DEEP HEAT MINING Basel, Preliminary Results

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Abstract

Geopower Basel-AG, a partnership of eleven public and private enterprises, endeavours to develop a geothermal cogeneration plant in Basel from an enhanced geothermal system. Basel, situated at the south-eastern margin of the Upper Rhinegraben has been selected as a suitable location for a pilot plant due to three favourable criteria: public and political willingness, favourable infrastructure (district heating grid, river cooling) and elevated heat flow. A refined microseismic monitoring system has been installed prior to drilling wells to a target depth of 5'000 metres, not only for visualizing microseismic acitivity during hydraulic stimulation, but also to observe the natural seismicity in this area of increased seismic hazard. The hydraulic stimulation process in well Basel-1 was stopped after six days when high seismic activity built up with magnitudes up to M 2.7. Four hours after shut in a seismic event of M 3.4 happened coinciding with the start of bleeding off to hydrostatic. Within 55 days after stimulation three after shocks with M >3 were recorded. The project has been suspended but not abandonned until further insight into the focal mechanisms is available and acceptable ways of reservoir enhancement become applicable.

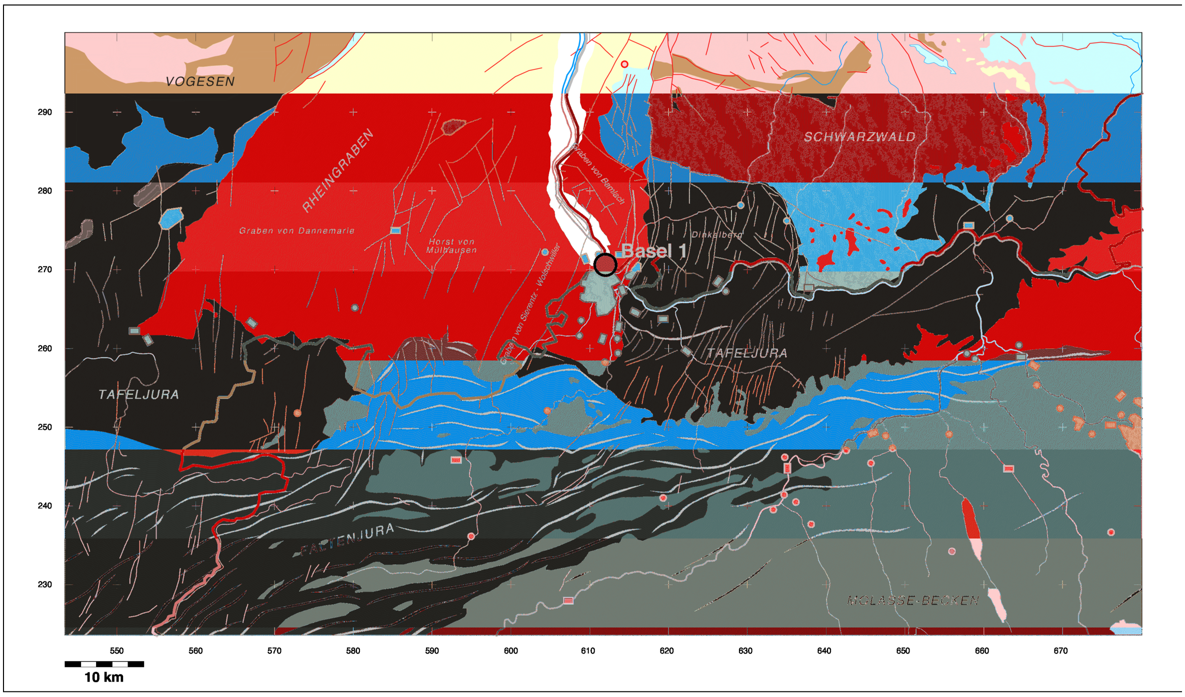
Introduction

Geopower Basel AG, a partnership of eleven public and private enterprises, endeavours to develop a geothermal power plant in the city of Basel from an Enhanced Geothermal System. The reservoir target is at 5 km depth in the crystalline basement with an expected formation temperature of 200°C. The goal is to develop an economically viable pilot plant for the cogeneration of heat and power based on a three well concept. According to results from production tests, two wells would be used as producers and one well as injector. The selection of a suitable power conversion cycle will be made depending on the production test results. The target is to produce about 30 GWh/a electricity to the grid and 48 GWh/a of heat for the local district heating grid.

In 2001 a reconnaissance well of 2755 m (Otterbach 2) assessed the sedimentary sequence, the temperature gradient and the stressfield in the granite. Well Otterbach 2 was designed to be used later as the key monitoring well of the microseismic system.

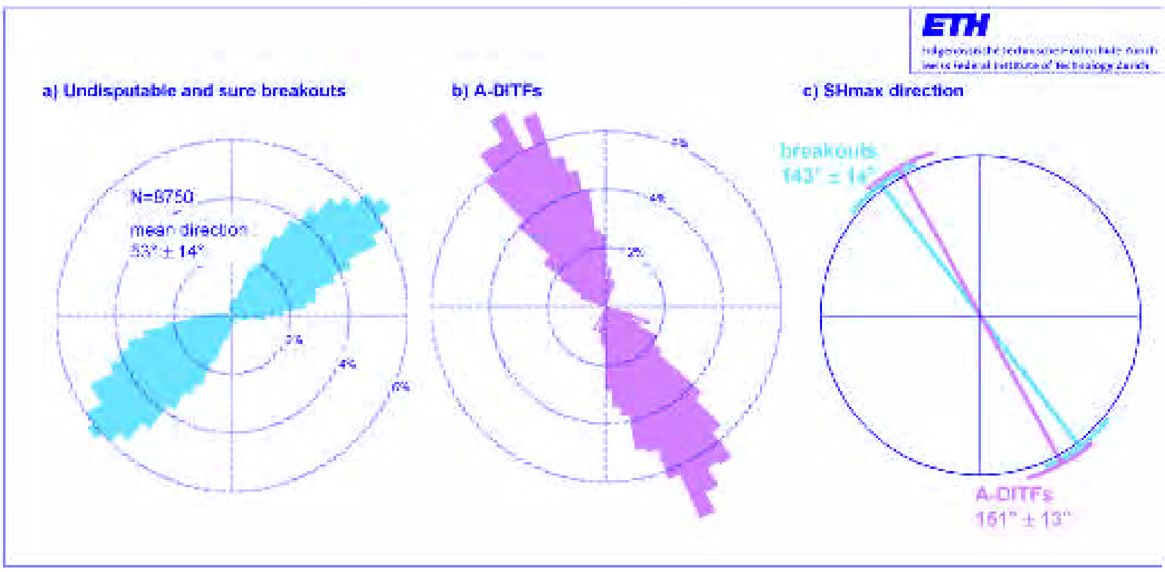
Geological Setting

Basel is situated in the southern Rhinegraben, close to the eastern boundary fault. (Fig. 1)



Figur 1: Situation map well Basel 1

Basel is also close to the northern foot hills of the Jura mountains, the northernmost topographical expression of the alpine collision. The Rhinegraben is an extensional feature of Oligocene age, whereas the dominating stresses in the south result from the ongoing compression of the much younger alpine system. The regional stressfield is characterized by strike-slip faulting with S_{Hmax} striking in a NNW direction. The maximum horizontal stress direction could be determined in well Otterbach 2 (147°) and in well Basel 1 (151° ± 13; Fig. 2) from the drilling induced fractures. The natural fractures identified by the UBI log in the basement section of Basel 1 show an average strike of 163°.

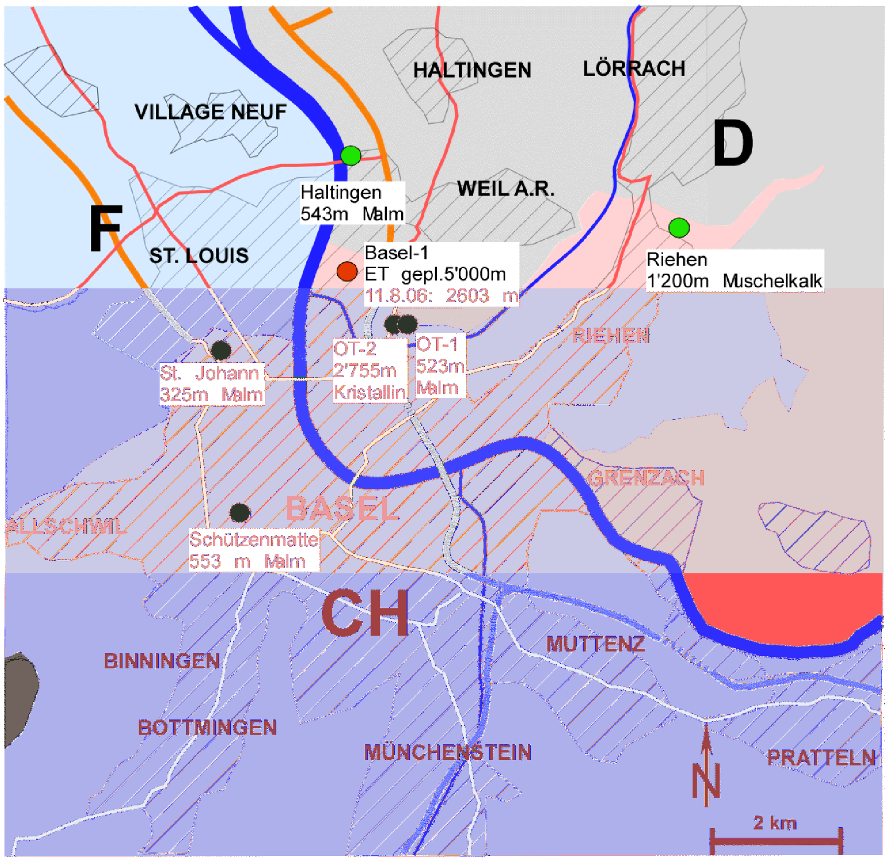


Figur 2: Summary of stress indicators in well Basel 1 (courtesy of B. Valley & K. Evans, ETH 2006)

Basel is known as an area of elevated seismic activity. In 1356 an earthquake with an estimated magnitude of 6.2 destroyed parts of the medieval city. On a global scale the Basel region is rated with a moderate seismic hazard (Giardini et al., 1999). In comparison entire Italy is rated with a higher seismic hazard. Seismicity recorded since 1975 indicate various seismic clusters in the area, trending along a northwest-southeast lineament across Basel. This lineament is not in line with known regional faults and has no surface expression. Depth control of the investigated natural events is rather imprecise (oral communication N. Deichmann), they are however interpreted to be located at depths between 10 to 25 km (Bonjer, 1997).

Exploration concept and drilling operation

The concept is to drill all geothermal wells from one location. The exploration programme comprises two exploratory wells to 5 km and a monitoring array of six wells ranging in depth from 300 to 2750 m. The monitoring array was drilled in 2005 and completed in April 2006. (Fig. 3).



Figur 3: Location map of monitoring wells and the Basel 1 well

The monitoring well configuration and depth is based on a simulation of wave field propagation of model source signals in the 3-D geological model (Hölker and Graf, 2005). The monitoring wells are equipped with 3-C seismometers. The analog signals are digitized at each individual station and transferred via a virtual private network link to a central server and data processing unit. The system is recording on a continuous base since February 2006.

Well Basel 1 was drilled between May and October 2006 to a depth of 5009 m. The well is cased down to a depth of 4638 m. The open hole section is drilled with a 9 7/8“ diameter down to 4850m and 8 ½“ diameter to the along hole end depth of 5009 m.

An open hole hydraulic stimulation was planned over a period of 21 days. The purpose of the hydraulic stimulation was to create a permeable fracture pattern for a large scale sub-surface heat exchanger. This enhanced reservoir was expected to have an ellipsoid shape with a horizontal axis of about 2.5 km, a vertical axis of about 1.5 km and a width of approximately 0.5 km in its center. The orientation of the horizontal axis was expected to be parallel to S_{Hmax}.

Seismic Monitoring

The micro seismic monitoring array serves a dual purpose. It was installed well prior to the Basel 1 drilling and stimulation operation to record the natural seismicity in the area. In the period from February to the start of the pre-stimulation no microseismicity was recorded within the target area. The main purpose was to detect and locate microseismic events during the reservoir enhancement and to map the fracture propagation.

In addition to the subsurface microseismic system the Swiss Seismological Service operates a surface strongmotion network. This network records vertical and horizontal accelerations and ground velocities at various locations throughout the city. It provides objective criteria to control and steer the stimulation process. A so called Traffic Light System was set-up to have well defined guidelines how to react in case of excessive seismicity. The system worked flawless, the decisions to reduce the injection and eventually to stop the stimulation process were based on these criteria.

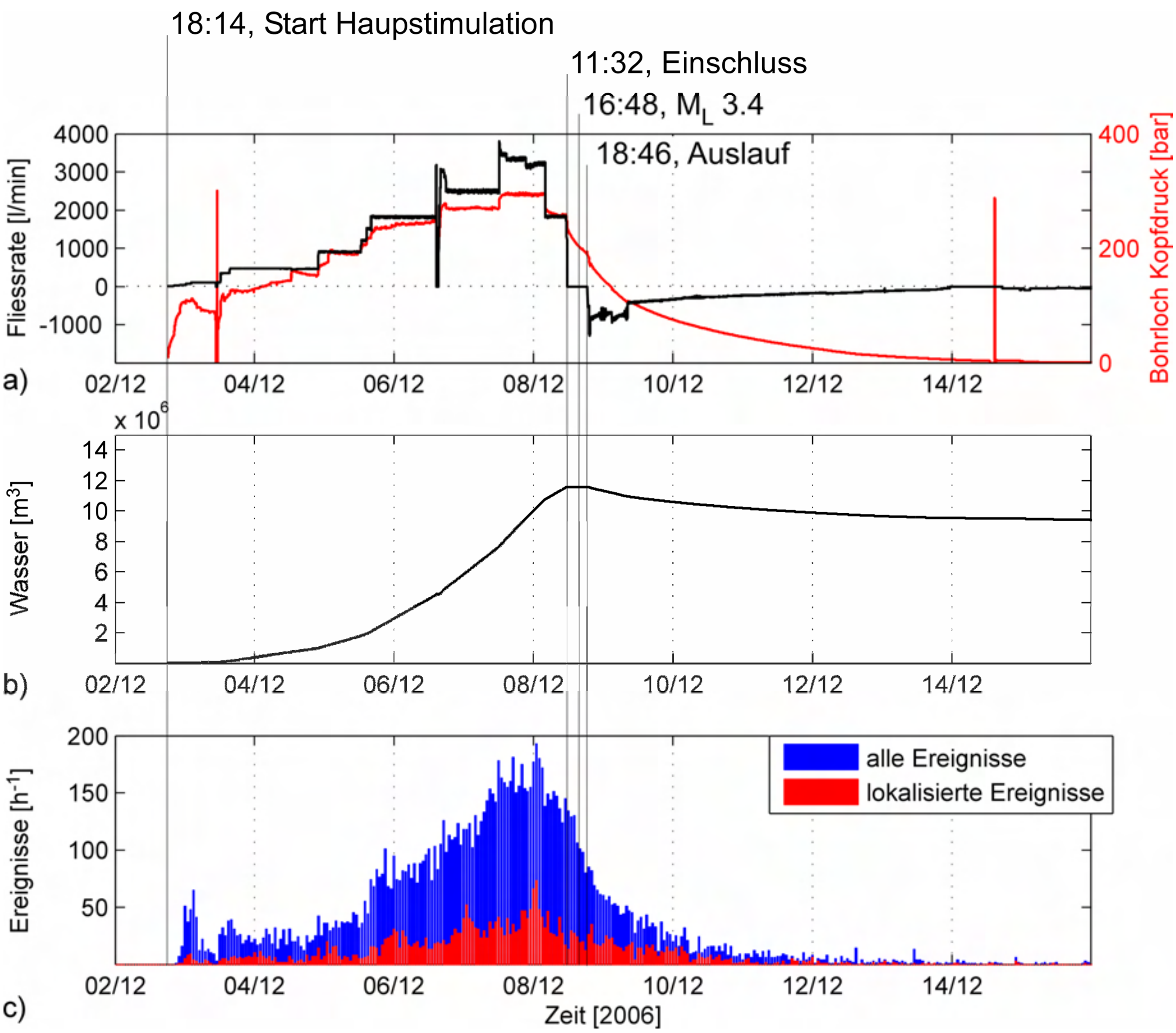
Hydraulic Stimulation

The stimulation was operationally divided in two phases. The first phase, the Pre-Stimulation phase, took place from the 23.-26.11.06 and contained several hydraulic tests to characterize the undisturbed reservoir. The results from the analysis of the hydraulic data provided hydraulic conductivities in the range of $10^{-9} – 10^{-10}$ m/s. These hydraulic conductivities are about one order of magnitude lower compared with other hydraulic conductivity data from hydraulic tests in the Black Forest crystalline basement (Stober and Bucher, 2007). Further, clear indication of bi-linear flow, observed during the hydraulic tests, suggest that the flow regime is dominated by single fractures. This Pre-Stimulation phase was followed by the Main-Stimulation phase, with the objective to enhance the permeability of the reservoir and to achieve a planned flow rate for operational circulation of 50 l/s at a draw down of = 500 m (50 bars).

The pre-stimulation test showed a wellhead pressure of up to 73.8 bars with an injection rate of only 10 l/min. Based on this information it was decided to ramp up the flow rates at a lower pace than initially planned. In the first 16 hours the flow rate was increased step-wise from zero to 100 l/min where the wellhead pressure already reached 110 bars. In the following days the flow rate was increased gradually with the aim not to overstep the seismic thresholds defined in the traffic light system. The maximum well head pressure of 296 bars was reached after five days of stimulation. With the exceeding seismic activity the injection rate was decreased on the sixth day after a seismic event of M 2.7 occured. In compliance with the traffic light system the flow rate was reduced from 3500 l/min to 1800 l/min. Since the seismic activity did not show a significant reduction it was decided to stop injection altogether and to shut in the well. The seismic activity remained high and after the occurrence of another event of M 2.7 in the afternoon of December 8 it was decided to bleed off the well. In the course of giving instructions to the rig crew to bleed off the well (17:48 local time of December 8) the event with magnitude 3.4 occured. The well was bled off to its natural hydraulic pressure within four days. Since then the well is left open. During the main stimulation a total of 11'566 m^3 water was injected within 6 days. Of the injected water about 2'800 m^3 flowed back to surface, leaving around 8'800 m^3 in the formation. To date it was not possible to test the change of reservoir permeability compared to the initial conditions.

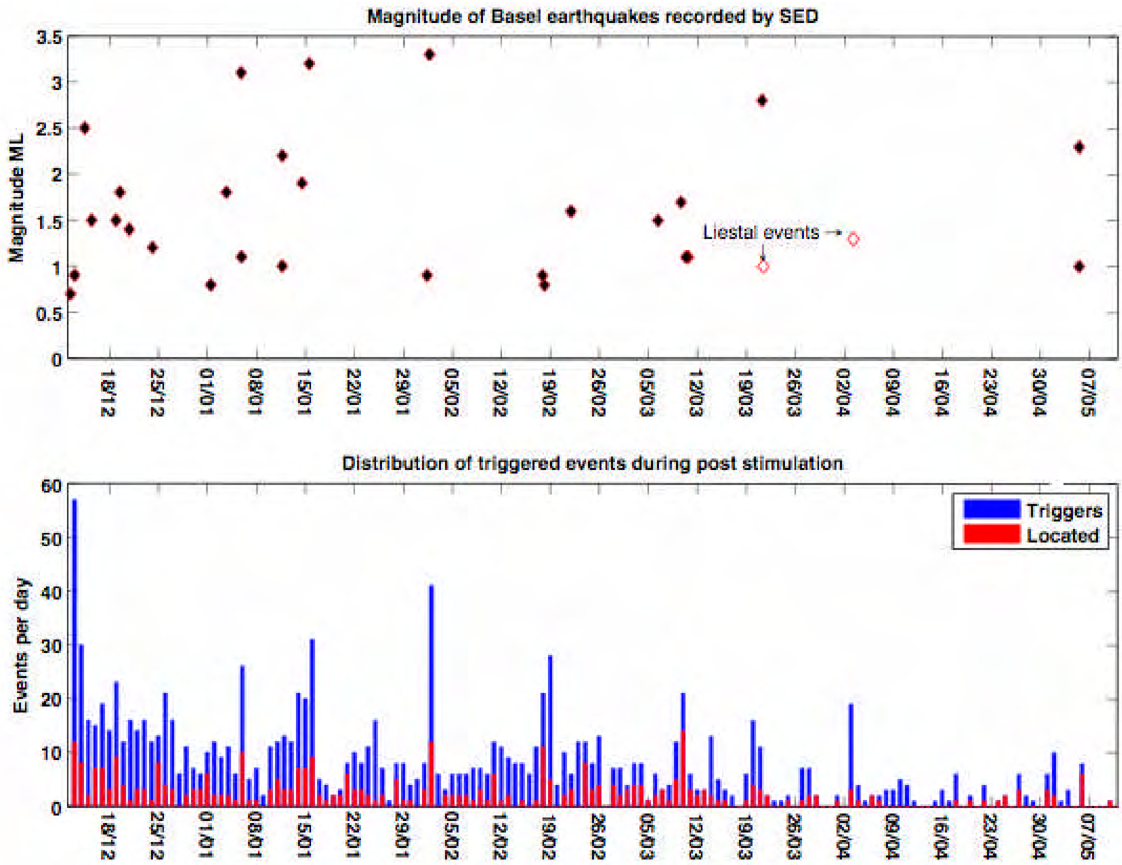
Seismicity

During the stimulation more than 13'000 microseismic events were recorded of which more than 3'000 could be located. The first microseismic events were recorded at the onset of the main stimulation and occurred as expected near the casing shoe, coinciding also with a permeable structure detected on the UBI log. In the course of the stimulation the microseismic events migrated radially away from the open hole section however reduced to a narrow near vertical plane parallel to the regional maximal horizontal stress direction. The microseismic activity increased with each step-up in the flowrate and reached a maximum of more than 190 events per hour during the maximum injection flow rate of 3'600 l/min.



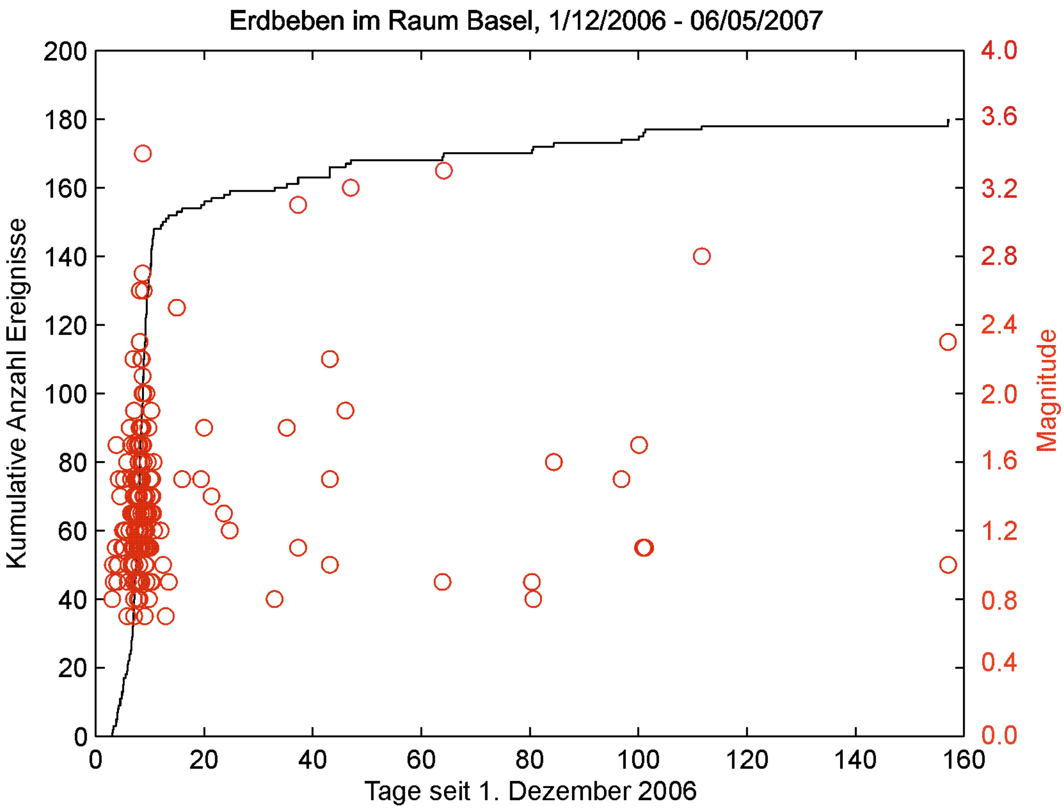
Figur 4: Flow rates, wellhead pressures, cumulative injected water volume, microseismicity and major seismic events during main stimulation.

The first seismic events of M < 1 were recorded with an initial flow rate of 10 l/min. The first event with M > 2 was recorded after four days of stimulation at a wellhead pressure of 270 bars and a flow rate of 2'500 l/min. The magnitudes did not show a significant increase, however the frequency of stronger events increased considerably. The main event of M 3.4 occurred four hours after shut in. The microseismic activity dropped sharply after bleeding off but did not stop at a low rate of about 10 to 20 events per day until more than 100 days after the stimulation (Fig. 5).



Figur 5: Post Stimulation Events

The main event of M 3.4 occurred at a depth of around 5 km in the lower, southern part of the stimulated area. Since then three additional events with M>3 happened in the reservoir. They all occured in the upper southern part of the reservoir at a depth of around 4 km. The first aftershock of M 3.1 followed 29 days after the end of stimulation a second aftershock of M 3.2 after 39 days and a third one of M 3.3 after 55 days. The last event with M>2 occured on May 6. (Fig. 6) Since the end of stimulation the reservoir continued to grow at its fringe. The post stimulation events indicating further growth are aligned along the prinicpal fracture plane mainly towards south.



Figur 6: Cumulative seismic events and magnitudes (N. Deichmann, SED)

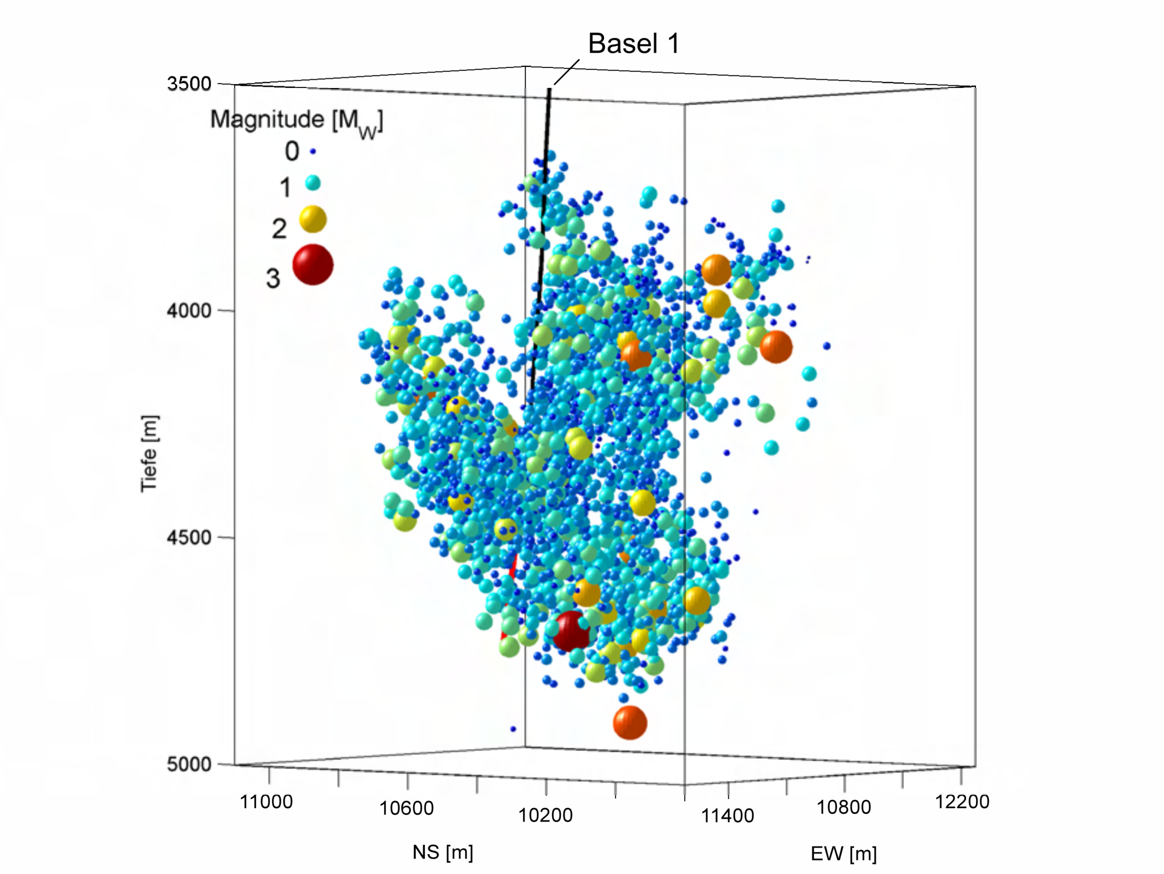
Public perception of the M 3.4 event

The surprising factor was the intensity with which the M 3.4 event was perceived in the city. It was described by many people as a very short and hard shock accompanied by a loud noise comparable to a supersonic bang. The largest ground velocity was recorded at the strong motion station Otterbach 2 with a ground velocity of 9.3 mm/s. According to the USGS instrumental intensity scale the event would not have exceeded the intensity of III which is clearly below any damage level. According to the reports from the public, the EMS intensity would rather be in the order of IV to V.

Due to the high publicity of the event and repeated calls to report damages over two thousand claims have been filed. The still ongoing investigations have found only minor damages so far. The great majority of reported damages are small cracks in plasterwork , often of disputable age. There are no claims of injury and no structural damage has been detected.

Results

The final picture of the reservoir geometry and focal solutions are still under investigation. Results about enhanced permeabilities are not yet available. The estimated volume containing stimulated, or at least seismically activated, fractures is restricted to an volume of approximately 40 - 80 Mio m^3 which is about 10 - 20% of the set target (Fig. 7).



Figur 7: Main stimulation event cloud

However the stimulation process was aborted after only a third of the planned time. With a post-stimulation flow test still outstanding we cannot draw conclusions about the achieved reservoir quality. The poor initial permeability suggest however, that we are not dealing with a pre-fractured hot-wet-rock system comparable to the Soultz reservoir at 3.5 km depth.

Temperature logs were obtained shortly after reaching final depth. Due to the highly effective mud cooling system it was not possible to obtain representative temperature data during wireline logging. From Horner plots we can however calculate a minimal temperature of 195 °C at 5'000 m.

Outlook

Due to the seismic events of unacceptable intensity, Geopower has decided on its own to suspend further drilling and stimulation activities until an independent risk analysis has been conducted. In the mean time all available data will be analysed to an extent, that the full experience of these tests can contribute to the further progress of EGS. The microseismic and the hydraulic monitoring system will be kept running and maintained in full operation. Post-stimulation production logging is planned. Geopower Basel is dedicated to continue the development of EGS despite this drawback. Whether the technology can be further developed at the Basel site or elsewhere depends entirely on the public acceptance of EGS. The risk analysis initiated by the government may contribute to such a process.

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