The Peculiar Shut-In Behavior of the Well GPK2 at Soultz-sous-Forêts

Martin Schoenball and Thomas Kohl

Karlsruhe Institute of Technology, Institute of Applied Geosciences

Keywords

EGS, induced seismicity, shut-in, Soultz, faults, triggering

ABSTRACT

A better understanding of induced seismicity occurring during the creation of an enhanced geothermal system is vital for future large scale application of geothermal power. Especially the occurrence of large magnitude events (M_W>2.0) after shut-in is lacking a comprehensive understanding. We analyze the stimulation of well GPK2 at the Soultz-sous-Forêts (Alsace, France) pilot site with emphasis on the shut-in. We observe a sudden change in spatio-temporal evolution of seismicity starting with shut-in that cannot be explained be currently available approaches to explain the occurrence of post-shut-in seismicity. We relate these observations to structural geological features of the reservoir surrounding well GPK2 such as large faults and the transition between two granite facies.

Introduction

The European deep geothermal research project at Soultz-sous-Forêts (Alsace, France) has been developed since 1987 (Genter et al. 2010). The geothermal reservoir is situated in a horst structure within the granite basement of the Upper Rhine Graben. The four production and injection wells reach up to about 5 km depth into the crystalline basement which is covered by 1.4 km of Cenozoic and Mesozoic sediments. In order to develop an Enhanced Geothermal System (EGS) several well stimulations have been conducted to enhance the productivity of the reservoir (Dorbath et al. 2009). These operations were accompanied by thousands of induced microseismic events. For the prediction of future reservoir performance, knowledge of the thermo-hydro-mechanical response of the geothermal reservoir to hydraulic stimulation and production is a key issue. The phenomenon of fluid induced seismicity is widely observed and may impose barriers for future large scale operation of EGS plants (Evans et al. 2012). The continued occurrence of large events after either massive fluid injection or production is stopped has been observed at a number of sites such as Soultz (Dorbath et al. 2009), Berlín in El Salvador (Bommer et al. 2006), Basel (Häring et al. 2008) and Landau (Bönnemann et al., 2010). The phenomenon has been puzzling science for several years. Few approaches exist that explain the observation by means of geometric spreading effects of the pressure perturbed volume (Baisch et al. 2006, 2010, Barth et al. 2013) or the variation of *b*-values with distance from the injection well (Goertz-Allmann et al. 2013). While all these approaches certainly explain part of the observations, mechanical effects of shut-in on the reservoir are still poorly understood. We revisit the case of the GPK2 stimulation in 2000 and analyze the spatio-temporal behavior of seismicity after shut-in to identify possible mechanisms that have been overlooked so far.

Stimulation of GPK2

The shallow section of the well GPK2 (ca. 3500m) was first stimulated in 1995 and 1996 by two massive fluid injections (Gérard et al. 1997). After deepening of the well, the deep part of the well was stimulated by massive fluid injection of about 25,000 m^3 of fresh water with flow rates of 30 to 50 ls^{-1} over a period of 6 days in June and July 2000 (Weidler et al. 2002). The stimulation of GPK2 was seismically recorded by both a down-hole and a surface network of seismometers. During the stimulation more than 30,000 events were detected by the down-hole network of which about 14,000 could be located by Dyer (2000). We use the seismicity catalog created by Dorbath et al. (2009). From the down-hole network, data from three stations with 4-component accelerometers at about 1500 m depth (i.e. at the top of the granitic basement) were used in the creation of this catalog. The temporary surface network consisted of 14 stations, 6 with 3-component velocimeters and 8 with 1-component vertical velocimeters. For further details on the monitoring network we refer to Dorbath et al. (2009). They obtained hypocenter locations using a modified version of HYPOINVERSE (Klein 1978) and station corrections, uncertainties are about 50 m in horizontal and 70 m in vertical directions. Event magnitudes were calculated from the duration of the coda (Charlety et al. 2007). To calibrate this duration magnitudes the moment magnitude was determined for several events with magnitudes in the range 0.7 – 2.9 using waveforms with good signal-to-noise ratio recorded during the stimulation of GPK3 in 2003 by Charlety et al. (2007). In total, locations and magnitudes of 7215 events were obtained by Dorbath et al. (2009). The largest event recorded during stimulation reached magnitude 2.5. The microseismic sequence obtained from the surface network used does not contain the largest events induced during the operation with magnitudes 2.6 and 2.7, respectively. They occurred after shut-in in mid-July and the temporary monitoring network was already removed from the field.

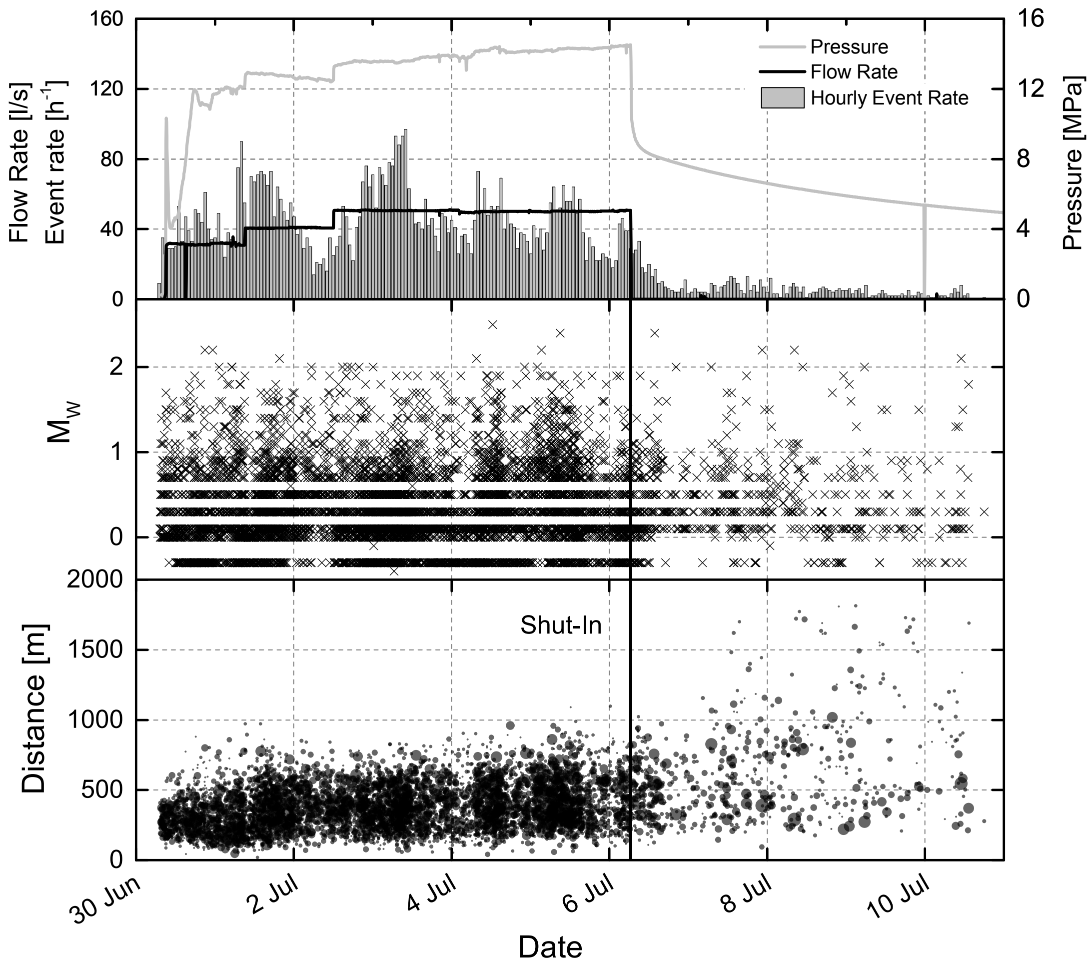

Figure 1. (top) Hydraulic data and seismic response in terms of hourly event rate during the stimulation. (middle) Magnitudes of events. (bottom) distance-time plot of the seismicity. Distance is calculated from the middle of the openhole section to the hypocenter. After shut-in a large increase of the maximum distances is observed.

Figure 1 shows the hydraulic data of the stimulation operation as well as the seismic response of the reservoir. At at flow rate of 30 ls^{-1} wellhead pressure settled at about 12 MPa. After increasing injection rate to 40 ls^{-1} pressure increased only by one MPa before falling off again to 12.5 MPa. At the last stage of pumping at 50 ls^{-1} wellhead pressure increased again by about one MPa to 13.5 MPa and increased continuously to about 14.5 MPa just before shut-in of the well. The event rate throughout the fluid injection phase was on the order of 50 events per hour. Towards the end of each injection rate step it decreased and increased strongly once the injection rate and hence wellhead pressure increased. No obvious correlation of event rate and fluid flow rate is observed. After shut-in seismicity fell off very quickly within one day, showing a behavior describable by Omori's law (Langenbruch et al. 2010). However seismic activity continued for several days at a constant level. No particular evolution of maximum magnitudes over time can be observed (Figure 1, middle). First magnitude M_W=2.2 events occur after only 12 hours of injection. The maximum magnitude event during injection of M_W=2.5 occurred after about four days of injection. The largest events of magnitude M_W=2.6 occurred only after 10 after shut-in (Dorbath et al. 2009).

The r-t-plot of the seismicity (Figure 1, bottom) shows some very remarkable features. Already after few hours seismicity propagated more than 500 m away from the well. Until shut-in seismicity progressed only slightly further outward to maximum distances of about 1000 m. But after shut-in suddenly events occurred at a distance of more than 1500 m away from the open hole section of the well. This behavior is analyzed by Michelet (2002) using the SBRC approach of Shapiro et al. (1999). That way she interprets the different spatio-temporal evolution in terms of hydraulic diffusivity. She finds the diffusivity during injection as D = 0.14 m²/s, whereas it is D = 0.30 m²/s after shut-in. As it is highly unlikely that hydraulic diffusivity changes just by the fact of shut-in this behavior cannot be due to the hydraulic properties of the reservoir rock, but must have some origin in a different mechanical behavior for the post-shut-in period versus the injection period.

Calò et al. (2011) discuss the change in the pattern of seismicity based on refined double-difference locations. Only for the post-shut-in period are they able to discern structures in the cloud of seismicity which clearly show a delineation of planar structures. In order to investigate the peculiar spatio-temporal evolution starting with shut-in of GPK2 we analyze the locations of seismicity. The high seismic activity section of the seismicity cloud has an ellipsoidal shape with the major axis extending about 1 km along a strike of N150°. The minor axis is roughly 400 m. In the following we operate in a coordinate system rotated clockwise by 30 degrees around the z-axis. In this coordinate system the major axis of the cloud stretches parallel to the y'-axis. We bin the events in

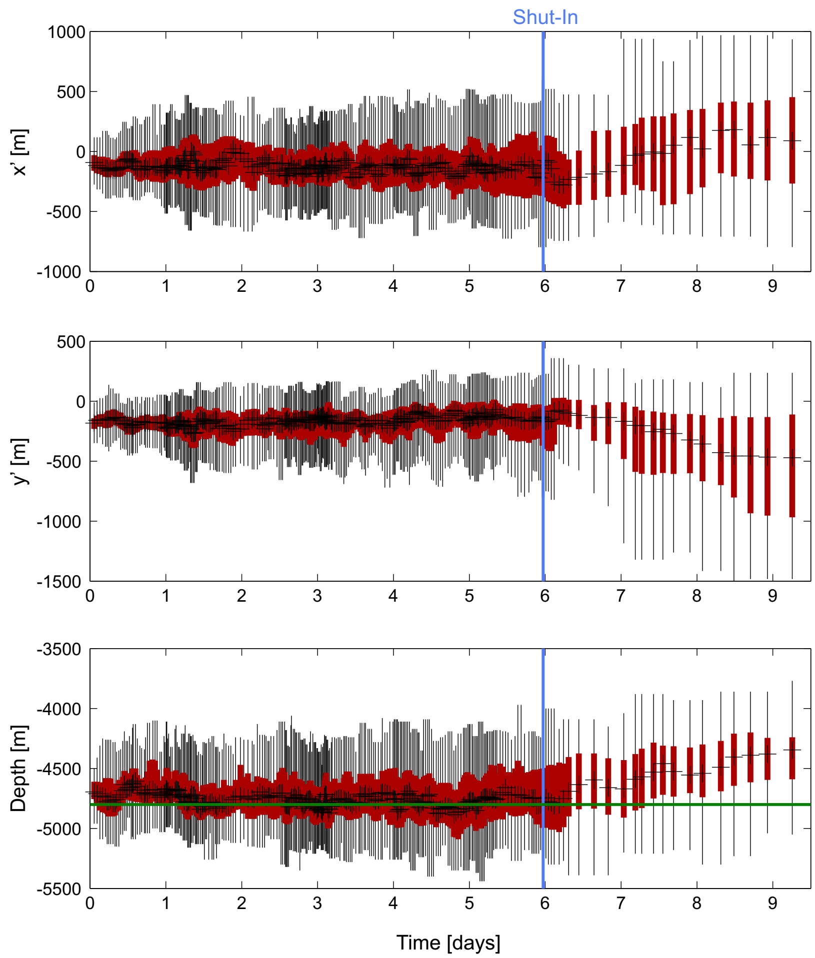

Figure 2. Boxplots for each coordinate in a rotated coordinate system. Black crosses are the median value for each time bin, red bars indicate the 25 and 75 percentiles, and black lines give the total range of values except for extreme outliers. The green line approximates the transition from the alterated monzogranite on top to the two-mica granite on bottom (Hooijkaas et al. 2006).

moving windows of 100 events each, overlapping by 25 events on either side. For each bin we display the statistical distribution of seismicity along each coordinate by means of the median, the 25 and 75 percentiles and the total scatter of locations in individual boxplots (Figure 2). During the stimulation phases no obvious trend is seen in either of the coordinates, which means that the seismic cloud grows similarly in all directions. However, this changes considerably upon shut-in when clear trends become discernible on all three coordinate components. The x'-component does not show any systematic changes until one day after injection. However from that point it shows a drop of the median coordinate by about 150 m, dropping further later on. The y'-component shows a jump by 150 m two hours after shut-in. Then, after one more day median coordinates drop considerably to regions previously untouched. The vertical z'-component shows a remarkably steady decrease of depth starting two hours after shut-in, continuing till the end of the recording.

During the later stimulation of well GPK3 in 2003 a dual stimulation was performed by also injecting in GPK2 5.5 days after start of injection in GPK3 (Dorbath et al. 2009). GPK2 was shut-in after 30 hours of injection, while injection in GPK3 continued for another three days. A similar behavior of the z'-component as described above for the stimulation in 2000 is observed upon shut-in of GPK2. No peculiarities are found for the shut-in of GPK3 later on. Therefore we conclude that GPK2 shows a special behavior of shut-in which is probably related to the structures connected to the well and reactivated during the stimulation operations.

Our interpretation of this observation is constituted of different elements. First we have to note that the open hole section is situated in two different facies of granite. After Hooijkaas et al. (2006) the crystalline basement constitutes of a two-mica granite and a more altered porphyritic granite on top of it. The boundary between the two granites was found at a depth of 4820 m and 4836 m (MD) at the wells GPK2 and GPK3, respectively. The transition between these two granite facies is marked in Figure 2 (bottom) by the green line. During injection seismicity occurs on both sides of this transition depth. However, after shut-in seismicity systematically migrates into the shallower porphyritic granite facies. This might be due to the contrast in mechanical properties, such as fracture compliance, friction angle and compressive strength of the two granite facies. Second, the planar features visible in the relocations by Calò et al. (2011) after shut-in demonstrate that few large fractures have been reactivated upon shut-in. As demonstrated by Schoenball et al. (2012) for the same stimulation experiment, rupture of small asperities of a larger fault structure can trigger rupture on neighboring asperities of the same fault structure by static stress transfer. During the injection period however, seismicity occurred in a volumetric fracture network rather than on single fracture structures. In such an environment, the triggering mechanism is less effective. Additionally, the perturbation of the stress field by the increased pore fluid pressure is expected to be much larger close to the well, than more than 1 km away from the well. Therefore static stress transfer contributes only negligibly to the total stress perturbation close to the well and especially during injection (Catalli et al. 2012). Complementary observations of variations of the electric potential during and after the stimulation revealed a remarkable increase of the streaming potential following shut-in (Darnet et al. 2006). This is interpreted as a persistent fluid flow in the reservoir following shut-in. This underpins our hypothesis that following shut-in fluid is pushed into single fractures leading to high flow rates and enhanced seismicity.

Conclusions

We have shown remarkable features of well GPK2 at Soultz when subjected to hydraulic stimulation and specifically shut-in. While no trend in the location of seismicity was observed during injection a clear trend was observed for the shut-in period. Unlike observations in other wells at Soultz show, seismicity starts to migrate upwards just after shut-in. This could be related (1) to the presence of two mechanically different granite facies and (2) to large scale fault structures which permit propagation of seismicity e.g. by static stress transfer.

Acknowledgements

We thank EOST, Strasbourg for providing the seismic catalog and GEIE for providing the hydraulic data. We are grateful to EnBW Energie Baden-Württemberg AG for financial support.

References

Baisch, S., Vörös, R., Rothert, E., Stang, H., Jung, R., & Schellschmidt, R. (2010). A numerical model for fluid injection induced seismicity at Soultz-sous-Forets. *International Journal of Rock Mechanics and Mining Sciences*, *47*(3), 405–413. doi:10.1016/j.ijrmms.2009.10.001

Barth, A., Wenzel, F., & Langenbruch, C. (2013). Probability of earthquake occurrence and magnitude estimation in the post shut-in phase of geothermal projects. *Journal of Seismology*. doi:10.1007/s10950-011-9260-9

Bommer, J. J., Oates, S., Cepeda, J. M., Lindholm, C., Bird, J., Torres, R., Marroquín, G., et al. (2006). Control of hazard due to seismicity induced by a hot fractured rock geothermal project. *Engineering Geology*, *83*(4), 287–306. doi:10.1016/j.enggeo.2005.11.002

Bönnemann, C., Schmidt, B., Ritter, J., Gestermann, N., Plenefisch, T., Wegler, U., Schulz, R., Heidbach, O., et al. (2010). *Das seismische Ereignis bei Landau vom 15. August 2009*. Hannover.

Calò, M., Dorbath, C., Cornet, F. H. H., & Cuenot, N. (2011). Large-scale aseismic motion identified through 4-D P-wave tomography. *Geophysical Journal International*, *186*(3), 1295–1314. doi:10.1111/j.1365-246X.2011.05108.x

Catalli, F., Meier, M.-A., & Wiemer, S. (2012). The role of Coulomb stress changes for injection induced seismicity. *Geophysical Research Letters*, *40*, 72–77. doi:10.1029/2012GL054147

Charléty, J., Cuenot, N., Dorbath, L., Dorbath, C., Haessler, H., & Frogneux, M. (2007). Large earthquakes during hydraulic stimulations at the geothermal site of Soultz-sous-Forêts. *International Journal of Rock Mechanics and Mining Sciences*, *44*(8), 1091–1105. doi:10.1016/j.ijrmms.2007.06.003

Dorbath, L., Cuenot, N., Genter, A., & Frogneux, M. (2009). Seismic response of the fractured and faulted granite of Soultz-sous-Forets (France) to 5 km deep massive water injections. *Geophysical Journal International*, *177*(2), 653–675. doi:10.1111/j.1365-246X.2009.04030.x

Dyer, B. C. (2000). *Soultz GPK2 stimulation June / July 2000, seismic monitoring*. SOCOMINE.

Evans, K., Zappone, A., Kraft, T., Deichmann, N., & Moia, F. (2012). A survey of the induced seismic responses to fluid injection in geothermal and CO2 reservoirs in Europe. *Geothermics*, *41*, 30–54.

Genter, A., Evans, K., Cuenot, N., Fritsch, D., & Sanjuan, B. (2010). Contribution of the exploration of deep crystalline fractured reservoir of Soultz to the knowledge of enhanced geothermal systems (EGS). *Comptes Rendus Geoscience*, *342*(7-8), 502–516. doi:10.1016/j.crte.2010.01.006

Gérard, A., Baumgärtner, J., Baria, R., & Jung, R. (1997). An attempt towards a conceptual model derived from 1993-1996 hydraulic operations at Soultz. *NEDO International Geothermal Symposium*. NEDO, Sendai, Japan.

Goertz-Allmann, B. P., Goertz, A., & Wiemer, S. (2011). Stress drop variations of induced earthquakes at the Basel geothermal site. *Geophys. Res. Lett.*, *38*(9), L09308. doi:10.1029/2011gl047498

Häring, M. O., Schanz, U., Ladner, F., & Dyer, B. C. (2008). Characterisation of the Basel 1 enhanced geothermal system. *Geothermics*, *37*(5), 469–495. doi:10.1016/j.geothermics.2008.06.002

Hooijkaas, G. R., Genter, A., & Dezayes, C. (2006). Deep-seated geology of the granite intrusions at the Soultz EGS site based on data from 5km-deep boreholes. *Geothermics*, *35*(5-6), 484–506. doi:10.1016/j.geothermics.2006.03.003

Klein, F. W. (1978). *Hypocenter location program HYPOINVERSE, Part1: user guide to version 1,2,3 and 4. U.S. Geological Survey, Open-file Report 78-694* (p. 113).

Langenbruch, C., & Shapiro, S. A. (2010). Decay rate of fluid-induced seismicity after termination of reservoir stimulations. *Geophysics*, *75*(6), MA53–MA62. doi:10.1190/1.3506005

Michelet, S. (2002). *Rock site Source Parameter Analysis and Interpretation for Microseismic Data from the Soultz-sous-Forêts Hot Dry Rock Site*. PhD thesis, Université Louis Pasteur - Strasbourg.

Schoenball, M., Baujard, C., Kohl, T., & Dorbath, L. (2012). The role of triggering by static stress transfer during geothermal reservoir stimulation. *J. Geophys. Res.*, *117*(B9), B09307. doi:10.1029/2012jb009304

Shapiro, S. A., Audigane, P., & Royer, J.-J. (1999). Large-scale in situ permeability tensor of rocks from induced microseismicity. *Geophysical Journal International*, *137*(2), 207–213.

Weidler, R., Gérard, A., Baria, R., Baumgärtner, J. & Jung, R. (2002). Hydraulic and micro-seismic results of a massive stimulation test at 5 km depth at the European Hot-Dry-Rock test site, Soultz, France. *Twenty-Seventh Workshop on Geothermal Reservoir Engineering*, vol. 27, pp. 95–100, Stanford University, Stanford, California, USA.