Modeling Induced Seismicity in Abandoned Enhanced Geothermal Systems

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1. Ten years of induced seismicity in the Basel Deep Heat Mining Project

THE stimulation of the reservoir in the Deep Heat Mining Project in Basel was abruptly terminated in 2006 due to high induced seismicity risk. Many earthquakes with a moment magnitude above the threshold value that had been considered by the implemented traffic light system were observed during the next few months and damage to many local infrastructures was reported. The well was left open for a period of more than 4 years, the water volume produced during this period accounts for less of 40% of the total injected volume, the frequency of induced events was reduced to very low values and the well was permanently shut in 2011.

Although more than 10 years have passed since the last injection of fluids, seismicity is not only still observed in the reservoir, but also its frequency has significantly increased. This observation begs the question of whether the stimulation of the reservoir is really terminated and the induced seismicity risk diminished. Since the probability of similar unsuccessful EGS stimulations to occur cannot be excluded, we aim to study the long term importance of various mechanisms regarding their potential for induced seismicity. Here, we start by studying the effect of pore pressure changes due to the initial injection.

2. Estimating mean rates of seismicity with a 1D cylindrical flow model

A cylindrical one dimensional (1D) non linear and single phase pore pressure diffusion model is employed (Gischig and Wiemer, 2013). The permeability inside this 1D volume increases non linearly with pore pressure, it cannot decrease, and the rate with which it increases has been calibrated so that the 1D model returns similar well conditions to those observed in Basel both during the first 11 days since the main stimulation started and during the build up of pressure that followed the shutting of the well in 2011.

The pore pressure distribution that the calibrated 1D model returns for today (approximately 10 years since the last injection of fluids), is plotted in Fig. 1. In the same figure, the time evolution for two different scenarios is plotted; i.e. keeping the well shut for the next 15 years or opening it for half a day per day. The results imply that future pore pressure inside the stimulated volume will be reduced a lot faster if the well opens than if the well remains closed. However, pore pressure decrease at a high rate is expected only inside a small portion of the total reservoir volume that is pressurized. Pore pressure perturbations that are now away from the well will continue diffusing outwards, they will increase the pressure in a much larger reservoir volume, and they will be affected by the opening of the well only at much later times.

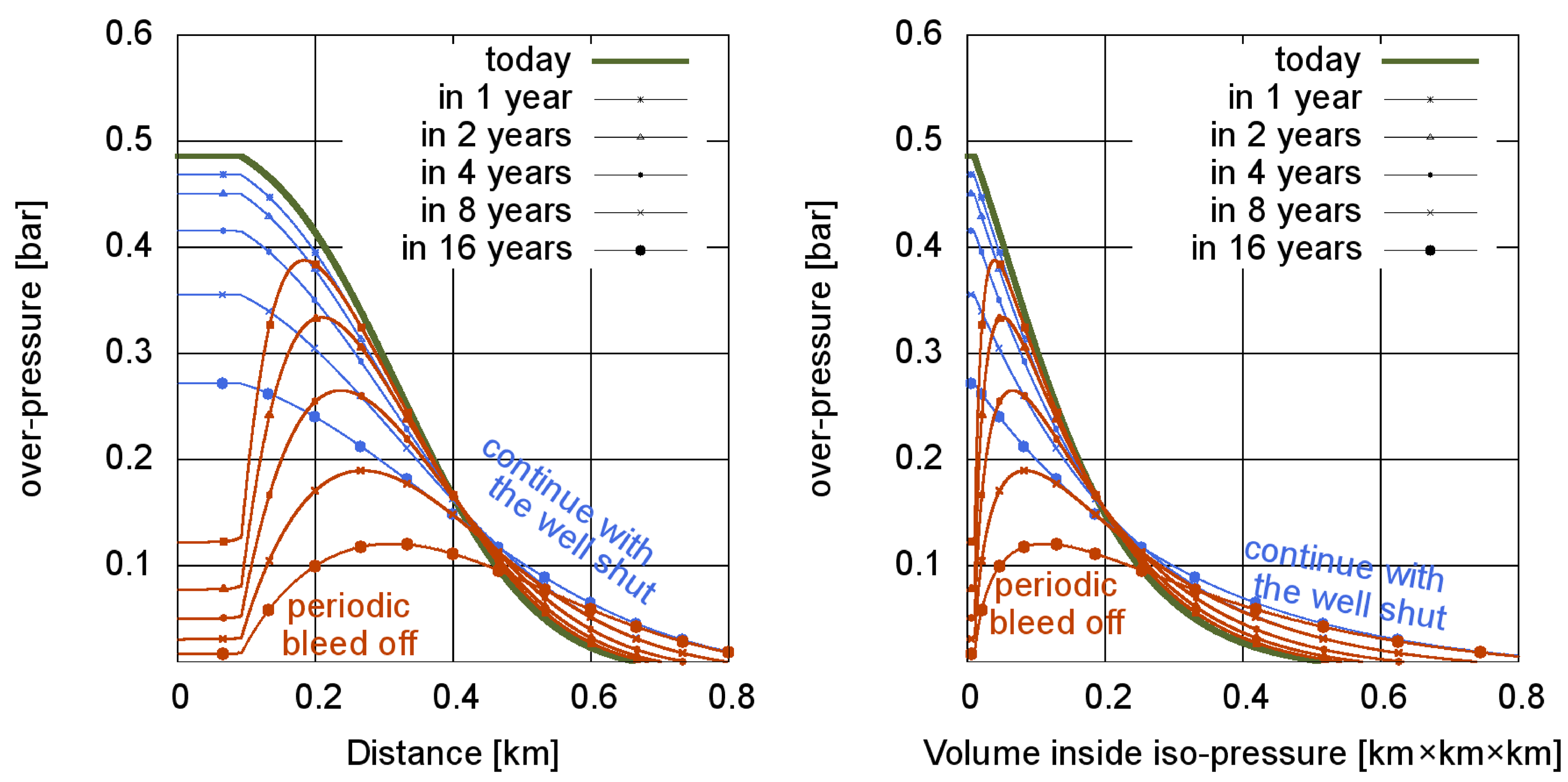

Figure 1: *On the left, the estimation of pore pressure changes today and its evolution for two different future scenarios are plotted. On the right, the same results are plotted as a function of the volume size enclosed by each radius.*

The rate with which the maximum experienced overpressure increases is numerically integrated over the whole 1D volume. The integral's value, which is here simply called 'seismicity rate factor' and is described in the legend of Fig. 2, is proportional to the expected rate of seismicity events that occur because a fracture reactivates for the first time, when a uniform probability is considered both for the values of overpressure that can cause seismicity and for the spatial distribution of potential hypocenters. This way a quick qualitative assessment can be obtained of the the rate with which new fractures are reactivated due to pore pressure diffusion. The time evolution of this integral is plotted in Fig. 2 for various scenarios. The time evolution of the integral suggests that the rates of new induced seismicity in the 1D model would have been close to 40% less today if the well had never shut. This increase is mainly caused by the pressure build up at the well that follows the its shutting. But the rate of new reactivations in 10 years from now is expected to be 50% less if the well opens and does not remain shut.

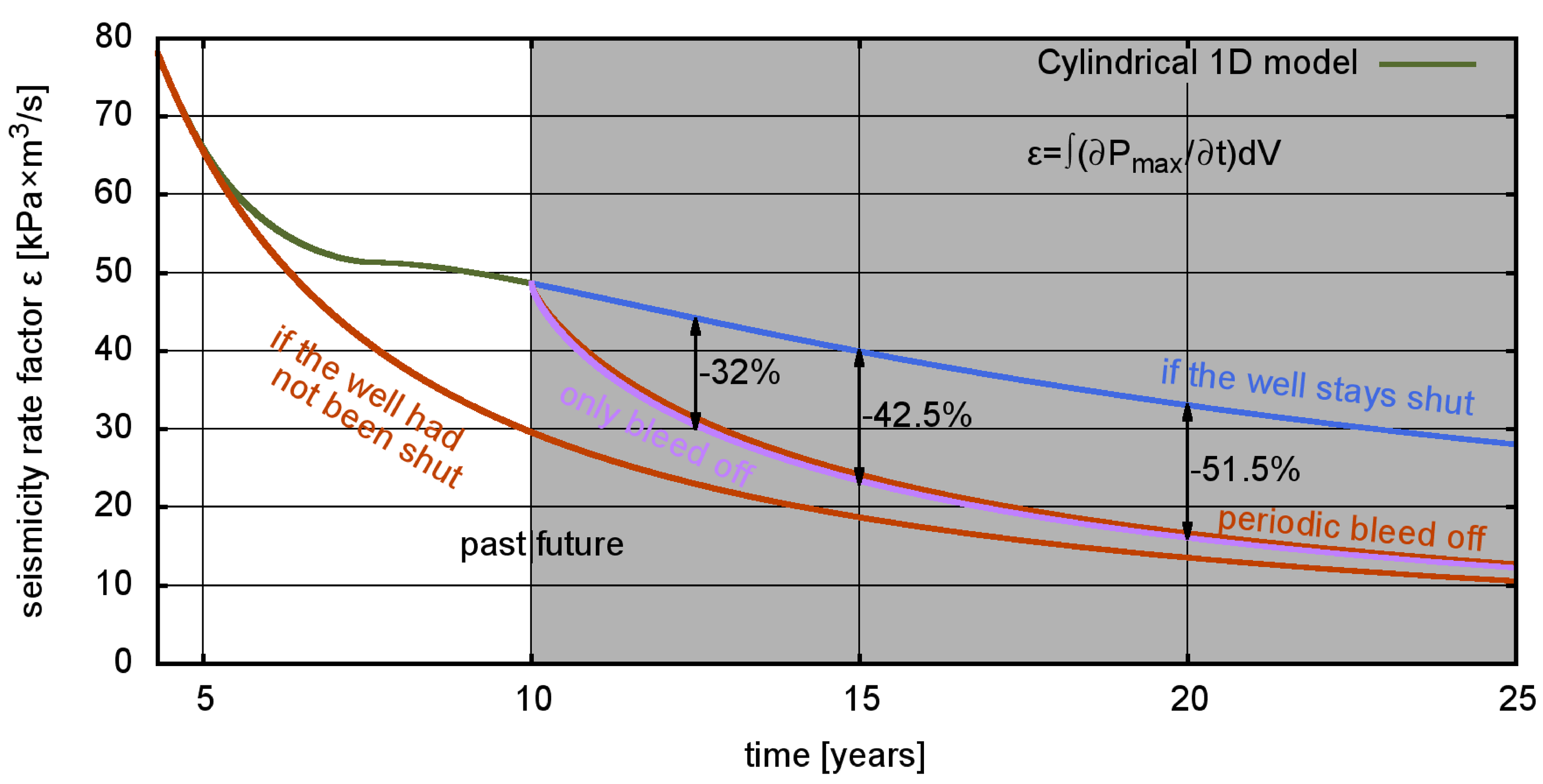

Figure 2: *Evolution of seismicity rate factor for various 1D solutions inside a cylindrical reservoir volume V.*

3. Distribution of pore pressure change in a 3D discrete fracture model

Here, a three dimensional (3D) hybrid model that employs deterministic discrete fracture modeling for flow and stochastic modeling for seismicity is employed, and the two almost independent diffusion processes implied from the 1D model are studied with it. The fracture of networks that the 3D flow model considers consists of the ruptured surface areas of all the earthquakes that were observed in Basel and their moment magnitude was greater or equal than 1.5, and of few more fracture surfaces that improve the interconnectivity between the ruptured surfaces. Each fracture that corresponds to an observed event is disc shaped, centered around its relocated hypocenter (Kraft et al., 2014), and its orientation is one of the two planes of its focal mechanism (Terakawa et al., 2012), which orientation is either the one that is better aligned with the rest of the hypocenters (Deichmann et al., 2014)) or it is the most probable plane according to the pore-pressure estimated by the flow model and the stress distribution considered by the stochastic model. The two side views of the network of discrete fractures that resulted from one such forward simulation with the hybrid model is presented in Fig. 3.

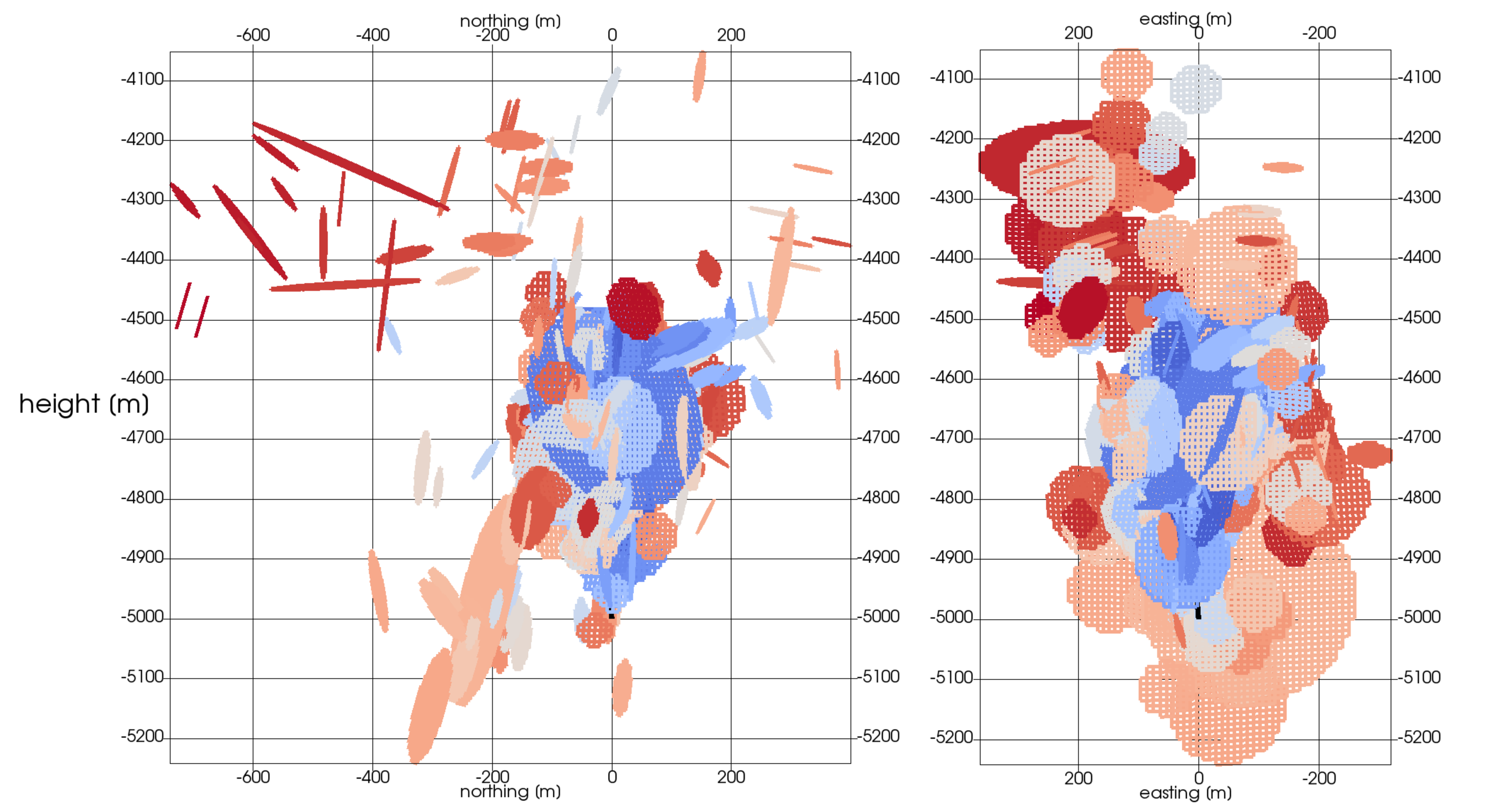

Figure 3: *The network of discrete fractures derived from a forward simulation with the hybrid model is presented above, Note that the bottom of the well is located at $(0,0,-5.km)^T$.*

The simulation with the 3D hybrid model and the above fractures returned non-negative pressure changes inside a large reservoir volume for the 10th simulated year, which result is in agreement with the 1D model. A local maximum for the pore pressure that surrounds the well is also formed in the 3D simulation, and pore-pressure perturbations diffuse from this locus of points with locally maximum pressures both towards the well and away from it. Two snapshots of the simulated pore pressure increase are plotted in Fig. 4 for the 8th day and the 5th year since the last injection. Note that the gradient of the pore pressure change is indicative of the direction towards which pore pressure diffuses.

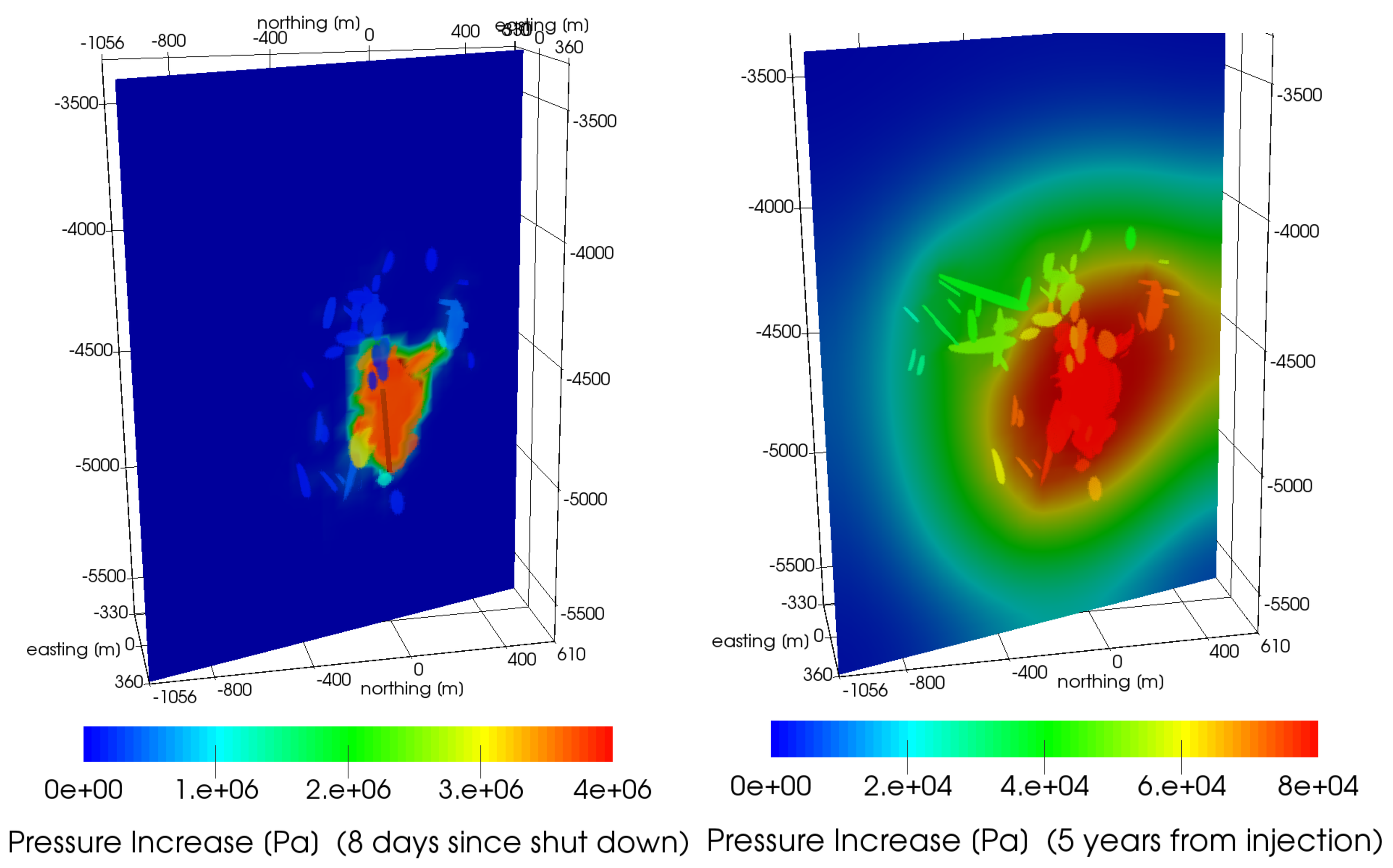

Figure 4: *On the left, the distribution of the simulated pore pressure change for the 8th day since the last injection and on the right for the 5th year since the last injection are plotted along a 2D slice of the 3D discrete fracture model.*

4. Conclusion

Here, the long term effects that pore pressure diffusion has to the induced seismicity are studied. Pore pressure diffusion is simulated both with a 1D cylindrical model and with a 3D model that considers a realistic network of fractures. In all simulations, values of pore pressure that are large enough to induce further seismicity are computed. Such large values are slowly diffusing towards the unstimulated volume and can potentially induce further seismicity. Well operations, such as opening a well, have limited capability for quickly reducing the pore pressure there. Additionally, the seismicity rate factor is introduced, which factor is a simple to compute integral and it allows quick estimations of whether the frequency of induced seismicity events is going to increase or not. The factor is computed for the 1D solutions and according to it, shutting an open well leads to a higher frequency of events, but opening a shut well can decelerate it again.

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