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Concepts of soft stimulation treatments in geothermal reservoirs

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ABSTRACT

Enhanced geothermal systems (EGS) allow for widespread use of enormous untapped geothermal energy potential. EGS measures are generally intended to improve productivity (or injectivity) of a geothermal reservoir by increasing the overall transmissivity of the reservoir rocks. Soft stimulation approaches are under development to enhance the reservoir performance with treatments that negate potential hazards such as induced seismicity or environmental contamination. Scientific progress has been made on topics such as fluid-rock interaction on a local scale, determination of the stress field on local and regional scale and analysis of induced seismicity. Hydraulic treatment concepts including mitigation of triggered or induced seismic events were also proposed as an outcome of the GEISER-project.

A hydraulic stimulation treatment, designed to incorporate the results of this scientific progress, has been performed in a granodioritic hard rock reservoir, including complete flowback of the injected fluid volume, at Pohang (South Korea), with the result that no earthquake of moment magnitude ≥2.0 was induced. However, results of this controlled treatment demonstrated insufficient impact on enhancement of system productivity so far. Experience at Klaipeda (Lithuania) indicates that sandstone reservoirs require a complex analysis of the interaction of physical, chemical and biological processes during operation. Based on this, we have developed an iterative approach with a sequence of treatment, analysis, feedback, ranking of induced processes and final measures. Our approach resulted in comprehensive guidance for adequate treatment of unproductive sandstone reservoirs.

These various methods are dependent on the geological system, comprising the rocks, the rock structures, the tectonic situation and the stress field. Hydraulic treatments sometimes induce

seismic events that can, in some cases, be felt at the surface and jeopardize public acceptance of a project. Hydraulic, thermal, and chemical treatments are options to address EGS requirements in different geological settings with different geothermal exploitation strategies. These issues are addressed by the DESTRESS (Demonstration of soft stimulation treatments in geothermal reservoirs) project.

1. Introduction

Besides controlled enhancement of the geothermal reservoir, sustainable operation presents a challenge, as newly opened fractures may close again with reduced reservoir pressure and because of chemical interactions, thus reducing permeability. This paper presents a concept-based approach to develop EGS while considering site-specific geological requirements. The overall objectives of DESTRESS are three-fold: i) to increase reservoir transmissivity, ii) to maintain productivity and iii) to minimize induced seismicity and other environmental impacts.

The overall concept covering these objectives is referred to as "soft-stimulation", a collective term that encapsulates specific reservoir stimulation techniques. Soft stimulation includes techniques such as cyclic/fatigue, multi-stage, thermal and chemical stimulation. The concepts are based on experience in previous projects, on developments in other fields (mainly in the oil and gas sector), and on scientific progress on topics such as fluid-rock interaction improved determination of stress fields, and the analysis of induced seismicity.

We shall demonstrate stimulation treatments that enhance reservoir performance in several geological settings covering both hard rocks (e.g. granites) and sediments (which, combined, represent ~80% of potential European geothermal reservoirs), and systems where operations may have caused significant reduction in productivity due to mineral precipitation. For each site-specific case, risks will be minimized, monitoring systems will be deployed and environmental impacts will be reduced. Lessons learned will be disseminated to the public. All the steps included in the DESTRESS approach are designed to be transferrable to other sites, so the concepts can become the basis for a standardized procedure for the development of EGS projects.

2. Business case

The goal is to demonstrate advanced stimulation treatment methods fulfilling environmental constraints based on fundamental risk management. Reith et al. 2017 have previously shown how the business case both for general geothermal deployment across Europe, and for individual cases within specific geological settings, can be evaluated, de-risked and improved. The cost of specific treatments and their benefits can be quantified using a cash flow analysis (fig.1). Stimulation leads to more thermal energy extraction and higher revenues; therefore, when natural productivity is low, investment in stimulation treatments is needed to produce economically viable projects. In general, the results of stimulation should lead to good practice for applying treatments, and their specific costs should be available for the geothermal industry. The goal is to reduce life cycle costs of geothermal heat or electricity and to estimate the required investment and resulting benefit from the treatment.

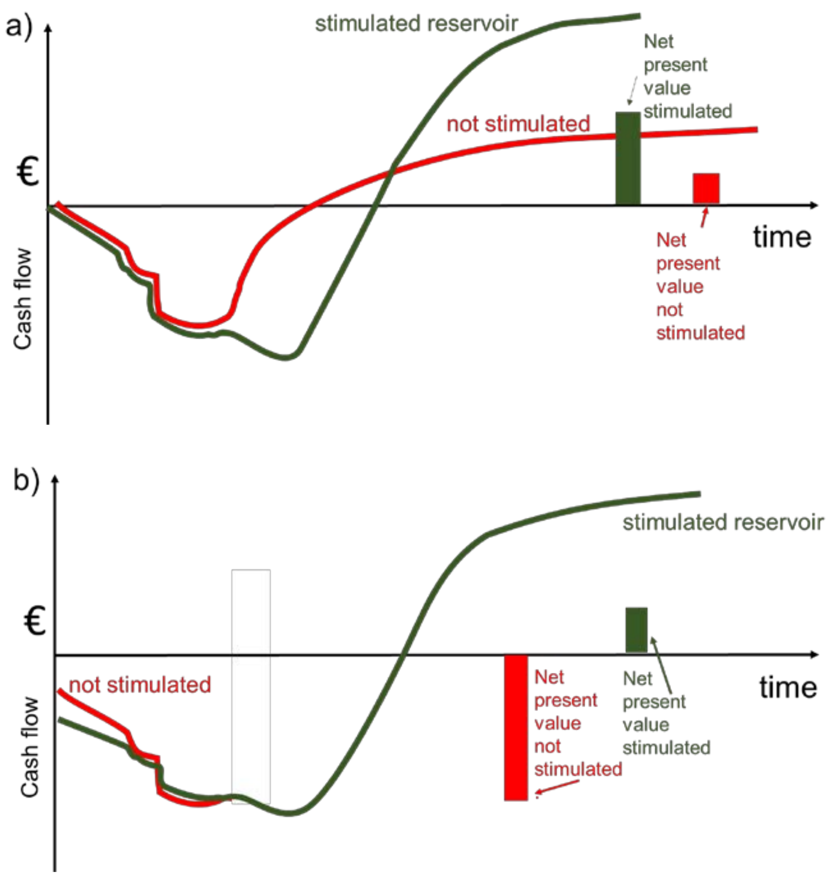


Figure 1: Cash flow and long-term (i.e. on a timescale of several decades, a typical project lifespan) net present value of geothermal projects: green = with stimulated reservoir and red = not stimulated reservoir. a) geothermal systems with (a priori) low productivity and b) geothermal systems with (a priori) no productivity. Treatments produce an increase in cash flow (resulting in steeper slope of longer duration) and improved net present value. Cash flow is calculated as revenue minus capital and operational expenditure. DESTRESS will contribute to quantifying such curves.

3. Sites

Geothermal sites at various stages of development were selected within DESTRESS. Sites with access to the reservoir with geothermal wells were chosen to demonstrate the DESTRESS soft stimulation concept (Table 1). Due to uncertainties in the development of all the sites, fall back options were provided for unforeseen situations such as problems with drilling. Several sites are available as contingency sites.

Two case studies were selected in this paper which cover the spread of geological settings for geothermal projects in Europe: sandstone reservoir rocks at Klaipeda, Lithuania (Section 4), and granodiorite reservoir rocks in Pohang, South Korea (Section 5). Both sites have not been fully treated (i.e. the target productivity was not yet reached), but significant intermediate steps are reported here.

Table 1: Site options to demonstrate the DESTRESS concept:

Site	Rock type	Production Horizon	Upper Depth (m)	Thick -ness (m)	T (°C)	Salinity (g/l) or el. conduct.	No of wells
Klaipeda (LT)	Clastic rocks (SS)	Lower Devonian (Viesvile formation) aquifer	990	128	38	92.8	4 wells since late 1990s
Westland (NL)	Clastic (fractured) rocks (SS)	Triassic	4000	175	140	~70	1 well 2017
Mezőberény (Hu)	Clastic rocks (SS)	Upper-Pannonian rocks of the Újfalui Formation	1600	98-121	88	5360 µS/cm	2 wells
Soultz-sous-Forêts (GPK4) (Fr)	Fractured granite	Carboniferous fractured granite	4500	500	200	~100	5 wells, operation since 2008
Rittershoffen (GRT1) (Fr)	Fractured clastic rocks (SS) and fractured granite	Fractured Triassic sandstone and Carboniferous fractured granite	1920	680	>160	~100	2 wells
Pohang (Ko)	Grano-diorite	Permian fractured granodiorite	~ 4000 top open hole	>1000	140	~3 / ~10	2 wells (1 dev.)
Haute-Sorne (CH)	Granite		5000	1700			planned

LT=Lithuania, HU= Hungary, Fr=France, Ko= South Korea, CH=Switzerland, GPK4 & GRT1=names of wells, SS=sandstone. Data were provided by site owner or determined within DESTRESS. The salinity values at Pohang are from wells PX-1 and PX-2, respectively. The value in well PX-1 might have been affected by previous well stimulation activity.

4. Case study for soft rocks: Klaipeda

Figure 2 shows the design of the Klaipeda low-enthalpy geothermal project; Fig. 3 shows the decline in injectivity observed over more than a decade of operation. Reasons for this injectivity decline were investigated. This site was selected to demonstrate different stimulation techniques in a sandstone reservoir within the DESTRESS project. Brehme et al. (2018) showed that due to low injectivity, production rates from the field are currently reduced, with negative commercial implications. When their flow is reversed, the injector wells exhibit productivity indices 40 times higher than their injectivity indices (fig. 3).

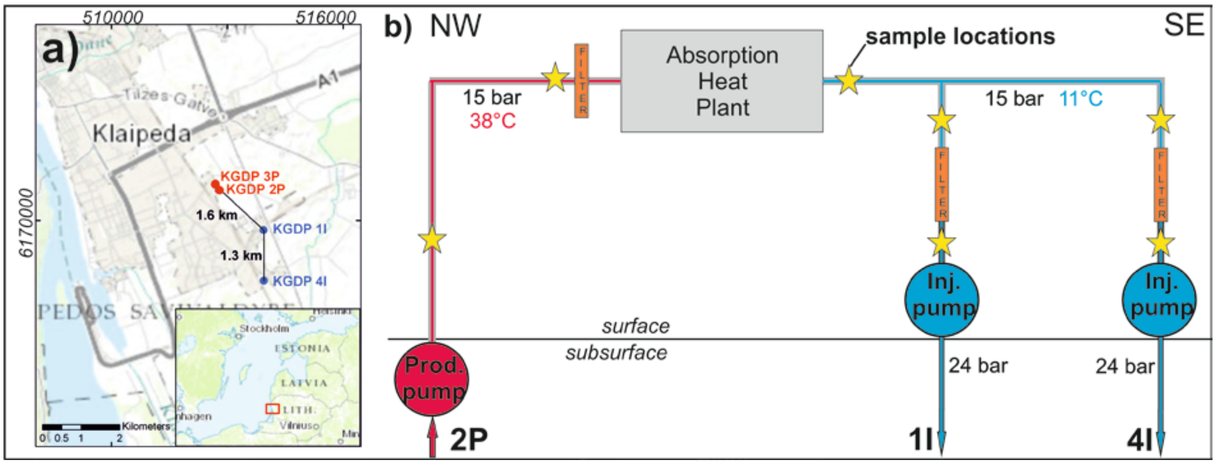


Figure 2: The geothermal plant at Klaipeda (Lithuania); a) location of wells (2P and 3P are production wells 2 and 3, 3P being unused, 1I= injection well 1, and 4I=injection well 4). b) arrangement of pumps and pressure and temperature of the transported fluids (Brehme et al. 2018).

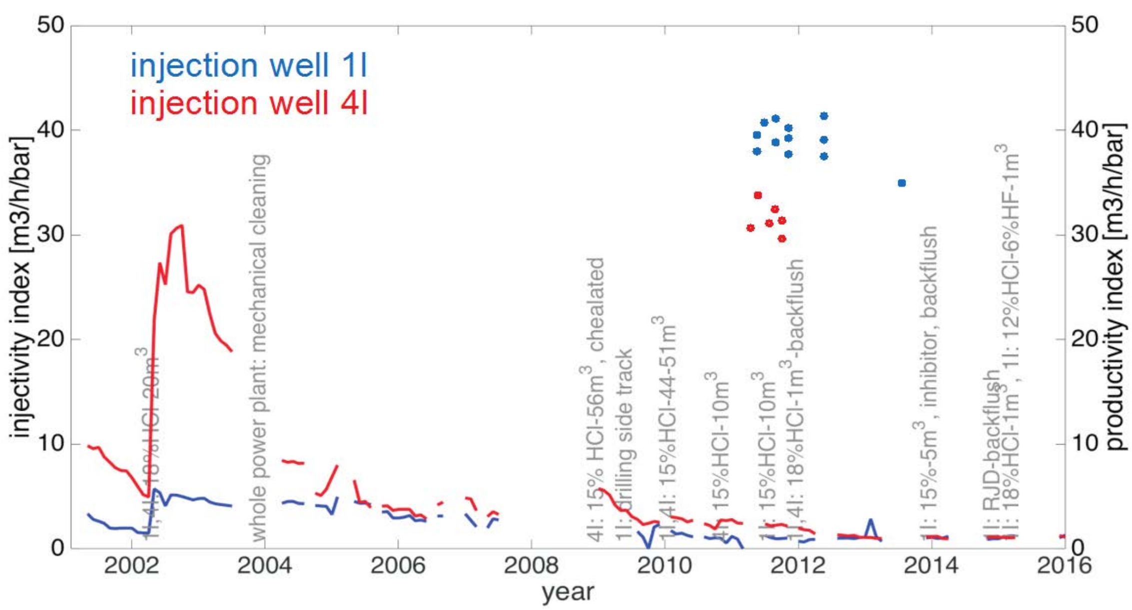


Figure 3: Injectivity and productivity indices of the two Klaipeda injection wells including effects of stimulation treatments between 2001 and 2016. Lines show daily measurements of injectivity index, dots show single production tests in well 1I (blue) and well 4I (red) (Brehme et al. 2018).

In 2001, the initial injectivity indices were 10 $m^3h^{-1}bar^{-1}$ in well 4I and 3 $m^3h^{-1}bar^{-1}$ in well 1I. After the start of geothermal heat production, injectivities began to decrease. A first acidizing attempt in 2002 resulted in injectivity increases from 5 to 31 $m^3h^{-1}bar^{-1}$ (well 4I) and 1 to 6 $m^3h^{-1}bar^{-1}$ (well 1I) (fig. 3). Since then, injectivity has progressively decreased to ~1 $m^3h^{-1}bar^{-1}$ in both wells. Several attempts have been made to overcome these low injectivities. Treatments include acidizing, reverse pumping, use of bactericides, radial jet drilling, and drilling a side track in one of the injection wells. However, these treatments achieved only short-term improvements and at most 1.3 (1I) and 2.7 $m^3h^{-1}bar^{-1}$ (4I) absolute injectivity increase. The strongest decrease was observed in 2003, when massive gypsum precipitations forced shutdown of the plant. At that time, the wells and surface installations had to be completely cleaned before restarting operations. Since then, a sodium phosphonate-based gypsum inhibitor has been added to the fluid at the production well head and gypsum precipitation has been successfully avoided.

In general, injectivity decline in aquifers is related to clogging processes in spatially correlated structures, where few highly permeable structures control the main flow volume. We assume that solids are entrained within the injection fluid of Klaipeda and clog in proportion to where they are injected. The few highly permeable structures are blocked by the finest particles originating from field operations and therefore injectivity drops rapidly leading to a near-wellbore damage zone. This clogging results in an exponential injectivity decline across the exposed interval (Brehme et al. 2018). Nevertheless, the Klaipeda geothermal field faces decreasing injectivities while productivities from these wells are remarkably higher. It is inferred that the declining injectivity is due to a skin effect close to the borehole, which can be partially removed by production.

Reasons for pore clogging at any site, such as this, should be understood and avoided as early as possible (e.g. during well completion), to minimize long-term aquifer degradation. Preliminary field data can be utilized to identify potential risks during initial reservoir development stages. The interaction of physical, chemical and biological processes is especially important to consider, for example microbiologically triggered corrosion.

Brehme et al. (2017) developed a new approach incorporating all relevant processes and adjusted production and injection scenarios based on multidisciplinary observations. Most potential scenarios at the Klaipeda site have been ranked based on a feedback adjustment procedure (fig. 4). Applying this method suggests that, besides fines migration, the most probable reasons for injectivity problems at Klaipeda are clogging of filter screens and/or pores by precipitation of minerals, corrosion-particles, biofilm, pollution by drilling mud, or a combination of these factors. As the next stage, borehole logs, camera inspection and production and injection tests have to be used to further rank scenarios. Specific stimulation treatments have to be designed after re-evaluation for each scenario. Precipitations and biofilm have to be removed and lifted by chemical-mechanical cleaning. Fine particles and corrosion material have to be removed by long-term production tests. The damaged zone in the open hole of the injection well has to be hydraulically bypassed, for example with frac-packs or similar methods. Any new observation is followed by a re-evaluation and re-ordering of scenarios based on an updated database.

Therefore, the feedback adjustment procedure is a promising approach for a sustainable reduction of formation damage.

However, operation of the Klaipeda plant has been paused since 2017, because it could not compete with waste-incineration or wood-pellet plants for economic supply of heat. Therefore, it was decided to demonstrate the soft stimulation and the feedback adjustment procedure at Mezőberény, a site in Hungary in a comparable geological setting (i.e., a sandstone reservoir) with similar injection problems.

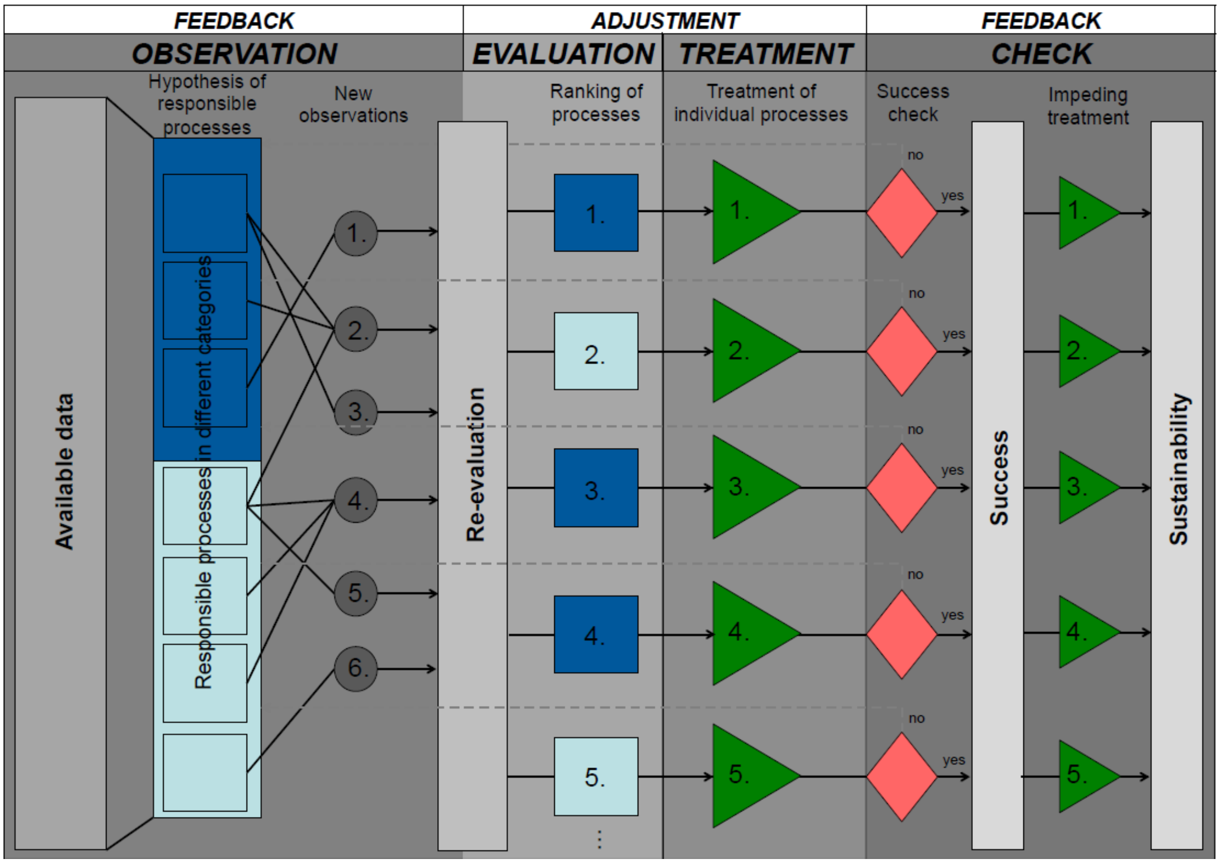


Figure 4: Feedback Adjustment Procedure for developing geothermal stimulation treatments (Brehme et al., 2017)

5. Case study for hard rocks: Pohang

The first Korean EGS project was launched in December 2010 by a consortium of research institutes, universities and industrial partners (Song et al., 2015). This site is located near the city of Pohang in the SE part Korea (fig. 5). The fractured granodiorite reservoir has been exploited by the deviated well PX-1 drilled to 4217 m TVD (true vertical depth) and the 4348 m deep vertical well PX-2. Ahead of DESTRESS involvement at the site, multiple stimulation treatments were performed in 2016 and 2017 to improve hydraulic performance (Kim et al., 2017; Park et al., 2017; Hofmann et al., 2017). A total of five hydraulic stimulations has been carried out from Jan 2016 to Sept 2017 with total injection of 12,691 m^3 and flow back of 6917 m^3 resulting in net injected volume of 5,734 m^3.

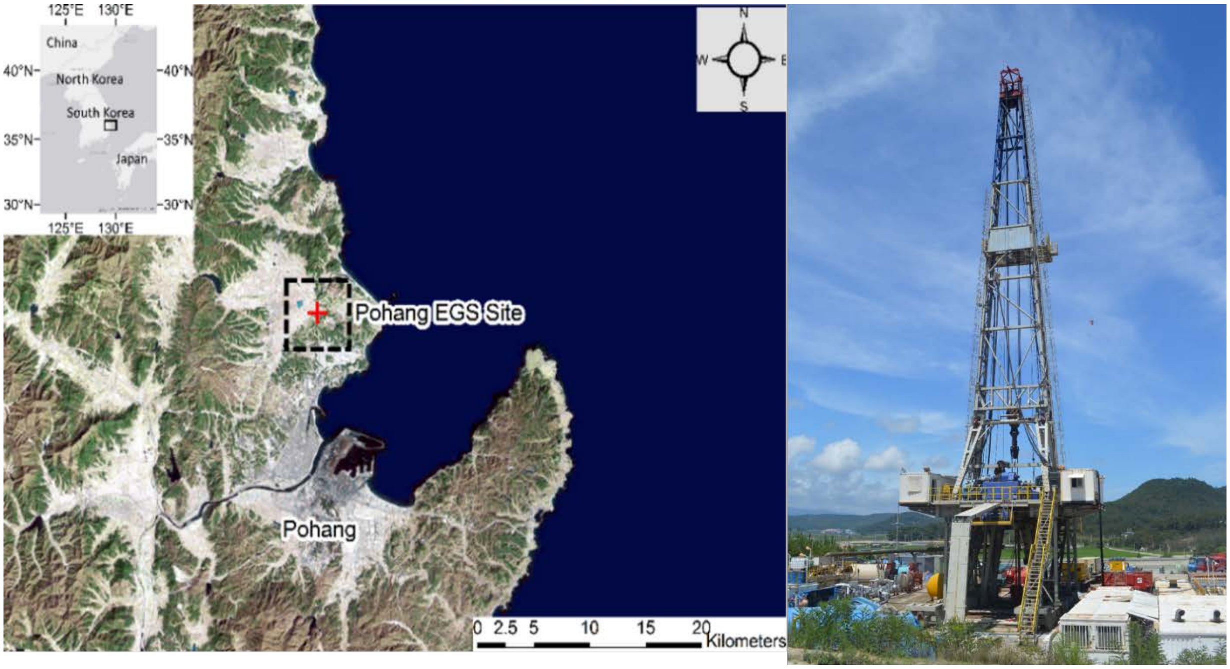


Figure 5: Location of the Pohang EGS project (left, Farkas et al., 2018) and view of the site (right).

A major earthquake recently drew increased attention to operations at the site, and their potential connection to the seismic event. On 15 November 2017 a M_L=5.4 seismic event was reported by the Korean Meteorological Authority (KMA, 2017) in the vicinity of this EGS project. How human activity might have played a role in causing this earthquake, as speculated by Grigoli et al (2018) and Kim et al. (2018), is still unclear; potential links are currently under investigation. The Pohang EGS project is suspended pending independent investigation of the cause of the earthquake. Therefore, DESTRESS operational activities at the Pohang site have ended and alternative sites shall be considered for implementation. Nevertheless, we report here on findings of DESTRESS so far.

Whereas for well PX-2 the stimulation mechanism was interpreted as tensile fracturing with breakdown at a wellhead pressure of ~73 MPa (Park et al., 2017) – probably due to mud loss induced damage of the near borehole surroundings - shear stimulation is the more anticipated stimulation mechanism in PX-1 with much lower wellhead pressures required for fracture opening (fig.8 (see below)). The site history indicates seismic events above magnitude 2.0 caused by fluid injection (Kim et al., 2017). We designed the cyclic soft stimulation treatment with to limit the resulting seismicity to magnitudes (moment magnitudes; M_W) no greater than 2.0, as described below.

In the cyclic soft stimulation concept injection rates alternate between a high injection rate phase and a low injection rate phase. Three different cycle types may be applied at three different time scales with different purposes (fig. 6). Short term cycles intend to weaken ("fatigue") the rock by inducing micro cracks before macroscopic failure through pressure pulses. This fatigue hydraulic fracturing concept was introduced by Zang et al. (2013, 2017, 2018). Besides reduction of the magnitude of induced seismic events, this procedure is also intended to increase the stimulated reservoir volume and the heat exchanger area due to more complex fracture growth and to reduce the breakdown pressure which results in lower injection pressures required to stimulate the rock.

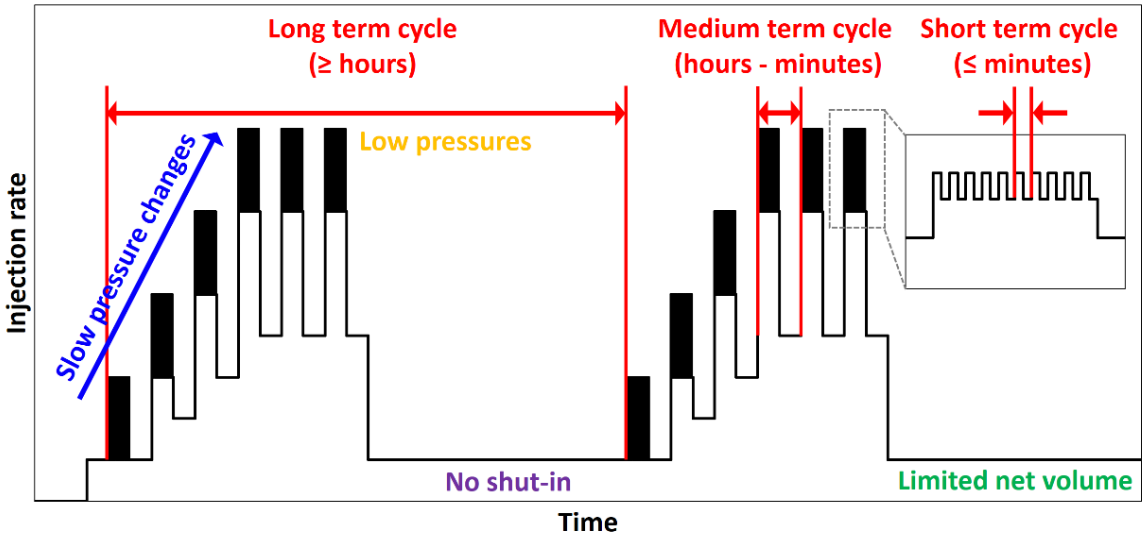


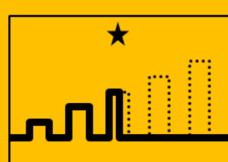
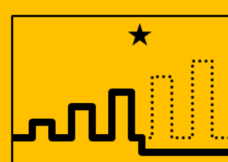
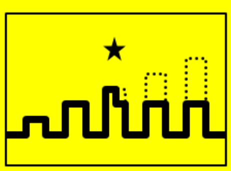
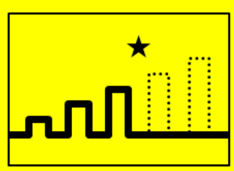
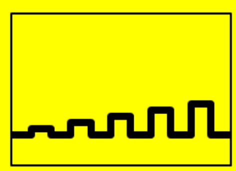
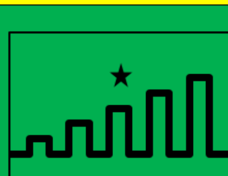
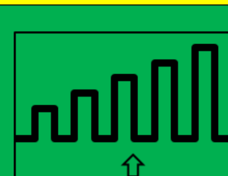
Figure 6: Cyclic soft stimulation concept with long term, medium term and short term cycles in combination with slow pressure changes, low pressures, no shut-in (but flow back) and limited net injection volume (Hofmann et al 2018b).

In medium term cycles the hydraulic energy is divided into small parts as compared to continuous injection. The purpose of this is to also divide the radiated seismic energy into smaller parts as compared to a large single seismic event. Thus, the idea of these cycles is to induce more small events (i.e, $M_w << 2$) instead of some larger events (i.e., $M_w > 2$).

During the high injection rate phase of a long term cycle the reservoir is stimulated. Afterwards the pressure is slowly reduced to close parts of the activated fracture system. During this relaxation phase the reservoir can relax and stresses introduced into the system are released. This is needed as seismicity usually occurs with a delay after injection and seismic magnitudes continue to increase even after shut-in. Inclusion of this relaxation phase in the project design means that if relatively large magnitude seismic events do occur, the operator is given additional time to observe this seismicity and to adapt the future injection schedule.

Seismicity was monitored by a geophone chain in well PX-2 and several surface and downhole seismometers within a 7 km radius of the site. Parts of this monitoring system were used for the real-time triggering of the seismic traffic light system. If a ground velocity above a certain threshold was detected, an automatic email was immediately sent to the stimulation team. The earthquake was then located and its magnitude (M_W) determined. The operations were then adapted based on the seismic traffic light system's guideline for this M_W value (fig. 7). The dataset of earthquakes thus analysed in ‘real time’ at the site was subsequently re-analysed to confirm the accuracy of the ‘real time’ locations and M_W determinations.,

The traffic light system was adapted for this cyclic soft stimulation to avoid induced seismic events of $M_W \geq 2.0$ by including different action items for events that occur during high-rate injection phases or during low-rate or base rate injection. The different stages are summarized as follows: Stage 1 (green): The treatment can be continued as planned. This is independent of the injection phase in which the event occurs. Stage 2 (yellow): If the event occurs during a high rate phase, the flow rate is reduced to the level of the previous high rate phase and subsequent high rate phases during that long term cycle are also limited to the maximum injection rate before the seismic event occurred. Stage 3 (orange): If the event occurs during high rate injection, the flow rate is reduced to the base rate and it is not increased again during that long term cycle. Stage 4 & 5 (red): The pressure will be released by flow back.

M_w	Stage	Injection rate (Event @ high rate)	Injection rate (Event @ low rate)	Adjusted injection rates for next cycle
> 2.0	5	Flow back	Flow back	Flow back
1.7 - 2.0	4	Flow back	Flow back	Flow back
1.4 - 1.7	3			
1.0 - 1.4	2			
< 1.0	1			

Legend: ★ Induced seismic event ▬ adjusted injection rate ▪▪▪ planned injection rate

Figure 7: Seismic traffic light system used for the cyclic soft stimulation treatment in Pohang well PX-1 in August 2017 (Hofmann et al 2018c).

Figure 8 shows the wellhead pressure, injection rate, injected net volume, and peak ground velocities of events detected in real-time during the cyclic soft stimulation treatment. The results of this first field application of the cyclic soft stimulation concept are summarized as follows: Cyclic injection, during eight days, of 1756 m³ of surface water at flow rates of up to 10 l/s and a maximum wellhead pressure of 22.8 MPa resulted in smaller magnitude seismic events as compared to the previous treatment at Pohang well PX-1. The largest induced event was successfully limited below M_W 2.0. The whole amount of injected fluid was subsequently released, in accordance with stage 4 of the traffic light system.

These first results indicate that cyclic soft stimulation, an adapted traffic light system and prior reservoir knowledge can be applied at field scale to mitigate seismic risk from hydraulic stimulation treatments. The hydraulic performance – determined from shut in phases and from pulse testing - was pressure dependent with an increase up to productivities of 0.76 $m^3h^{-1}bar^{-1}$ and fracture opening at elevated well head pressures of 15 MPa – 17 MPa, but lacks a significant permanent productivity increase above 0.12 $m^3h^{-1}bar^{-1}$.

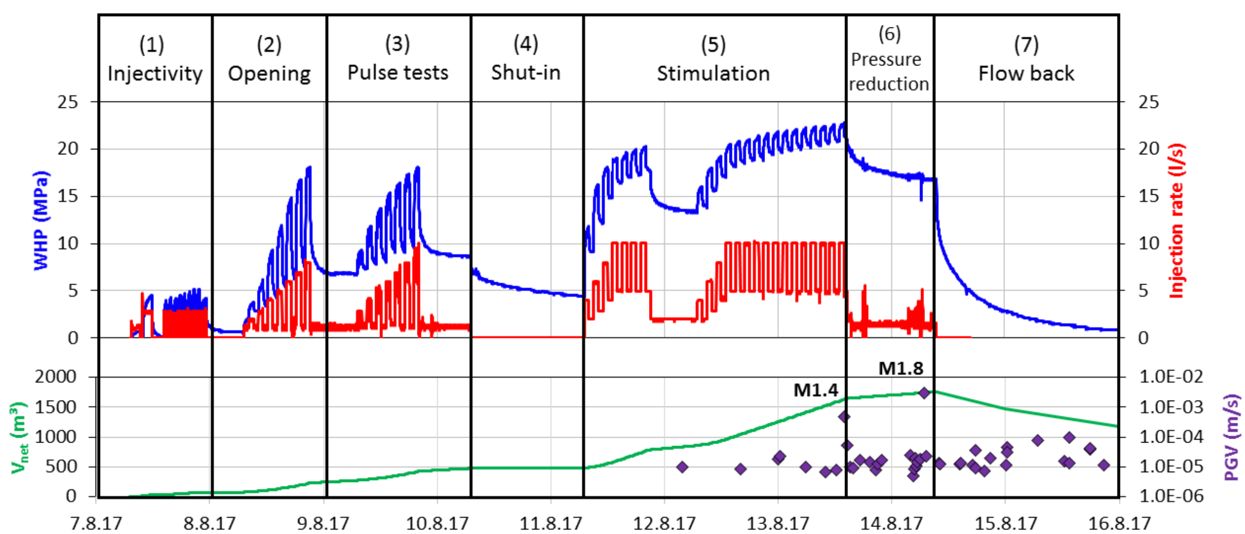


Figure 8: Overview of well head pressure (WHP), injection rate, injected net volume (V_{net}), and peak ground velocity (PGV) during the course of the cyclic soft stimulation treatment in PX-1 in August 2017 (Hofmann et al 2018a and Hofmann et al 2018c). The treatment is subdivided into seven phases: (1) initial injectivity determination, (2) fracture opening pressure determination, (3) hydraulic pulse tests, (4) shut-in, (5) main cyclic soft stimulation treatment, (6) pressure reduction due to orange traffic light alarm, and (7) complete flow back due to red traffic light alarm. The orange traffic light alarm was initiated due to an earthquake with M_W (determined in the field) 1.4, later revised to M_W 1.2. The subsequent red traffic light alarm was initiated due to an earthquake with M_W (determined in the field) 1.8, later revised to M_W 1.9.

Further field tests are needed to prove the reliability of the cyclic soft stimulation concept and refine the injection scheme. Longer field experiments with larger volumes, divided into multiple stages, would have the potential to show if the hydraulic performance can be significantly and sustainably increased, which are an absolute necessity to prove the economic benefits of our methodology.

6. Conclusions

The aim of achieving enhanced performance of geothermal reservoirs while minimizing environmental impacts requires specific stimulation concepts based on the geological setting and the needs of the plant operation. This paper presents such concepts for two sites, which may be considered as endmembers of geological setting variation across Europe.

The experience at the Klaipeda site, in sandstone, indicates that a complex analysis of the interaction of physical, chemical and biological processes during operation is a prerequisite for design of stimulation treatment. Each process that affects injectivity may require a special measure to enhance the production and fulfill environmental constraints. We therefore developed an iterative approach, the so called feedback adjustment procedure. This sequence of treatment, analysis, feedback, ranking of induced processes and final measures should lead to the adequate treatment for soft rock reservoirs, such as sandstone. We will test, and refine, our methodology further at the Mezöbereny site in Hungary.

The hard rock case study at Pohang, in fractured granodiorite, focuses on hydraulic stimulation enhancement measures that negate relatively large magnitude seismic events. The August 2017 treatment in Pohang well PX-1 utilised a cyclic soft stimulation scheme. This resulted in no induced earthquake with moment magnitude above 2.0, either during injection or during subsequent complete flowback. However, the productivity enhancement was insufficient for improved operational performance. The extended application of the cyclic soft stimulation concept at Pohang, originally envisaged, cannot now be done as this project is now suspended because a M_W 5.5 earthquake occurred near the site. The reasons why this event occurred are matter of scientific debate, and beyond the scope of the current paper, but will be addressed by the DESTRESS consortium in future publications. To inform this issue, it is essential to bring together relevant geometric, hydraulic and seismic data to develop a physically-based understanding of the processes involved. In this way a reliable basis for robust risk assessment before future stimulation can be prepared for similar sites. In the meantime, the demonstration of cyclic soft stimulation, including a significant enhancement of the productivity, is planned at another site in Europe.

The DESTRESS-project is ongoing. At the half-way point of the project life cycle, our results confirm the practicability of soft stimulation which has to be designed based on local requirements. Other sites presented here will be further investigated to demonstrate our approach and to assess both risks and the overall cost estimations for EGS developments.

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