have considered both results in the subsequent risk assessment.

In addition to the directly induced seismicity, we also assessed the impact of the geothermal project on natural seismic activity in the Basel region. Stresses in the subsurface will be changed during the development and operational phase of the geothermal facility. These changes are partially associated with deformational processes within the reservoir, especially during the development phase. Stresses are also affected by the additional fluid pressure and the gradual cooling of the reservoir. The combination of such changes may have an impact on the natural cycle of stress accumulation and stress release in the area.

We ran computer simulations, based on the derived models, to calculate these stress changes. Figure 4 depicts the stress changes on the largest surrounding fault (Rhine Valley Flexure), related to a 30 year operation period of the geothermal facility. Some areas on the fault exhibit increased stresses (red colours), corresponding to a higher seismic risk. At the same time there are areas exhibiting decreased stresses (blue colours), which are synonymous with a lower seismic risk. To have a significant impact on the occurrence of a large magnitude earthquake, these changes must be effective over a significant area. Such an area is in the order of 100 km^2 for an earthquake with magnitude M_w=6.5.

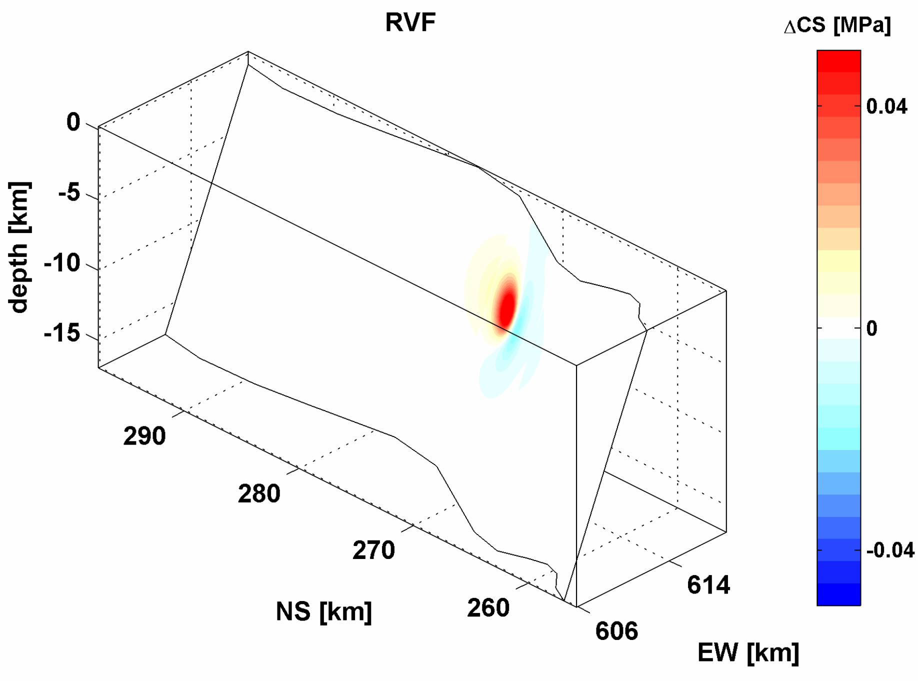
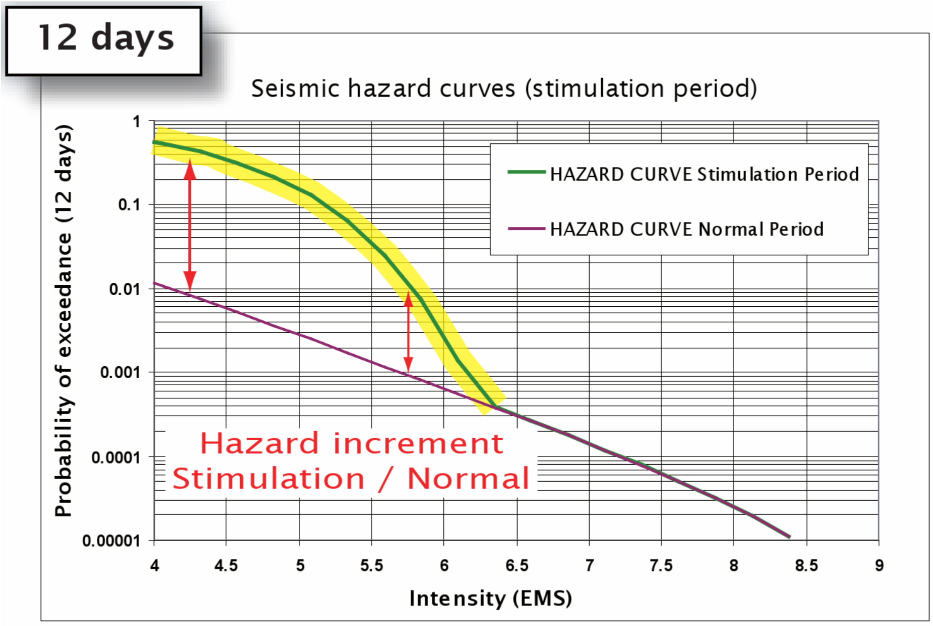


Figure 4: Example of relative stress changes on the largest fault of Figure 2 after operating the geothermal facility over 30 years. Red colours indicate stress increase, blue colours stress decrease. For further details see Appendix AP4000.

We ran corresponding computer simulations for all surrounding faults. The parameters were systematically varied in order to account for the remaining uncertainties of the various model parameters. The resulting multitude of possible models yields a wide range of stress variations. They all have in common, however, that the order of magnitude of these variations is too small to have a significant impact on the recurrence cycle of large earthquakes. The development and subsequent operation of the geothermal facility therefore has a negligible impact on natural seismicity.

The negligible aspect of the geothermal facility on natural seismicity becomes especially obvious in a probabilistic modelling of the seismic risk. In such models, we calculate the probability for an earthquake of a given intensity to occur, whereas intensity is a measure of the impact of an earthquake at the surface. Compared with natural seismic activity, the only additionally increased probability for the occurrence of earthquakes is for those in the range of relatively low intensities (Figure 5).

The geothermal reservoir has the largest impact on seismic hazard during the development phase. The natural seismic hazard in the immediate vicinity of the geothermal facility is exceeded by a factor of 50 during this period. This additional hazard decreases with distance from the geothermal facility. At a distance of 15 km, the additional hazard is reduced to 7 times the natural hazard.



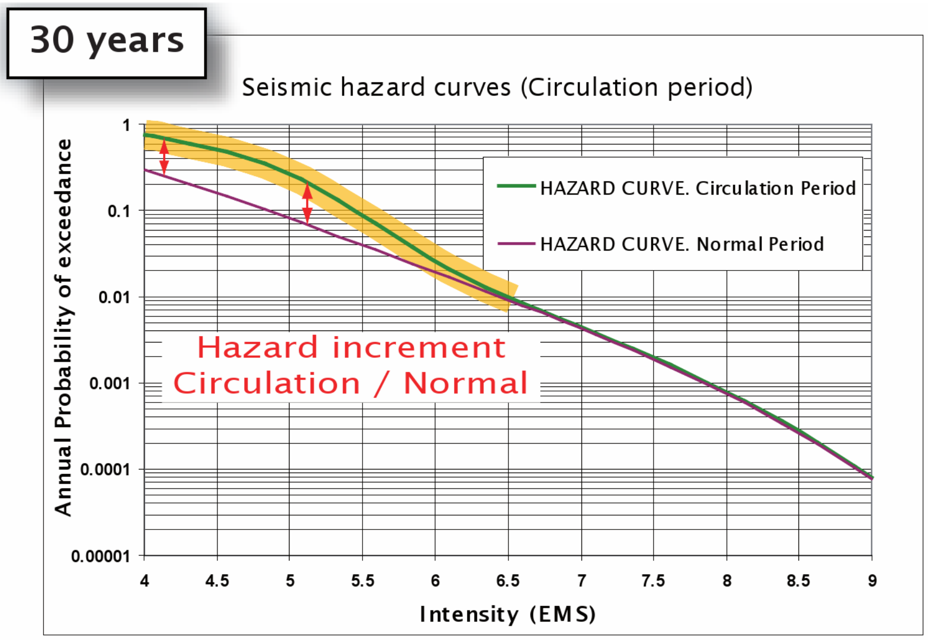


Figure 5: Modelling the probability of exceedance of earthquake intensity at the geothermal facility. The upper diagram displays the probability of exceedance during a 12-day development phase. The lower diagram shows the probability of exceedance within one year of a 30-year operational phase. The corresponding probabilities for natural seismic activity are depicted for comparison. The probabilities depicted in this figure are related to a location in the immediate vicinity of the geothermal facility. For further details see Appendix AP5000.

Having investigated the impact of the geothermal reservoir on the variation of seismic activity, we also assessed potential damages related to seismicity. To estimate possible related damages, we surveyed the building stock within a radius of 12 km around the facility. After classifying the buildings with respect to their vulnerability, we modelled the probability of exceedance of a given property damage. The relations were calibrated with the compensated property damages associated with the earthquake of December 8th, 2006.

Our estimates predict property damage in the order of 40 million CHF to be expected in case of continued development of the geothermal reservoir. Such damages are comprised of minor, non-structural damages, which we expect to occur in large numbers due to the high population density. There is a 15% probability that damages might even exceed 600 million CHF in an extreme case. During the projected facility's operational period of 30 years, the most probable property damage is set at 6 million CHF per year. Based on expert judgement, we do not expect relevant property damages to infrastructural facilities to result from the induced earthquakes.

We also analysed the risk of damage to persons, caused by property damages such as collapsing buildings. We consider this risk related to the geothermal facility to be negligible compared to the natural seismic risk of the area.

The risk of damage to persons and property damage are both outside the boundaries of risk criteria defined by the Swiss ordinance on major accidents (Figure 6). The objective of this ordinance is to protect population and environment against exceptional, rare events in installations causing serious damages, whereas the geothermal project can be expected to cause only minor personal damage. This risk is below the threshold of severe societal risk according to the criteria of the Swiss ordinance on major accidents. The expected property damage, however, is deemed unacceptable according to these criteria in terms of both frequency of occurrence and value of damage. We reach the same conclusion by comparing to other technical risks in Switzerland, where in some cases potential cumulative damages are less.

In light of the considerable property damage risk in Basel, we evaluated alternative concepts for developing the geothermal reservoir at its current location. We assume that additional development (hydraulic stimulations) is required to improve the low hydraulic conductivity and productivity of the reservoir to ultimately make the project economically viable. Any development activity will inevitably be accompanied by seismic activity.

We did not asses the seismic risk related to the development and exploitation of a shallow hydrothermal reservoir, utilizing the existing well. It is worth mentioning that in Riehen, a geothermal facility nearby has been utilized for thermal energy production for 15 years at a depth range of 1500 m. There is no known seismic activity that can be attributed to this facility. We note that alternative utilization concepts at the Basel location require a separate risk assessment.

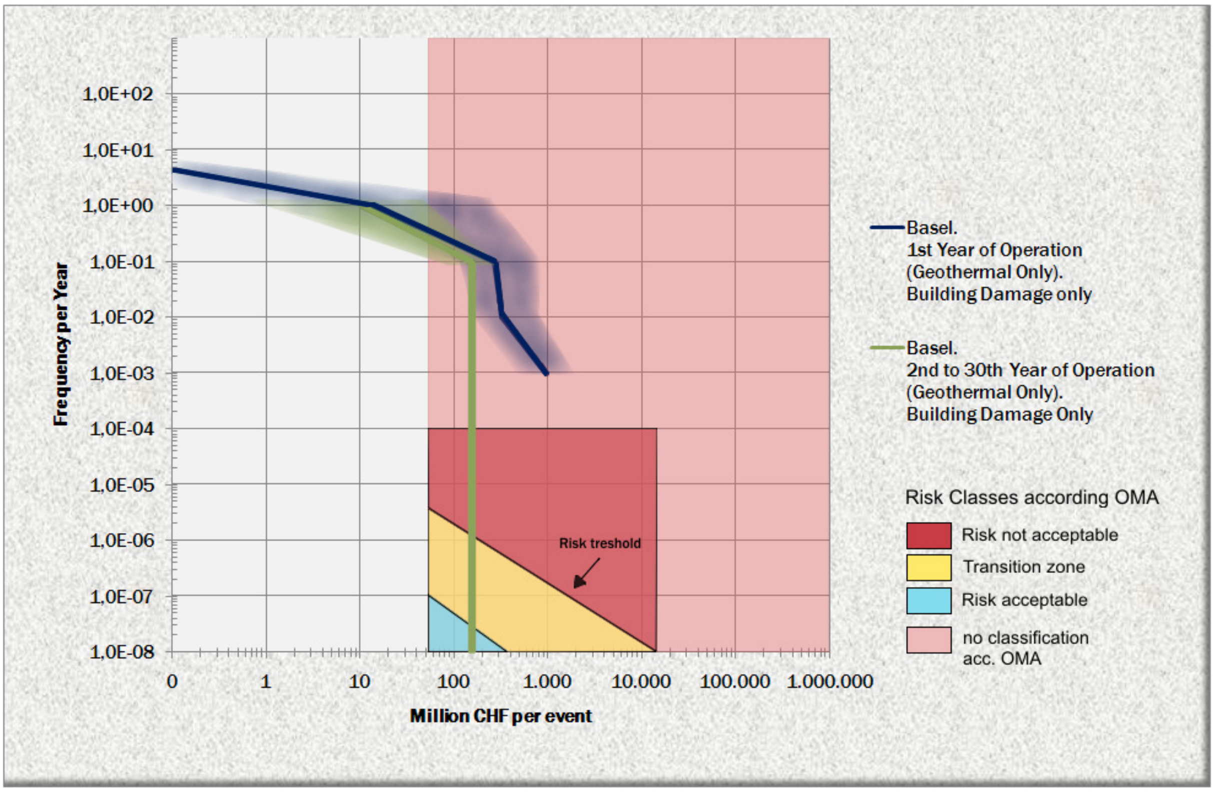


Figure 6: Risk appraisal according to the Swiss ordinance on major accidents (OMA). For the first year of operation, damages related to the development phase have also been considered. Therefore, the damage frequency in the first year (blue line) is larger than in the following years (green line). See Appendix AP6000 for further details.

From a seismic risk perspective, the location of Basel is unfavourable for the exploitation of a deep geothermal reservoir in the crystalline basement. Other locations in Switzerland may have a significantly lower seismic risk. A thorough evaluation of site specific risks should be required for future geothermal project developments in Switzerland. The findings of this Basel study constitute an important data point for future risk assessments. After analyses of the data acquired by the suspended project and after comparison with experiences made in other similar geothermal projects, we consider the Basel earthquakes caused by the geothermal project as exceptionally strong.

GLOSSARY

Expression	Explanation
Fault	A planar fracture surface in the subsurface in which the rock on one side of the fracture has moved with respect to the other side.
Fault Zone **Zone of Weakness**	Zones of complex deformation associated with faults in the subsurface.
Induced Earthquake	Seismic activity within the geothermal reservoir caused by developing and operating a geothermal facility or any other structure (hydroelectric dams, oil and gas installations, waste injections etc.).
Magnitude	Measure for the size of an earthquake. Magnitudes are usually derived from the amplitudes (less frequently by other parameters) of a seismogram. The local magnitude M_L is generally known as the magnitude on the Richter scale. The moment magnitude M_w utilized in the appendices is commonly used in scientific research.
Major Accident **Prevention of Major Accidents**	Exceptional events occurring at installations or traffic infrastructure having a considerable impact off-site or on the infrastructure (deaths or injuries among population, air or water pollution, soil contamination etc.). In Switzerland, the protection of the population and the environment is based on the Swiss Ordinance on Major Accidents (OMA). The legal basis is given by the article on civil protection of the Environment Protection Law (Art. 10 USG). The Swiss Ordinance on Major Accidents specifies this legal article in respect to its practical implementation.
Probabilistic Modelling **Risk Assessment**	Methods for quantitative risk assessment with the objective to estimate the probability of occurrence of a hazardous incident within a risk-scenario.

Seismic Hazard	Seismic hazard is a measure for the occurrence of an earthquake of given size at a given location within a specified period of time.
Seismic Intensity	Qualitative classification of the size of an earthquake on a scale from 1 to 12. The scale quantifies the effects of an earthquake on the Earth's surface, humans, objects of nature, and man-made structures. The EMS-98-scale is the most commonly used scale (European Macroseismic Scale 1998).
Triggered Earthquake	Natural seismic activity that may be triggered by developing and operating the geothermal facility.
Vulnerability	Here: Quantitative estimate of the loss susceptibility of one or more buildings of the same type with respect to earthquakes of variable intensity.

APPENDIX

CONTENTS

Report	Title
AP 2000	**Structural model of potential seimogenic faults**
AP 3000	**Induced seismicity**
AP 4000	**Triggered seismicity**
AP 5000	**Seismic hazard and risk assessments during three reference time periods (normal, stimulation and circulation)**
AP 6000	**Technology risk comparison of the geothermal DHM project in Basel, Switzerland - Risk appraisal including social aspects**
AP 7000	**Recommendations**