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Relation between Induced Microseismicity and Fracture Network in the Basel Geothermal Site

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Summary

Permeability creation during hydraulic stimulation of Enhanced Geothermal System (EGS) reservoirs is accompanied in part with induced microseismicity. A satisfactory reservoir characterization is required to mitigate the seismic risk and evaluate different development scenarios with valid hazard assessment. Creating a representative three dimensional structural model in the early stages of reservoir creation is difficult because of insufficient information on the geometry of fracture network from deep boreholes data. In this analysis, we characterized the spatial patterns of induced microseismicity in the Basel geothermal system and analyzed the rupture radius distribution. We generated and analysed synthetic data to help us with the interpretation of the correlation function of spatial patterns. Assuming a constant stress drop on every seismic event, the rupture radius distribution showed a power-law distribution. The correlation function of induced patterns showed a slope of 2 indicating the existence of a fractured zone. In addition, the existence of repeating events explains the observed drop on the local slope of the corresponding correlation function.

Introduction

Commercial developments of Enhanced Geothermal System (EGS) require hydraulic stimulations to achieve sufficient flow rates. This operation increases the permeability within the reservoir by shearing on rough surfaces and/or generating new fractures. This operation is commonly associated with relatively large numbers of microseismic events. These events may be sufficiently large to be felt by the public and lead to project suspension such as the Basel geothermal project in Switzerland (Häring et al. 2008).

Creating a highly permeable network providing a flow path without inducing damaging events needs stimulation protocols based on representative reservoir characterization, particularly including the distribution and properties of discontinuities such as fractures and faults. Normally, our information from the underlying fracture network in the early stages of reservoir creation is not adequate for constraining a three dimensional discrete fracture network (DFN) model. It can be assumed that for small earthquakes, the earthquake hypocenters correspond to the centers of circular failure planes, known as discontinuities. Thus, induced microseismicity patterns may reveal the structure of underlying fracture network and possibly constrain the stochastically-generated DFNs.

In this analysis, we investigate the possible correlation between the statistical properties of fracture network and induced microseismicity patterns. Here, we analyze the microseismicity in Basel geothermal project and characterize the clustering and size distribution of induced events. Then, we generate statistical scale invariant fracture networks and try to simulate the influential parameters such as repeating events and existence of a fractured zone on the resulting microseismicity. The results of this analysis is applied for developing a real-time statistical model to forecast the maximum magnitude of earthquakes during fluid injection.

Microsesimicity in the Basel geothermal site

Hydraulic stimulation in Basel geothermal system induced 14,578 events between December 2006 and March 2007 of which 3460 were located (details provided by Häring et al. (2008) and Dyer et al. (2010)). Kraft and Deichmann (2014) performed a high precision analysis of the waveform similarity and relocated 1980 of the initial catalogue. Figure 1 represents the spatial distribution of microearthquake hypocenters from top and side view.

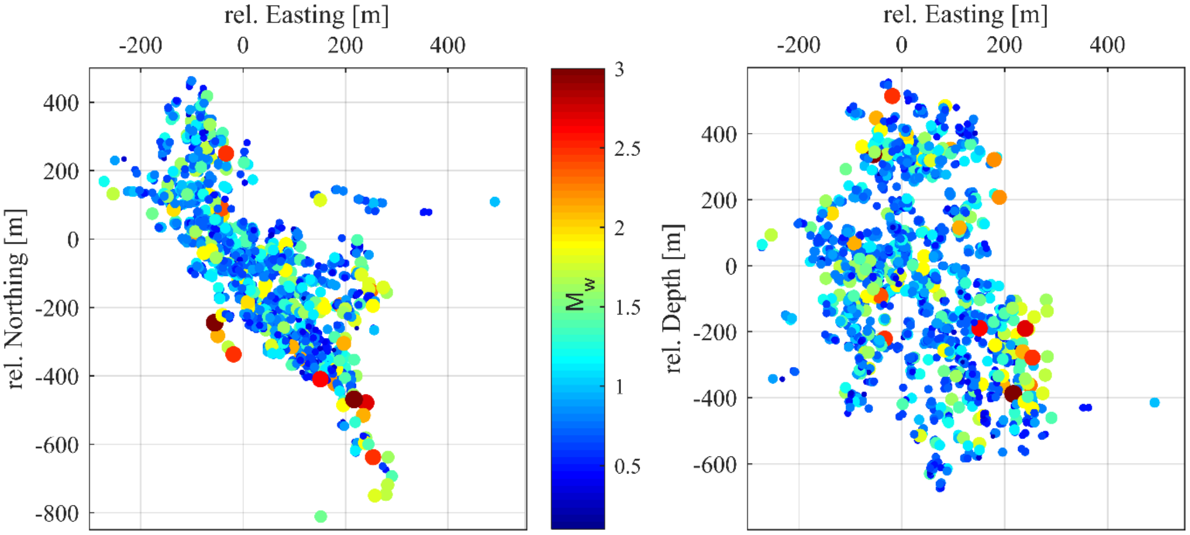

Figure 1 *The spatial distribution of induced microseismicity in Basel from top and side view. Microearthquake hyocenters are btained from relaocated earthquake catalogue by Kraft and Deichmann (2014).*

Spatial distribution of earthquake hypocenters can be characterize by two-point correlation function (equation 1). A correlation dimension is the exponent of a power-law being fit to the resulting correlation function

$$C(r) = \frac{2}{N(N-1)} N_p(r) \sim r^D \tag{1}$$

where N_p is the number of pairs having a distance less than r and N is the total number of induced events. Figure 2 (left) represents the correlation function of microearthquake hypocenters and its corresponding local slope. It shows that the correlation dimension of induced events are close to *2* in *50-100m* distance and drops to lower values for smaller distances *2-50m* and larger distances (> *100m*).

On the other hand, if every events represents a rupture on a failure plane, it is possible to assign a rupture radius by combining the definition of stress drop ($\Delta\sigma$) in equation 2, (Eshelby 1957) and moment magnitude (M_w) in equation 3 (Kanamori and Anderson 1975):

$$\Delta\sigma = \frac{7M_0}{16R^3} \tag{2}$$

$$M_w = \frac{2}{3}\,(log(M_0) - 16.1) \tag{3}$$

where, M_0 represents the seismic moment. The stress drop variations on seismic events in Basel are between *0.1-10 MPa* with an average of *2.26 MPa* (Goertz-Allmann et al. 2011). The majority of the computed stress drops are close to the average and if we assume the stress drop on all events equals to the average, the resulting rupture radius follows a power-law with an exponent of *3.55±0.07* (Figure 2 right).

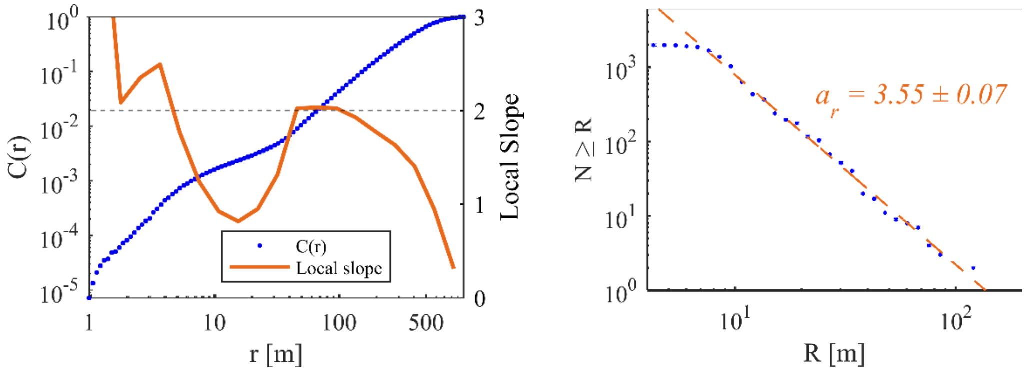

Figure 2 *Correlation function of microearthquake hypocenters in Basel geothermal site and complementary cumulative distribution (N) of computed rupture radius (R).*

Synthetic fractal fracture networks

Induced microseismicity revealed a clear clustering behavior and power-law size distribution in Basel. To interpret the spatial clustering of induced events, we chose a statistical model to generate fractal fracture patterns presented by Davy et al. (1990) as in equation 4,

$$n(l, L).dl = \alpha.L^D l^{-a_f}.dl \tag{4}$$

where, $n(l,,L)dl$ is the number of fractures whose length is in the range $[l, l + dl]$ and whose center belongs to a volume in three dimensions of size L, α is a constant, D is the correlation dimension of fracture centers and a_f is the power-law exponent of fracture length. Figure 3a represent the 3-D representation of a random DFN with the following parameters *D=2.7*, $a = 2.8$ and $\alpha = 0.02$.

Different factors influence the relation between the induced microseismicity and fracture networks such as uncertainty of hypocentral locations, repeaters on similar planes and existence of a fractured zone.

Here, we simulate the effect of repeating patterns and existence of a fractured zone on the resulting correlation function.

Repeating events are different ruptures on a particular structure and the resulting waveform of these events are very similar. To analyze the effect of repeating events on the resulting correlation function, we add *100* random fracture centers to the network of Figure 3a. We chose 10 random fractures and added 10 neighboring fractures to each one. The added fractures are located in a maximum *5m* distance. Figure 3b represents the resulting correlation function and the corresponding local slope to the network without and with repeaters.

Borehole images and induced microseismicity in deep boreholes confirms the existence of fractured zones, which are the main flow path in low permeable reservoirs (Deichmann et al. 2014, Evans et al. 2005, Valley and Genter 2007). The fractured zoned are densely distributed fractures in a particular depth interval. It can be assumed that the fractures are uniformly distributed in a certain width. If we generate a random realization of fracture centers randomly distributed in a *20m* interval (Figure 3c), the resulting correlation function is presented in Figure 3d.

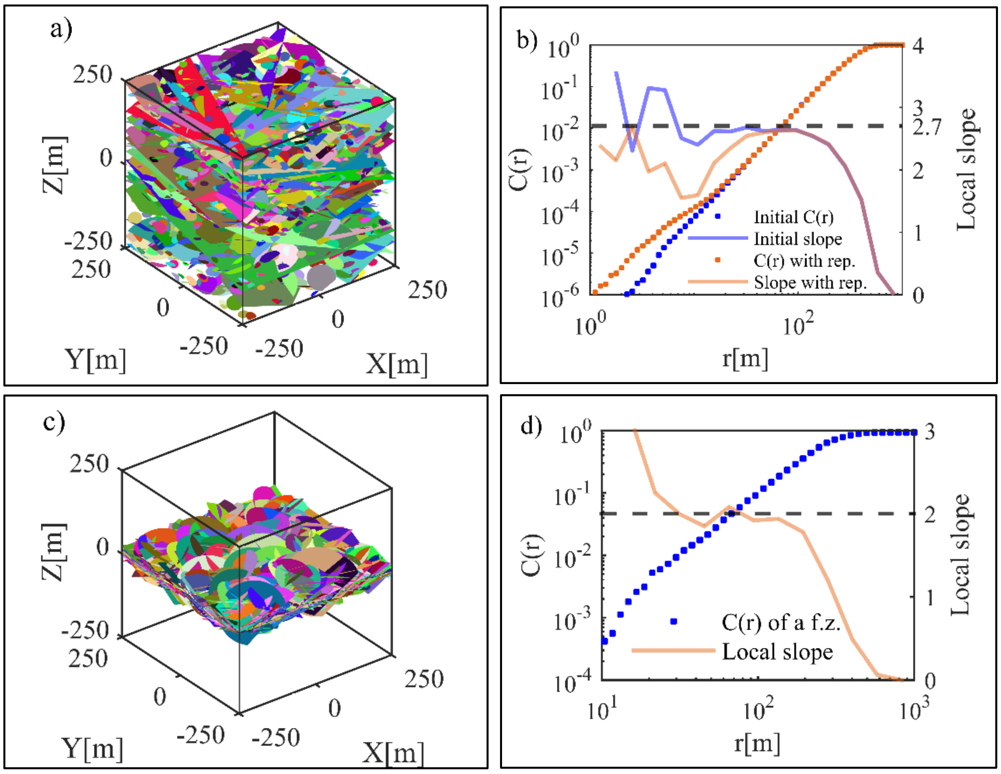

Figure 3 *(a) A random synthetic fractal fracture network generated by dual power-model with D=2.7,* $a = 2.8$ *and* $\alpha = 0.02$. *(b) Effect of repeating events on the resulting correlation function of the fracture network. (c) A 3-D representation of horizontal fractured zone of 20m width. (d) Correlation function of a fractured zone and its corresponding local slope.*

The analysis of repeating events on synthetic networks and the existence of a fracture zone helps to understand the observed correlation function of induced events in Basel. The observed correlation dimension of *2* reflects the existence of a fractured zone, which can be confirmed by the spatial scattering of induced events in Basel (Figure 1). Furthermore, the drop of the local slope of correlation function can be explained by the existence of repeating events.

Conclusions

The spatial clustering of induced microseismicity in Basel shows a fractal dimension of *2*, which reflects the existence of a fractured zoned, which provides the main flow path. Moreover, the local slope of the correlation function of induced events shows a drop because of repeating events. In addition, assuming a constant average stress drop on every event results in a power-law distribution of the rupture radius distribution.

Acknowledgements

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