Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Multi-fracturing and Cyclic Hydraulic Stimulation Scenarios to Develop Enhanced Geothermal Systems - Feasibility and Mitigation Strategies to Reduce Seismic Risk

Günter Zimmermann[1], Hannes Hofmann[2], Tayfun Babadagli[2], Jeoung Seok Yoon[1], Arno Zang[1], Fiorenza Deon[1], Luca Urpi[1], Guido Blöcher[1], Alireza Hassanzadegan[1], Ernst Huenges[1]

[1]Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany

[2]Department of Civil & Environmental Engineering, University of Alberta, Edmonton, AB, Canada

E-mail address: guenter.zimmermann@gfz-potsdam.de

Keywords: Enhanced Geothermal Systems, hydraulic fracturing, induced seismicity

ABSTRACT

Enhanced Geothermal Systems (EGS) are required to extract economic amounts of heat from low permeable geothermal reservoirs. We present various hydraulic stimulation scenarios to develop suitable down hole heat exchangers applying multi-fracturing designs and cyclic stimulation treatments. The aim is to control the fracture propagation and simultaneously reduce the risks of unwanted seismic events beyond a certain threshold depending on the vulnerability and exposure of people, buildings and infrastructure.

Stimulation treatments have to be designed individually for different environments. The layout depends on the geological environment as the recent stress field, preexisting fractures and fault zones and the properties of the different geological units involved. Based on the geological environment the technical and economical feasibility have to been proven. We present simulations and sensitivity analyses of hydraulic fracturing treatments from different geological environments. These include Rotliegend sandstones in the North-east German Basin, Limestone and Sandstone formations from the Western Canadian Sedimentary Basin and Granites from the Upper Rhine Valley graben structure.

The simulations include gel-proppant treatments to create tensile fractures as well as waterfrac treatments to create shear fractures to address the different rock types and their self propping potential to achieve sustainable fracture conductivities. We show that cyclic stimulation schemes can reduce the hazard potential in terms of decreased induced seismicity (less number of events with lower moment magnitudes and higher b-value) if compared to constant rate injections. Multiple fracturing treatments in deviated wells offer the opportunity to stepwise develop a suitable heat exchanger in performing a number of small scale stimulations which reduce the total number and magnitude of unwanted seismic events.

1. INTRODUCTION

The scientific principles of reservoir engineering are decisive keys for an appropriate development of geothermal resources. Conventional geothermal resources cover a wide range of uses for power production and direct application. For unconventional systems a large scientific and industrial community has been involved in developing so-called Enhanced Geothermal Systems (EGS). The concept involves different ways to increase access to heat at depth by improving exploration methods, drilling and reservoir assessment technologies for deep geothermal resources, and, ultimately, the stimulation of low-permeability reservoirs. These stimulation treatments are well established and well understood methods with ample experience in the oil and gas industry. To achieve the best results in terms of developing an appropriate down hole heat exchanger and a strategy to reduce the risk of undesired seismic events, this method should be designed individually depending on the reservoir rock properties, stratigraphic sequences, and structural geological setting. Radiated seismic energy is primarily related to the ability of the rock to shear which requires that there be a significant difference between the principal stresses. Designing a special concept of the well path, including sub horizontal sections in the reservoir and special alignment according to the stress field, offers the possibility for multiple fracture treatments in a well to develop the geothermal field. In case of generating mostly tensile fractures with minor shear displacement, sustainability of fracture opening can be assured by adding proppants (meshed sand or man-made ceramics). A cyclic injection design in combination with the multi-frac concept tends to produce less seismic events with significant lower total seismic energy release if compared to a constant flow rate and a single fracture treatment.

2. CASE STUDIES

2.1 Rotliegend sandstones (Groß Schönebeck, Germany)

At the geothermal research site at Groß Schönebeck several stimulation treatments were performed over the last ten years (e.g. Zimmermann et al., 2011). Here, we focus on the gel-proppant treatments (with meshed sand or man-made ceramics) and discuss the benefits of this kind of stimulation. The sandstone section is at about a 4100 m depth and the task has been to activate the near wellbore environment to connect the permeable sandstone layer to the well. This treatment was chosen to avoid generating mostly tensile fractures with minor shear displacement, ensuring sustainability of fracture opening by adding proppants. The aperture of the generated fracture depends on the amount of proppants used and can be up to 10 mm. The proppants are sphere like ceramics, which can be coated (a kind of resin) or uncoated, and consist of a specific corundum ($Al2O3$) and amorphous $SiO2$ fraction which depends on the desired mechanical strength of the material. The typical diameter varies between 0.5 and 2 mm. One crucial aspect is the mechanical and chemical integrity during the life cycle of the geothermal system to avoid closure of the fracture or unwanted reactions with the formation fluids (Deon et al., 2013). We could prove the long term stability from some retrieved proppants which did not show any damages after being in the formation for several years (Fig. 1). Transport of the proppants into the fractures is achieved with a high viscous gel, which disintegrates after successful placing the proppants at their designated location and is then flushed out. The treatment was simulated with the program FRACPRO (Cleary, 1994) by variation of flow rates and proppant concentrations until the best proppant placement result is achieved. Based on this configuration the real treatment was performed. Fig. 2 shows the result of the simulation based on the real stimulation treatment data. A production test after the stimulation confirmed the success of the treatment (Zimmermann & Reinicke, 2010). Almost no induced seismic events could be observed during and after the treatment (Kwiatek et al., 2010).

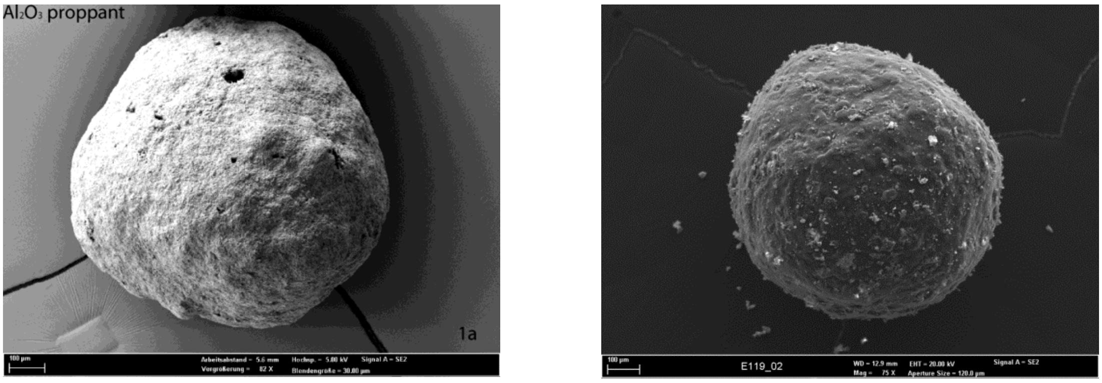

Figure 1: Scanning electron microscope images of proppants. Left: corundum based proppant before positioning in the well; right: retrieved proppant after several years in the well (modified from Deon et al., 2013).

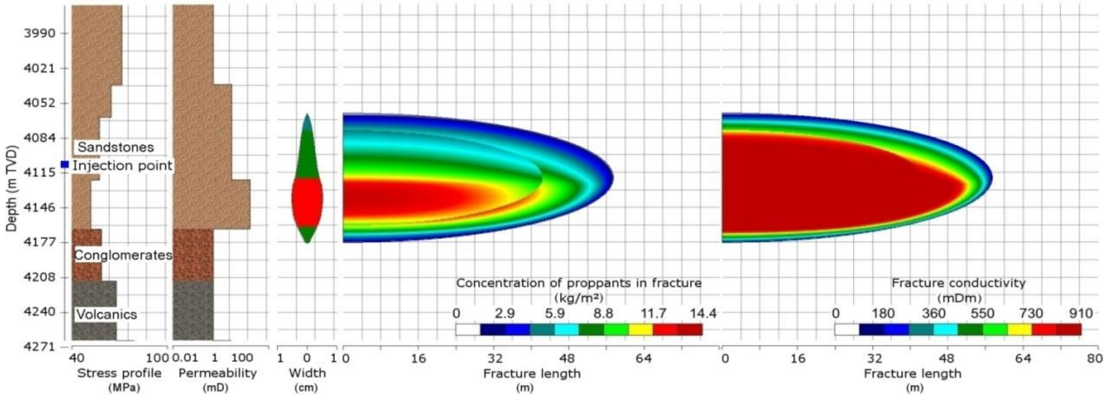

Figure 2: Results from the simulation of a gel-proppant frac based on the stimulation treatment data. Illustration of the proppant concentration and the achieved fracture conductivity (modified from Zimmermann and Reinicke, 2010).

2.2 Limestones and sandstones (Alberta Basin, Canada)

The Canadian province of Alberta has a high demand of thermal energy for both industrial (e.g. Hofmann et al., 2014a) and residential applications (e.g. Hofmann et al., 2013, 2014b), which currently is mainly obtained by burning natural gas. EGS technology could provide an alternative source for thermal energy production from deep aquifer systems in the sedimentary rocks of the Alberta basin that would be both sustainable and reduce greenhouse gas emissions. To achieve sufficiently high flow rates for an economic use the reservoir rocks need to be hydraulically stimulated. Fracturing simulations were performed with fracturing simulator MFrac (Meyer, 2011), and, similar to the Groß Schönebeck case, only gel-proppant treatments were analyzed.

A regional scale geological model of the Central Western Canadian Sedimentary Basin has been developed for an area around Edmonton with a horizontal extent of 200 km x 160 km (Weides et al., 2013). This model is based on stratigraphic data from about 7000 wells and includes all major formations from the surface to the Precambrian basement. In Central Alberta, four Devonian carbonate formations and the Cambrian Basal Sandstone Unit are identified as the highest geothermal potential zones. Figs. 3 and 4 show simulations of two scenarios of fracture propagation in the Cambrian Basal Sandstone Unit (Hofmann et al., 2014). The fracture propagation and, hence, the effective height that can be achieved, depends on the actual stresses within the Basal Sandstone Unit and the actual stress gradient within the Precambrian basement. An increased stress confinement decreases the additional growth into the basement and decreases the heat exchanger area compared to the "unconfined" scenario in Fig. 3. However, for both scenarios the Basal Sandstone Unit seems to be best suited for permeability enhancements by the conventional gel-proppant fracturing treatments. The other formations are less suitable for massive stimulation treatments due to a lack of a sufficient upper stress barrier or insufficient knowledge about the confinement potential. Based on the different initial reservoir permeabilities optimum fracture and well arrangements vary for each formation (Hofmann et al., 2014). In all investigated formations multiple stimulation treatments are needed to achieve economic production rates. The need for multiple stimulation treatments was also pointed out in similar studies, e.g. for the Malm limestone formation in the western part of the Molasse Basin in southern Germany (Hofmann et al., 2014c) and the Precambrian basement rocks in northern Alberta (Hofmann et al., 2014a).

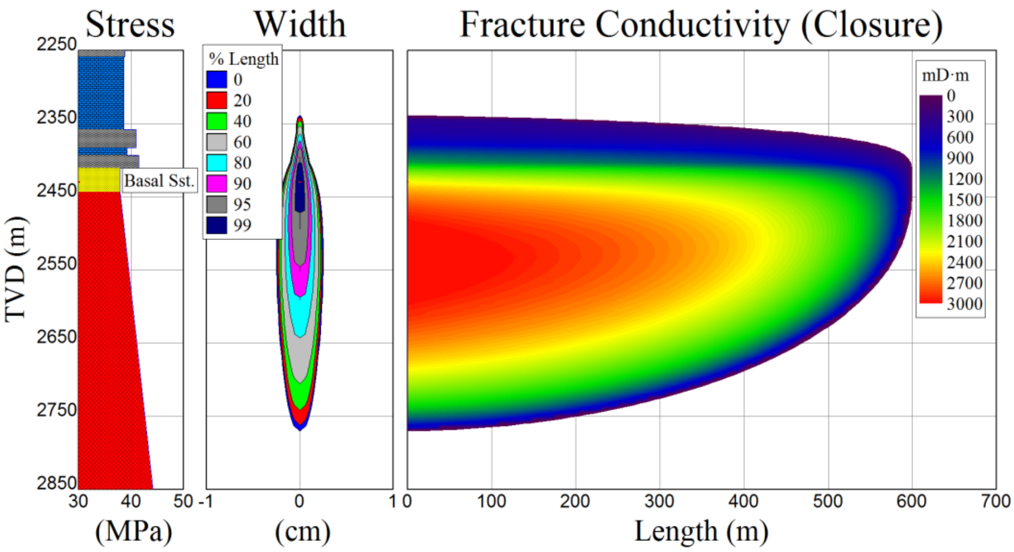

Figure 3: Modeled "unconfined" fracture growth from the Basal Sandstone Unit into the Precambrian basement rocks (Hofmann et al., 2014b).

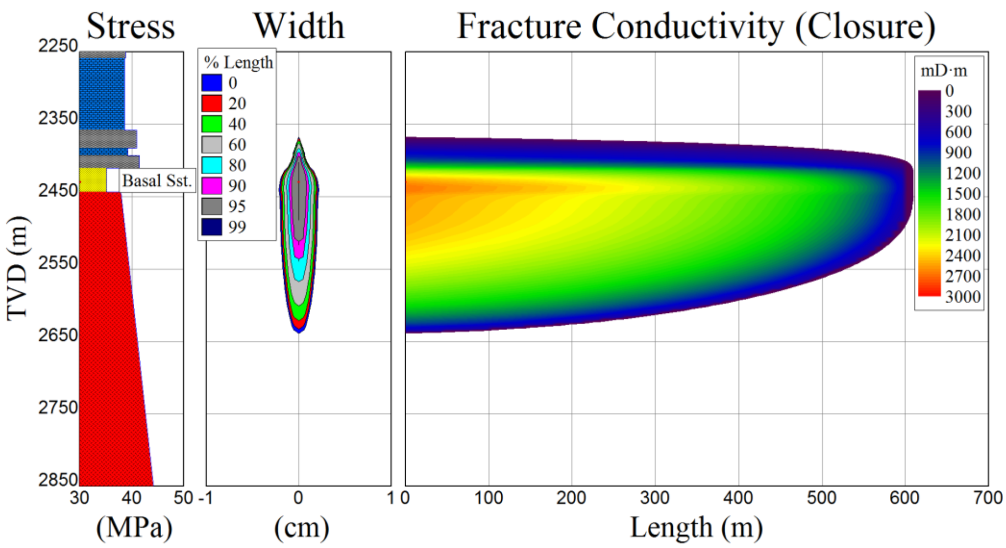

Figure 4: A lower stress in the Basal Sandstone Unit leads to the development of fractures with less height (Hofmann et al., 2014b).

2.3 Granites (Soultz, France)

To study the stimulation of multiple fracture systems in a crystalline environment, a conceptual 2D reservoir model was developed. We used the didcrete element geomechanical modeling software PFC2D (Itasca, 2008). The rock mass is modeled as an aggregate of non-uniform circular particles bonded together with Mohr-Coulomb strength parameters. For the theoretical background we refer to the work of Potyondy and Cundall (2004). The stress field was chosen to be anisotropic and only the horizontal stresses were taken into account. The petrophysical properties of the network were taken from the granites of the geothermal site Soultz-sous-Forêts, France (e.g. Baria et al., 1999; data taken from Yoon et al., 2014). The assumed depth is 4000 m. The model consists of 3 wells at a distance of 500 m from each other (Fig. 5). Various injection scenarios were modeled and the spatiotemporal developments of induced fractures were compared. The aim of optimization of the hydraulic treatments has been the development of an effective down hole heat exchanger (Yoon et al., 2013).

The method of multiple fracture generation offers a technically feasible option to increase the total surface of a heat exchanger in a reservoir. In this respect it is favorable that tensile fractures and corresponding shear fractures propagate mainly perpendicular to the least principle stress. This enables drilling in the target section of the well a deviated or horizontal section in the direction of the least principle stress, which, in this case, is the least principle horizontal stress direction. Isolating several parts of this section and stimulating it separately, it is possible to develop several fractures in a parallel alignment. Compared to a single massive stimulation, this offers the opportunity to generate a larger surface based on a certain number of smaller surfaces. Simultaneously, the released seismic energy in critically stressed reservoirs can be reduced considerably and decreases the probability of felt seismic events.

Two different scenarios with a constant flow rate and a cyclic injection scheme were compared. In both cases the injection took place at the three injection points of the model. Fig. 6 and Fig. 7 show the schedules and the results of constant and cyclic injection, respectively in terms of fluid pressure (normalized by the fracture breakdown pressure, FBP), moment magnitude, radiated seismic energy, hydraulic energy and cumulative seismic energy. Compared to the constant injection scheme the cyclic injection leads to a reduction of the number of seismic events as well as the number of events exceeding a certain threshold (here Mw >1). This holds true for the radiated seismic energy as well.

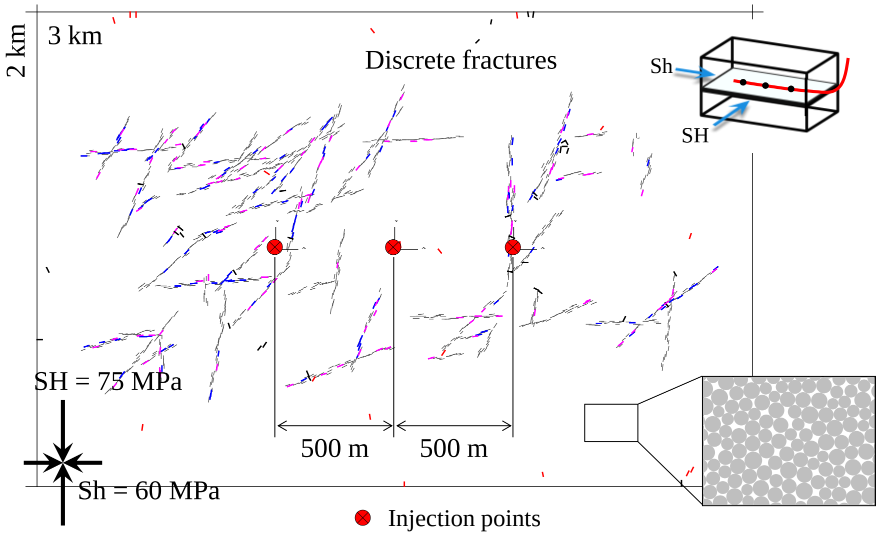

Figure 5: Representation of a fractured 2-D reservoir model. The model dimensions are 3 km x 2 km in an anisotropic in-situ stress field with the horizontal stresses SH=75 MPa und Sh=60 MPa. The three injection points in the horizontal section of the well are located at a distance of 500 m to each other.

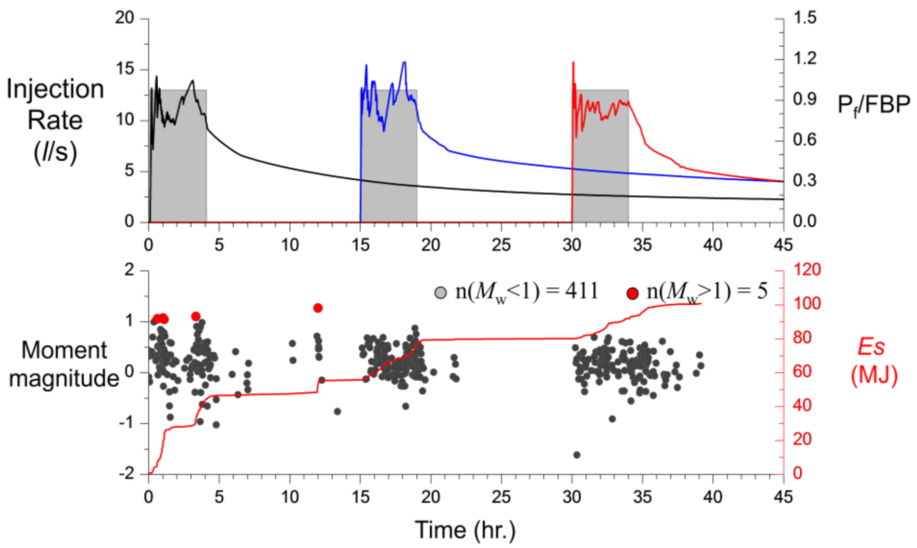

Fig. 6: Modeled results from constant rate injection. Rate of injection (top left axis), fluid pressure normalized by the fracture breakdown pressure (FBP) at the three injection points (top right axis), moment magnitudes Mw (bottom left axis) and cumulative amount of seismic radiated energy Es (bottom right axis) of the induced seismic events. Induced seismic events with Mw>1 are marked by red dots.

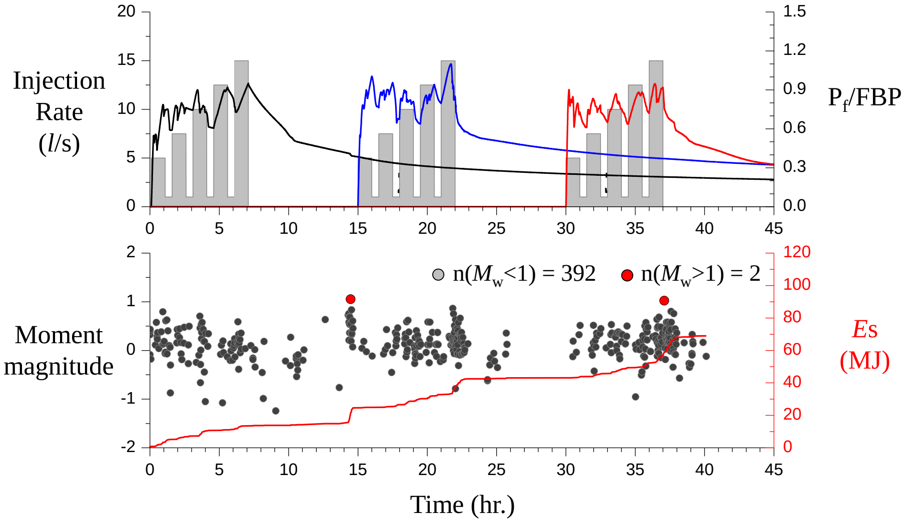

Fig. 7: Modeled results from cyclic rate injection. Rate of injection (top left axis), fluid pressure normalized by the fracture breakdown pressure (FBP) at the three injection points (top right axis), moment magnitudes Mw (bottom left axis) and cumulative amount of seismic radiated energy Es (bottom right axis) of the induced seismic events. Induced seismic events with Mw>1 are marked by red dots.

3. CONCLUSIONS

Hydraulic stimulations in EGS systems are carried out selectively, uniquely and controlled to achieve sufficient flow rates for the economic utilization of the earth's heat for direct heating and the provision of base load electricity. One focus of geothermal technology development is the sustainability of fracture opening. In case of generating mostly tensile fractures with minor shear displacement (and hence no self propping of the fractures), supporting procedures like adding meshed sand or proppants should be performed to keep the fractures open. This is especially the case for production wells with reduced formation pressure during production. The other focus is the optimization of stimulation treatments with respect to unwanted effects like induced seismicity and hence the reduction of the probability of felt events. Designing a special concept of the well path, including sub horizontal sections in the reservoir and special alignment according to the stress field, offers the possibility for multiple fracture treatments in a well to develop the geothermal field. In this respect special procedures like the cyclic stimulation and the multi-fracturing concepts are considered to optimize access to the geothermal heat.

REFERENCES

Baria, R., Baumgärtner, J., Gérard, A., Jung, R., and Garnish, J.: European HDR research programme at Soultz-sous-Forêts (France) 1987–1996. *Geothermics* **28**, (1999), 655–669.

Cleary, M.P.: Critical Issues in Hydraulic Fracturing of High-Permeability Reservoirs, *Proceedings*, European Production Operations Conference and Exhibition, 15-17 March, Aberdeen, United Kingdom, (1994).

Deon, F., Regenspurg, S., Zimmermann, G.: Geochemical interactions of Al2O3-based proppants with highly saline geothermal brines at simulated in situ temperature conditions. *Geothermics*, **47**, (2013), 53-60.

Economides, M.J., and Nolte, K.G.: *Reservoir Stimulation*, 3rd Edition. Wiley and Sons Ltd., United Kingdom (2000).

Hofmann, H., Weides, S., Babadagli, T., Zimmermann, G., Moeck, I., Majorowicz, J. and Unsworth, M.: Integrated Reservoir Modeling for Enhanced Geothermal Energy Systems in Central Alberta, Canada, *Proceedings*, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2013), SGP-TR-198.

Hofmann, H., Babadagli, T., and Zimmermann, G.: Hot water generation for oil sands processing from enhanced geothermal systems: process simulation for different hydraulic fracturing scenarios, *Applied Energy*, **113**, (2014a), 524-547.

Hofmann, H., Weides, S., Babadagli, T., Zimmermann, G., Moeck, I., Majorowicz, J., and Unsworth, M.: Potential for enhanced geothermal systems in Alberta, Canada, *Energy*, **69**, (2014b), 578-591.

Hofmann, H., Blöcher, G., Börsing, N., Maronde, N., Pastrik, N., and Zimmermann, G.: Potential for enhanced geothermal systems in low permeability limestones – stimulation strategies for the Western Malm karst (Bavaria), *Geothermics*, **51**, (2014c), 351-367.

Huenges, E.: *Geothermal Energy Systems : Exploration, Development and Utilization*, Ed. E. Huenges, Wiley-VCH, (2010), pp 463.

Kwiatek, G., Bohnhoff, M., Dresen, G., Schulze, A., Schulte, T., Zimmermann, G., and Huenges, E.: Microseismicity induced during fluid-injection: A case study from the geothermal site at Groß Schönebeck, North German Basin, *Acta Geophysica*, **58 (6)**, (2010), 995-1020.

Itasca Consulting Group Inc.: *PFC2D – Particle Flow Code in 2 Dimensions*, Itasca, Version 4.0, Minneapolis, (2008).

Meyer & Associates: *User's Guide Meyer Fracturing Simulators*, 9th ed, (2011).

Moeck, I., Kwiatek, G., and Zimmermann, G.: Slip- tendency analysis, fault reactivation potential and induced seismicity in a deep geothermal reservoir, *Journal of Structural Geology*, **31 (10)**, (2009), 174-1182.

Potyondy, D.O., and Cundall, P.A.: A bonded-particle model for rock. *International Journal of Rock Mechanics Mining Sciences*, **41**, (2004), 1329–1330.

Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., Drake, E.M., Garnish, J., Livesay, B., Moore, M.C., Nichols, K., M., Petty, S., Toksöz, M.N., Veatch Jr., R.W., Baria, R., Augustine, C., Murphy, E., Negraru, P., Richards, M.: The Future of Geothermal Energy: Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st century, *Massachusetts Institute of Technology*, (2006), ISBN: 0-615-13438-6.

Weides, S., Moeck, I., Majorowicz, J., Palombi, D., Grobe, M., Mareschal, J.-C.: Geothermal exploration of Paleozoic formations in Central Alberta, *Canadian Journal of Earth Sciences*, **50 (5)**, (2013), 519-534.

Yoon, J.-S., Zang, A., and Stephansson, O.: Numerical investigation on optimized stimulation of intact and naturally fractured deep geothermal reservoirs using hydro-mechanical coupled discrete particles joints model, *Geothermics*, (2014 online).

Yoon, J. S., Zimmermann, G., and Zang, A.: Multi-fracturing in geothermal reservoir and induced seismicity using particle based, discrete element-fracture network model, *Proceedings*, 38th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, (2013).

Zang, A., Yoon, J. S., Stephansson, O., and Heidbach, O.: Fatigue hydraulic fracturing by cyclic reservoir treatment enhances permeability and reduces induced seismicity, *Geophysical Journal International*, **195 (2)**, (2013), 1282-1287.

Zimmermann, G., Moeck, I., and Blöcher, G.: Cyclic waterfrac stimulation to develop an Enhanced Geothermal System (EGS) – Conceptual design and experimental results, *Geothermics*, **39**, (2010), 59-69.

Zimmermann, G., and Reinicke, A.: Hydraulic stimulation of a deep sandstone reservoir to develop an Enhanced Geothermal System: Laboratory and field experiments, *Geothermics*, **39**, (2010), 70-77.