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Why Injection in a Geothermal Sediment Reservoir Causes Seismicity in Crystalline Basement – It is not just Hydraulics

Sandra Schumacher

Leibniz Institute for Applied Geophysics, Stilleweg 2, 30655 Hannover, Germany

sandra.schumacher@liag-hannover.de

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ABSTRACT

The increasing number of deep geothermal wells has been accompanied by an increasing number of events of induced seismicity which can be related to the injection of water in geothermal plants. One example is the reinjection well Unterhaching Gt2 near Munich, Germany. Although injection pressures are quite low (below 10 bar), seismic events up to magnitude 2.4 have been recorded. The most striking aspect of these seismic events, however, is their location. The majority are located about 1.5 km below the open hole section of the well, and therefore occur within the crystalline basement well below the geothermal reservoir. This well intersects a steeply inclined fault zone, which provides the necessary hydraulic connection between the reservoir and the basement rock.

A simplified numerical model of the geologic setting of the well Unterhaching Gt2 has been designed in order to understand which processes lead to the observed induced seismicity. The aim of this model is not to replicate actual events, but to get a general understanding of the interaction of physical processes in the subsurface. To this end, sensitivity analyses of critical parameters such as injection rate, injection temperature or permeability of the fault zone will be performed.

1. INTRODUCTION

In recent years, cases of induced seismicity have been reported for wells in aseismic regions. Most of these wells were used for the disposal of liquids, e.g., wastewater of hydraulic fracturing procedures. In some cases, geothermal wells have also encountered induced seismicity. The use of geothermal energy naturally influences the reservoir as heat and water are withdrawn. However, most geothermal plants reinject the water in a way that pressure levels within the reservoir remain more or less stable. Despite these constant pressure levels and low injection pressures, induced seismicity in the surroundings of the reinjection well is sometimes experienced.

An example is the reinjection well Unterhaching Gt2, close to Munich in Germany. Here, the reservoir is a karstified limestone layer (Malm) of the Upper Jurassic, approximately 500 m thick, in which extraction and reinjection take place. The Malm itself consists of several layers of limestone, which show varying degrees of dolomitisation, karstification and marl content. As a result, only small portions of the Malm show high permeabilities. The lower layers of the reservoir are particularly tight.

Production and injection wells in the reservoir target depths of roughly 3.6 km. Flow rates of more than 100 l/s have been established with reinjection pressures below 1 MPa. Induced seismicity has been observed to occur near the reinjection well. On the Richter scale, most of the events are below M 1.0, but some reached magnitudes of up to M 2.4. Due to their location, they can undoubtedly be attributed to the reinjection process. In plan view, the origins of most quakes are located within a radius of 500 m around the open hole section of the well (Megies & Wassermann, 2014). However, the origin of the quakes is not within the reservoir but located in the crystalline basement with a cluster of events about 1.5 km below the open hole section of the well (Megies & Wassermann, 2014). As the reinjection well cuts through a steeply inclined fault zone (Lüschen et al., 2011), a hydraulic connection between reservoir, borehole and basement can be assumed and could be an explanation for the unexpected location of seismicity. However, this implies that the fault zone is hydraulically open well into the basement. A sketch of the geologic situation at the well Unterhaching Gt2 is given in Fig. 1. The various colours of the aquifer region indicate layers of different permeabilities, which have been included in the numerical model.

In addition to the karstic limestone layers, the well targeted a fault zone in the Malm as fault zones within the Malm have proven often to be hydraulically conductive and in some cases even provide the main flow paths for the water. A 3D seismic survey of the region has shown the fault zone to consist of fractured rock and to be several tens to about one hundred meters wide. This can be concluded from the observation of fault structures on several seismic lines, whose spacing was 15 m (Lüschen et al, 2011). Moreover, the fault zone is steeply inclined and may even be vertical due to the fact that on a vertical distance of about 500 m between top and bottom Malm the horizontal location of the fault zone does not change visibly. Given the resolution of the seismic survey, this leads to an inclination of about 80° or more. Due to a lack of reflectors, the location and depth of the fault within the crystalline basement cannot be determined. The fault itself is a normal fault, which is oriented in a 45° angle to the current stress field, which is dominated by the Alpine orogenesis. The throw of the fault is about 240 m at top Malm with the north-western block being higher than the south-eastern one.

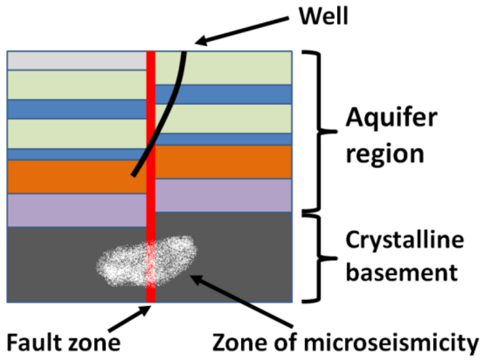

Figure 1: Sketch of the configuration of the model (not to scale). Different colours indicate layers with different permeabilities and in case of the crystalline basement also different mechanical properties.

2. NUMERICAL MODEL

For the numerical model the finite-element software COMSOL Multiphysics© with the Subsurface Flow Module and the Structural Mechanics Module is used. So far, only the thermo-hydraulic effects have been included in this model; the incorporation of mechanical aspects is ongoing work.

2.1 Dimensions

The analysis of the observed seismic events shows that the overwhelming majority of them are located within a radius of 1 km of the well's open hole section. The model dimensions were chosen to be much larger than 1 km in order to minimize numerical effects caused by boundaries. In the direction of the fault zone, the model is 6.5 km wide, perpendicular to the fault zone 6.05 km and the vertical extension is 3.035 km. The latter value is given by the distance between the top of the open hole section and the zone of microseismicity within the crystalline basement plus an additional kilometre of basement to reduce the influence of the model's bottom boundary.

2.2 Permeabilities

Due to the large scale of the model and a lack of information on flow paths within the karst aquifer, an equivalent porosity approach has been chosen for the hydraulic modelling of the karstic limestone layers. The permeabilities and the stratigraphy used for this approach have been taken from a hydrological model of the Malm aquifer in the region of Munich (Bartels et al., 2012; Bartels and Wenderoth, 2013). This regional hydrological model has an extension of 50 by 50 km and comprises all geothermal wells within this area drilled prior to 2011. The model was built in order to simulate the hydrology of the geothermal reservoir. For this, the operational data of all wells within the modelled area have been used and the model settings have been adjusted until the simulation results showed a good fit with measured data. Part of the model settings were the permeabilities and thicknesses of the different layers within the Malm. Therefore, values for these parameters, which have been adjusted to fit observations, have been taken from the regional model and used for the local model of the well Unterhaching GT2. It can thus be concluded that the permeabilities and the stratigraphy used for the local model are reasonable and given the lack of measurements the best data obtainable. The permeabilities range from $1.6*10^{-18}$ m^2 in the crystalline basement to $1.3*10^{-13}$ m^2 in the most conductive limestone layer.

2.3 Fault zone

With seismic data showing a very steeply inclined normal fault, the fault zone is assumed to be vertical in the numerical model. As no information on the location of the fault zone within the crystalline basement is available, the fault zone is assumed to continue vertically into it.

The approach of equivalent porosity, which has been used for the karstic limestone layers, is also used for the fault zone. This is based on the fact that the fault has been shown not to be a single fracture but a zone consisting of fractured rock. As before, the lack of information on actual flow paths within the fractured rock necessitates the simplification of the fault zone as a porous medium. Because of this approach of modelling the hydraulic system, the pore pressure within the fault will most likely be the determining factor for the onset of induced seismicity. Therefore, it is of great interest to analyse the influence of the operating parameters of the geothermal plant on this parameter.

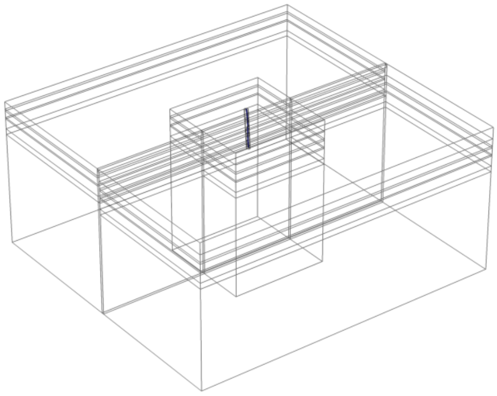

Figure 2: Wireframe model in oblique side view. The well's open hole section can be seen in the centre, where it cuts through the fault zone. The south-eastern block is to the front, while the north-western block is located at the back. The layers of different permeabilities, which constitute the Malm can be seen at the top the blocks.

2.4 Borehole

The borehole has been modelled as an assemblage of several hexahedrons in order to capture the deviation of the drillpath from the vertical. The simplification of a vertical borehole was not possible as the borehole had to cut through the vertical fault. Moreover, a vertical borehole would have a smaller surface area through which water can be injected into the reservoir, which might lead to higher than necessary injection pressures.

The last 26 m of the borehole, which cut into a comparatively tight part of the Malm, have been excluded from the simulations as model runs showed anomalous results in this area, which could only be resolved by an extremely high resolution (maximum element sizes of less than 5 cm). Only a small fraction of the injected volume is injected in this part of the model due to the very low permeability of the rock, which is more than two orders of magnitude lower than in other parts of the reservoir. As a consequence, this part of the borehole has been taken out of the model in order to save computation capacity for the areas of interest, i.e., the fault zone and crystalline basement.

Flow within the well has not been modelled as this would have required a resolution and computation time far beyond the scope of this analysis. Therefore, appropriate boundary conditions had to be chosen for the surface area of the borehole.

2.5 Boundary conditions

2.5.1 Temperature

Temperatures at the boundaries were determined using a depth-dependent temperature profile for the region of Unterhaching, which was generated using the Geothermal Information System for Germany (GeotIS) (Schulz et al., 2007; Agemar et al., 2014). This temperature profile is based on measured temperatures from wells and not on theoretical considerations about heat flow in the crust. However, this fact requires some interpolation between temperature data as not all wells were logged and only bottom-hole temperatures were available for some wells.

Moreover, this approach leads to a lack of knowledge regarding temperatures in the crystalline basement as no wells were drilled into these depths. The temperatures within the crystalline basement are calculated by extrapolating from temperatures in layers above. The resulting gradient within the crystalline basement is about 25 K/km and therefore slightly lower than the 30 K/km usually assumed in Germany (Stober and Bucher, 2012). The maximum temperature of the model is about 197 °C in 6 km depth.

The injection temperature of 65°C is used as boundary condition for the surface of the well's open hole section.

2.5.2 Mass flux

The injection pressure at reservoir depth is not known; reliable data exist only for the wellhead pressure. This poses a problem because the injection pressure is a critical parameter for the simulation. The measured injection rate was used to define flow into the reservoir. The mass of water injected per second is distributed over the well's surface depending on the outward pressure. For this, the integral over the well's surface as well as over the outward pressure on the well's surface is build. The mass flux through a surface element is then determined by following equation:

$$M = I\frac{\rho}{A} \quad \left(\frac{P_{max} - P_f}{P_{max} - P_{min}}\right) \;/\; \int \left(\frac{P_{max} - P_f}{P_{max} - P_{min}}\right) \qquad (1)$$

where M, I, ρ, A, P_{max}, P_f, P_{min}, are the inward mass flux at a given model element, the total fluid flow rate, the fluid's density, the total open hole surface area, the maximum pressure occurring along the open hole section, the pore pressure at the given model element, and the minimum pressure occurring along the open hole section, respectively. The last term of the equation gives the pressure integral along the open hole section.

2.5.3 Pressure

In order to be able to define sensible boundary conditions, several iteration steps are necessary until a static solution for the hydrostatic pressure in the undisturbed state (i.e. no injection or production taking place) is obtained. The first iteration assumes lithostatic pressure as boundary conditions in a 10 km by 10 km model without a fault. The result is strongly influenced by the boundary conditions. However, a vertical pressure profile, which is located at the centre of the model, is exported as a data set. This data set is then imported into the model for the second iteration step, where it provides the new boundary conditions. This process of exporting calculated pressure profiles and reimporting them as new boundary conditions is repeated twice until any boundary effects on the pressure distribution within the model can be ruled out. As the pressure distributions in the north-western and south-eastern block vary due to different burial depths of the units in question, the iteration process is performed twice, for the north-western and south-eastern block separately.

In the next iteration step, a model with the final model geometry was built and as boundary conditions for the north-western block the adequate pressure profile is chosen. For the south-eastern block, the pressure profile is determined using a similar approach. From the result of this simulation, a cut through the centre of the model perpendicular to the fault zone is performed and the data extracted as a new data set. This data set then provides the boundary conditions for the next iteration step. The whole process is repeated until no influence of the boundary conditions on the static result is discernible.

For the final model setup, the iterated pressure distribution is used along with the “Pervious Layer” function in COMSOL Multiphysics©. This function allows the definition of a pervious layer between two fluid reservoirs if, for example, pressure generated by the external reservoirs and its elevation as well as the conductance of the material between the external and internal reservoir are known. In this case, the internal reservoir encompasses the whole local model, while the external reservoir is defined by an undisturbed reservoir in indefinite distance. As such, the pressure exerted by the external reservoir is equal to the hydrostatic pressure of the undisturbed reservoir, i.e. the pressure distribution calculated via the iteration steps. The elevation of the external reservoir is equal to that of the internal reservoir. The conductance between both reservoirs is defined by the hydraulic conductivity of the material.

3. RESULTS

Preliminary results, which only include the thermo-hydraulic effects, show that pore pressure changes due to injection are small. In Figs. 3 and 4, the pore pressure change caused by the injection of 100 l/s for ten days is displayed.

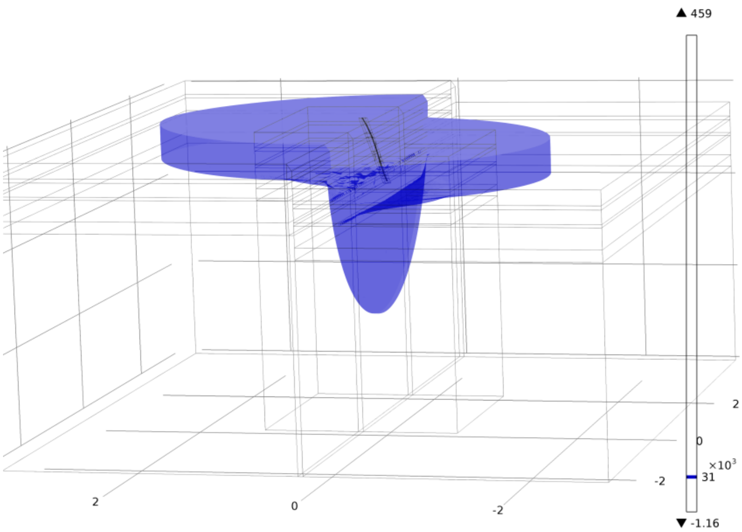

Figure 3: Isosurface for a pore pressure change of 31 Pa after ten days of injecting 100 l/s. Oblique view. Legend is in Pascal.

A striking observation is that even close to the borehole the increase in pore pressure is comparatively small and does not exceed 500 Pa. However, given the small measured wellhead pressures of less than 1 MPa, a huge increase in pore pressure due to injection alone would have been unrealistic. The model therefore can capture the hydraulic properties of the reservoir quite well. This becomes also apparent in the shape of the isosurface in Fig. 3, which is caused by the fault zone and the layers of different permeability, which constitute the model.

So far, the results clearly show that flow into the fault is small even if a high permeability is assumed all the way into the basement. As this is most likely not the case in reality, sensitivity studies with varying depth-dependent permeabilities will be performed.

Figure 4 depicts the change in pore pressure within the fault. It is apparent that the zone affected most by this pore pressure change is confined to the immediate surroundings of the well. Changes in pore pressure can be observed in depths relevant for microseismicity but with values of less than 100 Pa they are comparatively small. These results are in good agreement with observations as so far no direct correlation between wellhead pressure or injection rate and the triggering of induced seismicity could be found. It is therefore likely that only the combination of several effects leads to the triggering of seismic events.

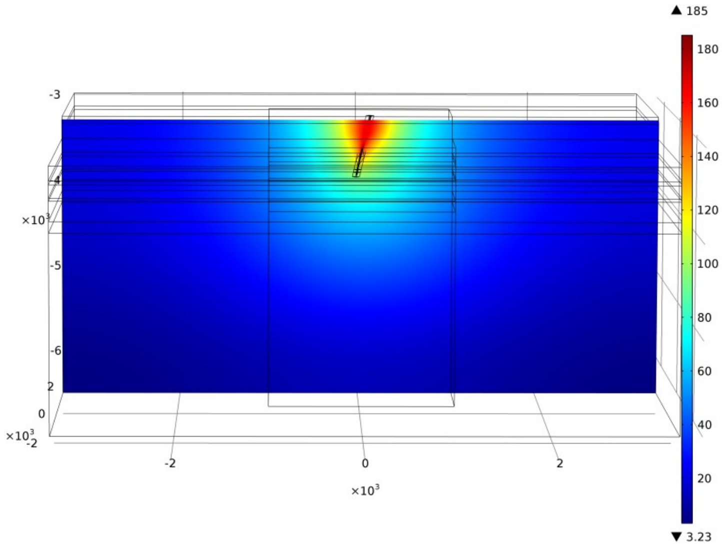

Figure 4: Pore pressure change within the fault zone after ten days of injecting 100 l/s. Legend is in Pascal.

Analysis of thermal stresses shows that they are confined to the immediate surroundings of the well and that they are far too small to have direct consequences for rock stability. However, they might influence the local stress field and act as a trigger for the induced seismicity.

4. CONCLUSION

Preliminary results indicate that in case of the geothermal well Unterhaching Gt2 the injection rate is not the only trigger of induced seismicity within the crystalline basement. Pore pressure changes within the fault zone are comparatively small with far less than 100 Pa in the depth of the induced seismicity after ten days of injecting 100 l/s. As the reservoir through which the fault cuts is highly permeable, it will be difficult to find a set of parameters (such as permeability of the fault) which leads to dramatically different results. The highly permeable reservoir will buffer significant increases in injection rate or pressure.

An alternative explanation would be a highly stressed fault, where slip can be triggered even by very low pore pressure changes. So far, the model does not include mechanical aspects like the orientation of the fault with respect to the local stress field and its magnitude. Therefore, future work will not only consist of parameter studies of parameters such as injection rate, temperature, or fault zone permeability but also of the incorporation of mechanical effects such as the influence of the local stress field into the model.

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