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Demonstration of an EGS multi-zonal stimulation system at the Bedretto underground rock laboratory

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ABSTRACT

The multi-stage hydraulic stimulation concept proposed by Geo-Energie Suisse, based on lessons learned from the Basel EGS project, was successfully demonstrated in 2020 and 2021 at the Bedretto underground rock laboratory in the granite of the Swiss Alps at a depth of 1100 m. The three main success criteria were met: first, a significant increase in flow rates and thus an increase in the energy output of an EGS project; second, detailed monitoring and mitigation of induced seismicity; and third, validation and qualification of advanced multi-stage stimulation devices from the oil and gas industry for geothermal applications.

The increase in flow rates predicted in 2016, using numerical modeling by factors between 3 and 6 for the multi-stage stimulation concept compared to single-stage stimulation was demonstrated in Bedretto in-situ at a reservoir scale of 1:3. Scaling the results from the field work to a deep EGS project such as Haute-Sorne in the Swiss canton of Jura yields a range of flow rates from 78 to 160 l/s. This value significantly exceeds the success criteria set at 65 l/s for the Haute-Sorne project. This is also a positive result given the inherent uncertainties. Applied to practice, this means that the electrical power of an EGS project can be increased from about 1.5 MW - if a single stimulation stage is carried out over the entire borehole reservoir section - to about 4.5 to 6 MW if a multi-stage stimulation approach is used.

1. INTRODUCTION

The great potential of petrothermal energy (i.e., energy from low permeable reservoirs) and basic feasibility of their utilisation has been shown in previous projects. Demonstration is required for solutions in the design and operation of a petrothermal system with high flow rates (> 50 l / s) and a long life (> 20 years). Demonstration of a long life is not possible within a few years duration of a project. However, the enhancement of reservoir transmissivity to achieve flow rates larger than 50 l/s with hydraulic stimulation meanwhile mitigating seismic risks is the key aspect of the DESTRESS EU-Horizon 2020 project as stated in the project proposal in 2016.

One of the options to achieve an important enhancement of reservoir transmissivity and thus flow rates and at the same time mitigating seismic risks is using the multistage stimulation approach. The multi-stage stimulation concept has been developed by Geo-Energie Suisse following the lessons learnt from the Basel 2006 project (Meier et al., 2015). Compared to conventional open-hole stimulation like in Basel it considerably improves the circulation rates (and therefore the energy output) and reduces the risks of induced seismicity.

Multi-stage stimulation is nowadays a very successful routine technology for unconventional oil and gas production. However, this technology has not been applied yet for geothermal applications, except for the petrothermal Otaniemi project of St1 in Espoo, close to the Finish capital Helsinki.

The Otaniemi first EGS multistage stimulation has been performed in 2018 at a depth of about 6400 m in the Finish crystalline bedrock utilizing a mechanical packer system for isolating five stages (intervals of the borehole). Note that five stages is a very small number for a multi-stage system, especially when accounting for a potential failure rate of around 30-50 % of zonal isolation equipment commonly reported in petroleum industry literature.

During the stimulation induced seismicity did not exceed magnitudes of M=2.0 (Kwiatek et al., 2019) . These seismic events were not felt at surface, but produced occasional noises that were perceived by some neighbours at night and were erroneously attributed to blasting at the tunnel construction site of the new metro line in the area (personal communication Tero Saarno). No official statement of St1 is currently available on the increase of transmissivity and final hydraulic flow tests between the injection and the production wells that were scheduled for 2021. However, at the key-note talk of the DESTRESS final conference on November 24th, 2020, Professor Illmo Kukkonnen reported that hydraulic conductivity is believed to be rather small and pressure dependent.

Apart from the Finish Otaniemi project of St1, the US Department of Energy has an important and large multistage EGS stimulation R&D project ongoing at the Milford site in Utah. The US Energy Department envisions Frontier Observatory for Research in Geothermal Energy (FORGE) as a dedicated site where scientists and engineers will be able to develop, test, and accelerate breakthroughs in enhanced geothermal system (EGS) technologies and techniques. Geo-Energie Suisse is a partner of Utah FORGE and will support especially advanced seismic monitoring with innovative technologies (https://utahforge.com/2021/04/01/partner-spotlight-geo-energie-suisse/).

In the US - apart of FORGE - the Houston based start-up company FERVO Energy aims to leverage multistage hydraulic fracturing technology to create more-efficient geothermal wells in Nevada that will power Google's data infrastructure as announced 2021 in the Journal of Petroleum Technology (https://jpt.spe.org/google-taps-fervo-energy-to-develop-enhanced-geothermal-systems-in-nevada).

In China, at the ARMA-CUPB Geothermal International Conference in 2019 in Beijing (China), SINOPEC reported on important progress with their EGS pilot project in the Gonghe Basin, that relies on hydraulic fracturing utilizing a multi-stage approach.

2. OBJECTIVES OF THE MULTI-STAGE STIMULATION TREATMENTS

Meier and Ollinger (2016) used Monte Carlo simulations to predict probabilistic flow rate distributions for the multi-stage EGS stimulation of the Haute-Sorne project in the Canton of Jura (Switzerland). The simulations were based on a large data set of transmissivity values measured in crystalline rocks along the Gotthard Base tunnels (8 km) and other tunnels in the Swiss central alps that intersect large gneiss and granite bodies at depths up to 2000 m. These transmissivity values were first reduced to account for a greater depth at around 5000 m at EGS sites in Switzerland, and then increased for the enhancement of stimulation utilizing relationships from literature.

From the theoretical work by Meier and Ollinger (2016) we expect with a probability of 50% that flow rates will be higher than 75 l/s after multistage stimulation (assuming that the failure of zonal isolation equipment is smaller than 50%), and that the flow rates will be in the order of 20 l/s or less for a project without or with only a single stage stimulation. Please note that these values are derived for an EGS project with strongly inclined boreholes with a length of 1000 to 1500 m within the reservoir and a hydraulic pressure difference in the order of 4 MPa (400 m).

The simulated results also constitute the working hypothesis for the multistage stimulation demonstration project in the DESTRESS proposal submitted to the EU in 2016. In chapter 5 (Figure 2) the simulated results are compared with the measurements. For the Haute-Sorne project a success has been defined with flow rates of 65 l/s. Based on the above predictions we set the goals for the multistage stimulation demonstration project at Bedretto as follows: The demonstration in Bedretto is considered to be a success if the sum of transmissivity values of a representative number and length of stages measured after multistage stimulation, scaled up to a borehole length of 1000 to 1500 m, and subject (computationally) to a pressure difference of 4 MPa, will result in flow rates equal or greater than 65 l/s.

3. DEMONSTRATION AT BEDRETTO VERSUS FULL SCALE DEEP EGS

The multi-stage stimulation concept has been developed by Geo-Energie Suisse following the lessons learnt from the Basel 2006 project (Meier et al., 2015). Compared to conventional open-hole stimulation it considerably improves the circulation rates (and therefore the energy output) and reduces the risks of induced seismicity.

However, until today the concept has rarely been demonstrated in the field, with the partial exception of the Helsinki stimulation in 2020. Demonstrating multi-stage stimulation is the primary goal of DESTRESS project in the deep underground rock laboratory in Bedretto in the Canton of Ticino. The rock laboratory operated by ETH Zürich lies in crystalline rock very similar to the crystalline basement in Haute-Sorne, in Basel and in Switzerland in general. At the 1100 m deep rock laboratory the stress regime (normal faulting to strike-slip), the fracture frequency and the permeability of the granite are similar to the deep well in Basel (3000-5000 m). The only major difference is the much lower rock temperature in the Bedretto rock laboratory, which is not a dominant parameter for hydraulic stimulation.

The scale of the reservoir at Bedretto is close to the scale of the Haute-Sorne project as schematically shown in Figure 1. The reservoir length (300 - 400 m) and the reservoir radius (“reservoir thickness”) perpendicular to the boreholes (50 – 100 m) are around ¼ to ⅓ of the planned Haute-Sorne EGS reservoir. The 350 and 400 m long boreholes ST1 and ST2 were drilled with the same diameter (8.5’’) to ensure that connectivity between the wells and the reservoir corresponds to the same conditions. The spacing (about 6 to 70 m) of the 14 stimulation stages along the 400 m borehole corresponds to the planned Haute-Sorne project with about 30 stages along a 1000-1500 m long borehole. The distance of 50-70 m between the injection and production boreholes is smaller by a factor of two to three compared to Haute-Sorne (100–300 m). In short, the concept demonstrated in the Bedretto laboratory is comparable to the one in Haute-Sorne, but at a reservoir scale of approximately one to three.

Therefore, all relevant rock mechanical and hydraulic processes took place at a similar field scale as in Haute-Sorne, with the advantage in Bedretto of a much closer and much more precise monitoring of the rock mechanical behaviour and the borehole equipment behaviour.

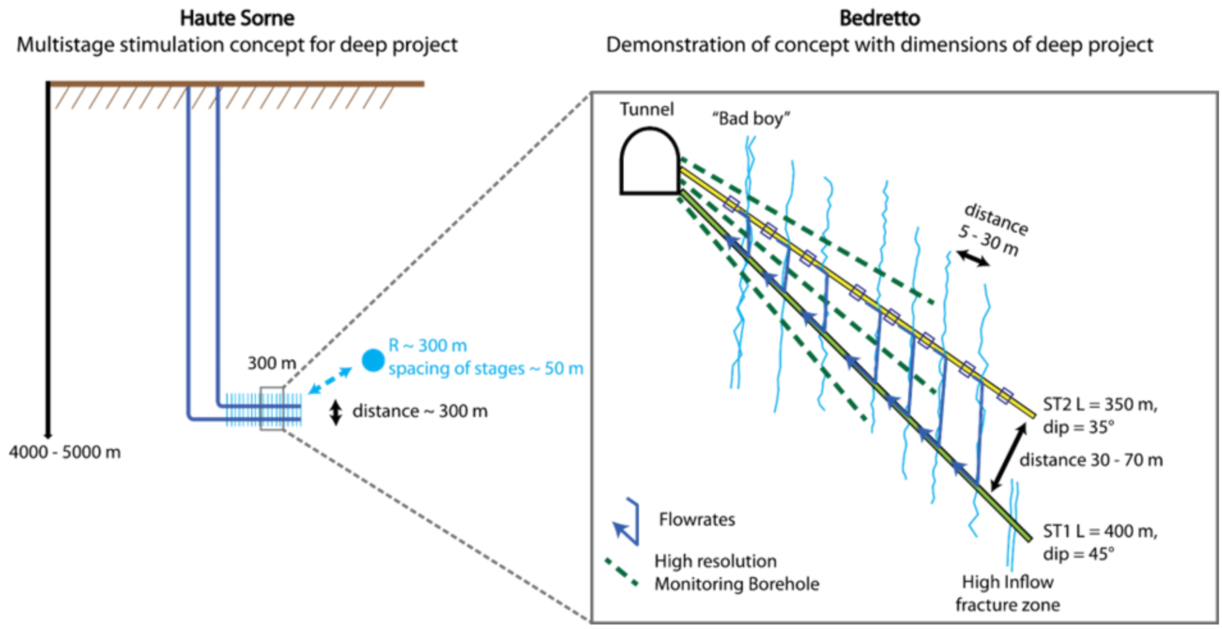

Figure 1. Schematic diagram of the deep multistage EGS project planned for Haute-Sorne and the DESTRESS demonstration in Bedretto. The demonstration has been done comparable to Haute-Sorne, but at a reservoir scale of approximately one to three and with much better possibilities to monitor the behaviour of rock mechanics, hydrogeology and borehole equipment.

4. MULTI-PACKER AND MONITORING EQUIPMENT

The multi-packer borehole completion system from the oil and gas industry, and installed in the 400 m long ST1 borehole with 14 packers (rated to 300 bar) and 14 valves in between the packers (sliding sleeves), worked reliably and as expected.

Also, multi-stage stimulations with a double packer system in ST2 and ST1 (before the installation of the multipacker) worked reliably and with comparable results to the multi-packer system. The double packer configuration allowed for much shorter stimulation intervals typically in the order of 6 to 8 m, with 2 m the shortest for mini-fracturing. In contrast, the multi-packer intervals are typically much longer in the order of 20 to 60 m and contain many smaller fractures. One interval is with 7 m the shortest, isolating a larger structure.

Innovative fibre optic technology installed together and attached to the multi-packer system performed very well. The DAS measurements provided valuable information on the open/close positions of the valves (sliding sleeves) between the packers (characteristic noise indicates the correct opening/closing). This is important for applications in deep wells, where virtually no control is possible from surface to the 4 - 6 km deep installed and mechanically moved sliding sleeves. The DTS measurements and especially the heat pulse measurements allowed us to identify flowing fractures within the intervals isolated by two packers.

The precision of the seismometer chain with 8 levels that was installed either in borehole ST1 or ST2 when injecting in the other well was especially good when hodogram analysis was performed.

5. INCREASE OF TRANSMISSIVITY, SCALING TO REAL EGS SYSTEM AND STIMULATED ROCK VOLUME

5.1 Increase of transmissivity

Before stimulation, the initial transmissivities of fractures intersecting the isolated intervals of boreholes ST1 and ST2 ranged from about 1E-10 to 1E-6 m^2/s. Two intervals in ST1 between about 330 and 400 m showed very high initial transmissivities in the order of 1E-5 m^2/s. These two intervals are strongly fractured and could not be stimulated, because the pumping capacity of maximum 800 l/min was not able to build up pressures sufficient for shear-stimulation at Bedretto (P_{shear} > 5 MPa). These two intervals were separated from the other intervals with the multi-packer-system.

The several orders of magnitude transmissivity increase is a good criterion for the success of stimulation. Traditionally, the stimulation factor has been calculated as the ratio of final transmissivity. The results of such calculation strongly depend on the geometry of the system (e.g., the presence or absence of a skin or "damaged" zone around the borehole) and on the flow characteristics (e.g., linear, bilinear or spherical flow, measured by the flow dimension). In addition, the stimulation factors calculated in this way (usually 100 to 10000) are not realistic in the sense that they do not reveal the actual enhancement of productivity of the EGS. To bridge this gap and demonstrate the actual effectiveness of multi-stage stimulation, we calculated the flow rates for a typical situation for a deep geothermal project. The flow rates (injection into or pumping out of a well) for a typical pressure build-up/drawdown of 400 m (ca. 4 MPa) were calculated based on the individual interval transmissivities before and after stimulation. The stimulation factor is then calculated as the ratio of final to initial flow rate.

Stimulation factors for all stages (except the two highly transmissive ones) initially containing some open fractures range in general between 2 to 200. For very low permeable stages without initially open fractures, the stimulation factors are as large as 14000. As expected, the stimulation factors were higher for initially low transmissive stages and smaller for initially higher transmissive stages. The calculated flow rates of each interval were summed up for all 11 intervals along both ST1 and ST2 covering a total length of 136 m (not including the two highly transmissive intervals). The total flow for the length of 136 m was 213 l/min before stimulation and ranged after stimulation between 644 - 871 l/min depending on whether or not the re-stimulations of certain intervals are accounted for (Table 1, upper part).

A typical design length for the horizontal well sections of a commercial EGS multi-stage stimulation project is in the order of 1000 to 1500 m (e.g., the design of the Haute-Sorne project). Thus, scaling up the results for the 136 m long well section to the length of a commercial project by a factor of 7.3 to 11.0 results in 1555 to 2343 l/min (26 to 39 l/s) for the flow rates before stimulation and 4701 to 9581 l/min (78 to 160 l/s) after multistage stimulation, which leads to an increase of circulating flow rate by a factor of about 3 to 4 (Table 1, lower part).

Borehole	Interval (May 2021)	Interval Length (m)	Q(4 MPa) L/min Begin	Q(4 MPa) L/min End	Stimulation factor
ST1	6	52	1.6	110-337.4	68.8-210.9
	4	8	0.0242	335.2	13868.4
	1-2	34	209	149	0.7
ST2	1	6	0.10	18.9	188.9
	2	6	0.06	5.5	87.4
	4	6	0.87	3.1	3.6
	5	6	0.85	17.8	20.9
	6	17.5	0.39	4.5	11.5
TOTAL		135.5	212.9	644-871	3-4.1

Haute-Sorne Borehole lenght	Scaling factor	Q L/sec (4 MPa) before	Min Q L/sec (4 MPa) after	Max Q L/sec (4 MPa) after
1000 m	7.38	26	78	107
1500 m	11.07	39	119	160
Range		26 - 39	79 - 119	107 - 160
El. Power MW (approximately)	At dt 100 °C	1.5	4.5	6.0

Table 1. Per-interval and global stimulation factors (above) and ranges for flow rates scaled to a deep EGS project (below). The flow rate ranges in blue correspond to the situation before and the ranges in green after stimulation indicated in the Figure below.

A comparison between the upscaled measured flow rates and their increase due to multi-stage stimulation with the theoretical predictions in the 2016 DESTRESS project proposal shows a rather good agreement. Firstly, we predicted a factor of about 3 to 6 increase of flow rates (and thus energy) utilizing a multi-stage stimulation approach, and secondly, a cumulative frequency of 50% for flow rates of 20 l/s for a single stage (comparable to the situation without stimulation), and of 120 l/s for the case of a successful multi-stage stimulation. The measured and upscaled values (before stimulation 26 to 39 l/s; after multistage stimulation: 78 to 160 l/s) confirm the predictions of 2016 within the inherent range of uncertainty.

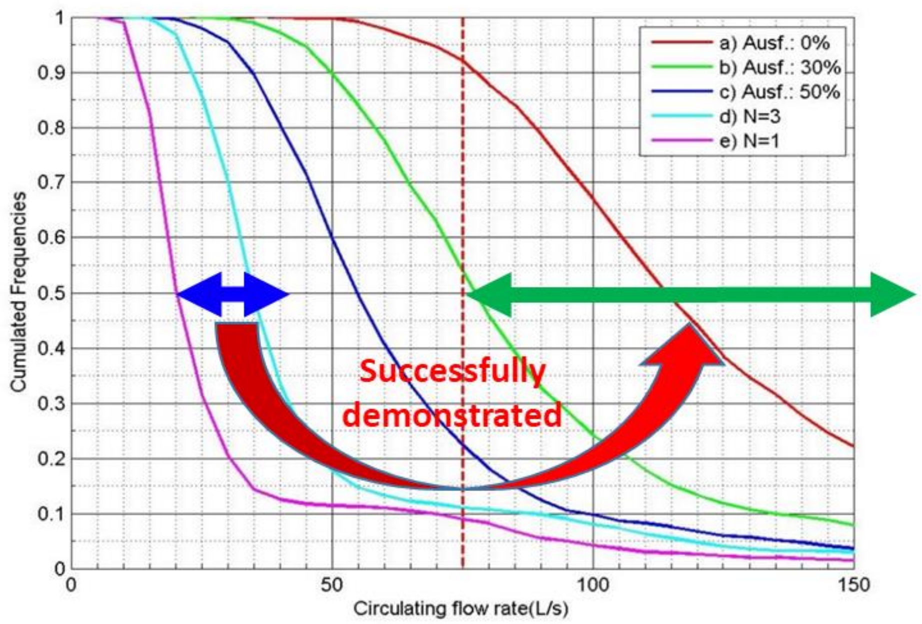

Figure 2. Increase of scaled up flow rates from before (blue) to after (green) stimulation demonstrated at Bedretto.

5.2 Scaling the results to a typical deep EGS multi-stage stimulation project

Table 1 summarizes the per-interval stimulation factors. To minimize the impact of local intervals with very small and large stimulation factors (as low as 0.7 and as large as 14000), the individual flow rates are added to consider the complete stimulated sections, thus yielding the overall stimulation factor of the system.

The overall stimulation factor of the system is in the range 3-4, which is in good agreement with the theoretical predictions made in the 2016 DESTRESS project proposal (from 3 to 6 in terms of energy, and thus, of circulating flow rate). This result can be extrapolated to the scale of an actual EGS with a horizontal segmented borehole section of about 1000-1500 m, which corresponds to 30-40 stimulated stages separated some 25-50 m (Table 1,lower part). In terms of flow rate, and assuming the same density of existing fractures and a stimulation factor from 3 to 4, the initial flow rate scales to 1566-2343 L/min (26-39 l/s), whereas the flow rate after stimulation scales up to 4733-9581 L/min (78-160 l/s).

Assuming a conservative temperature difference of some 100°C between injector and producer boreholes of an EGS, the circulating flow rates before and after stimulation represent 1.5 MW and 4.5-6 MW, respectively. This proves the effectiveness of the multi-stage stimulation concept.

5.3 Hydro-mechanical observations

Injectivity and transmissivity seem to be higher when stimulating with higher injection flow rates. Some intervals that showed 1-dimensional flow regime (i.e., flow along preferential flow channels) before stimulation, showed 2-dimensional radial flow regime after stimulation indicating an improvement of injectivity close to the well. After stimulation, some intervals showed a 3-dimensional spherical flow regime indicating that stimulation resulted in a very good interconnectivity with fractures of the neighbouring intervals. A weak hydraulic connectivity was clearly identified within the stimulated fracture network over about 60 m between the bottom of borehole ST1 and the bottom of borehole ST2.

Clear signatures of shearing of natural fractures in the order of a few mm have been observed in boreholes CB1 and ST2 when comparing acoustic televiewer measurements before and after stimulation (Figure 3 and Figure 4). The visually detectable shearing confirms the permanent increase of transmissivity, and that shearing is the dominant mechanism for the transmissivity increase. No shearing has been observed for small volume minifracturing tests.

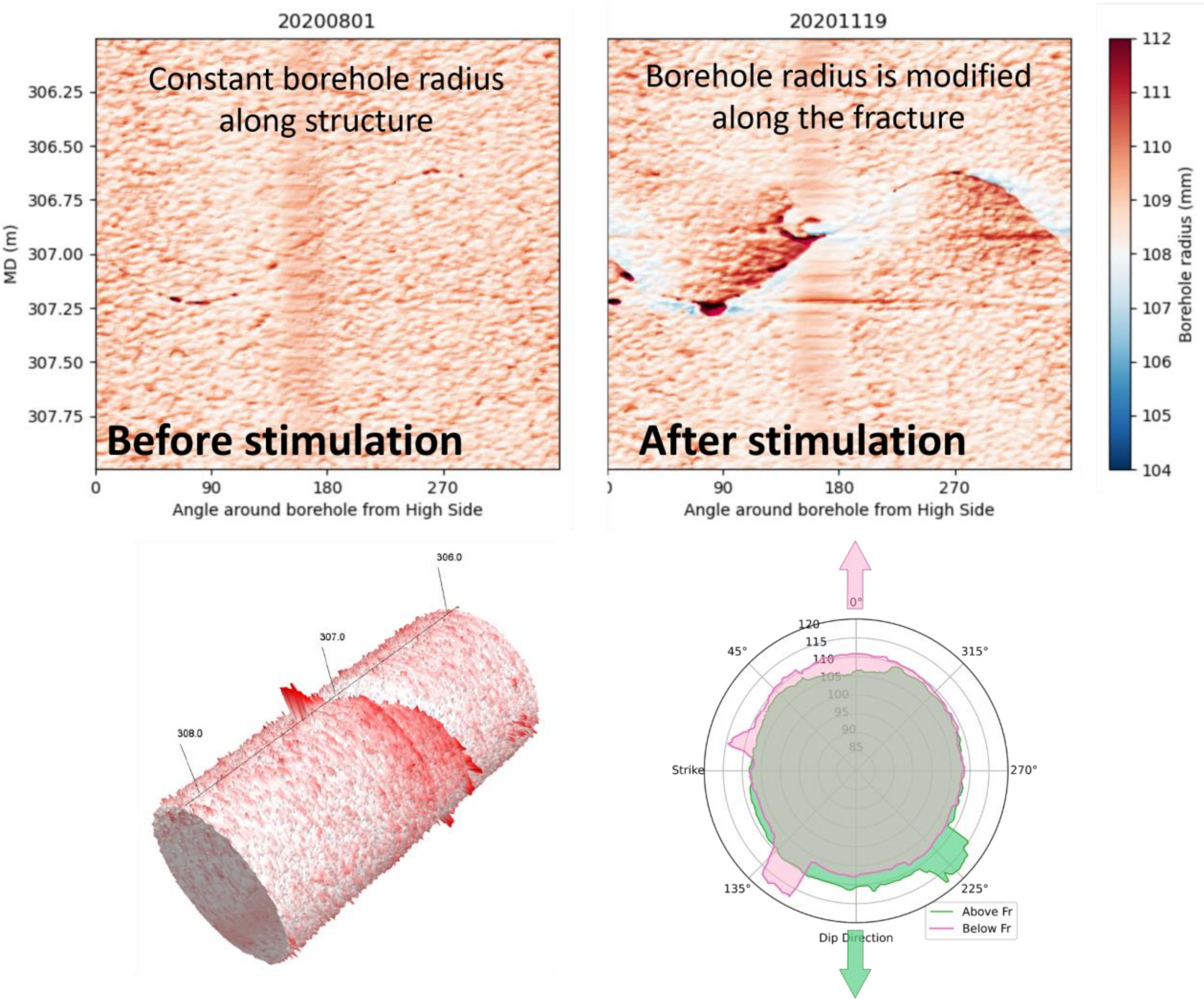

Figure 3. Natural fracture showing shear displacement after stimulation in borehole ST2.

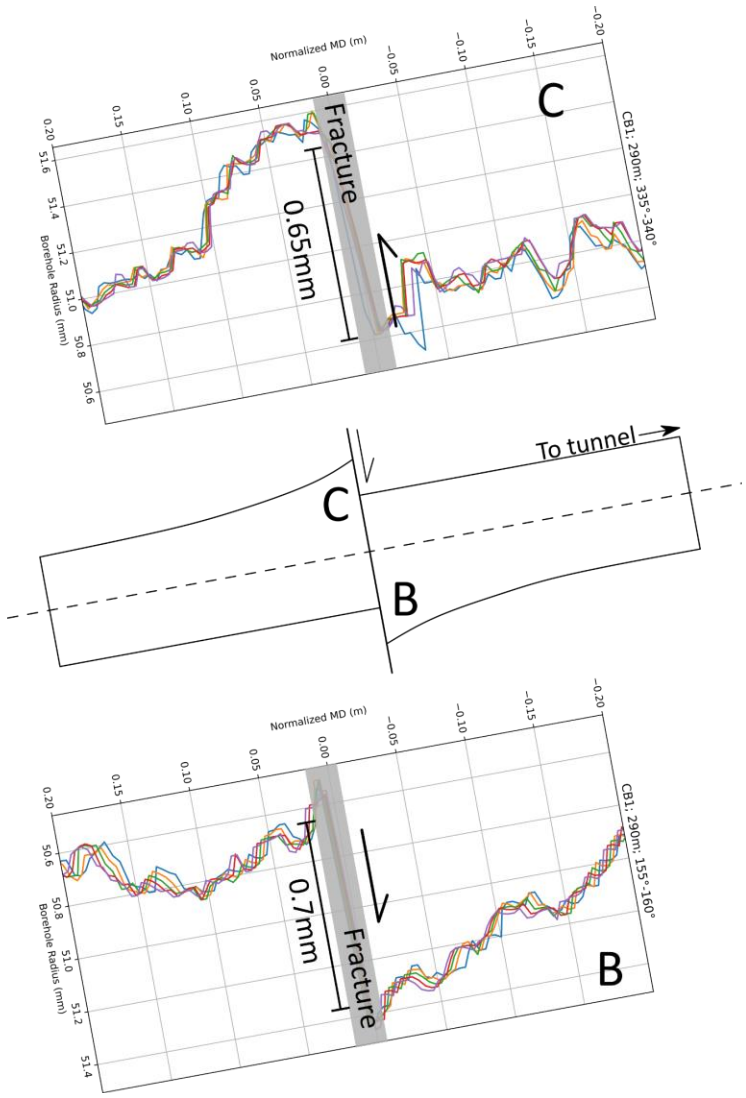

Figure 4. Reconstruction of shear displacement along a natural fracture in borehole CB1. Sub-millimetric displacements were identified using ATV data

The rock of the reservoir has been drained first during several years by the tunnel, and lately by the newly drilled boreholes, which drastically reduced the pressure at the formation. Thus, it did not behave as critically stressed, with shearing-induced microseismicity and corresponding transmissivity increase starting already at low injection pressures, as it had been the case for example at the Basel EGS project. Instead, at Bedretto the jacking pressure (pressure necessary to open the fractures at the borehole, in general slightly higher than the minimum principal stress) needs to be attained first, which allows the injection of large volumes of water. Once the fracture opening pressures were reached, large flow rates could be injected with only a small additional increase of pressure.

5.4 Spatial and temporal distribution of micro-seismicity

Microseismicity was recorded in 21 of the stages. In total, 8807 microseismic events were detected, out of which the hypocentre and the moment magnitude could be estimated for 2422 of them. Their moment magnitude ranges from -3.34 to -1.6 and their distribution is plotted in Figure 5. The completion magnitude Mc of the total catalogue is -2.965 and the effective b-value for all stages and for this Mc is 1.91±0.15. In general, Mc was stable and low throughout the stimulations, contrary to the b-value that varied significantly with stages and was always higher than the effective. The median of the b-value for the stages was 2.9 and the standard deviation almost 2. The evolution of the best fitting parameters with stages and the increasing trend for Mc are plotted in Figure 6.

Typical dispersion of seismicity was observed for all stages in line with what is expected; i.e. the average distance of seismicity from the injection point increased with time, and when an already stimulated stage was stimulated again then migration would resume from where it stopped. The median volume of the convex hull of the recorded clouds per stage is is $7.8{\cdot}10^4$ m^3, and the volume of the convex hull of the total cloud of microseismicity is approximately $1.7{\cdot}10^6$ m^3. The clouds of microseismicity for the November-December 2020 and for the May 2021 stimulations, are plotted in Figure 7.

The seismic cloud extended in general up to about 50 m from the injection point after some 10 to 24 hours of injection. Further injection did not extend the seismicity cloud noticeably. The spatial distribution of seismicity clearly shows that most of the stimulated features of a specific stage (except the few ones showing 3-dimensional spherical flow regime) are separated from stimulated features of other stages, indicating the high value of the multi-stage stimulation concept.

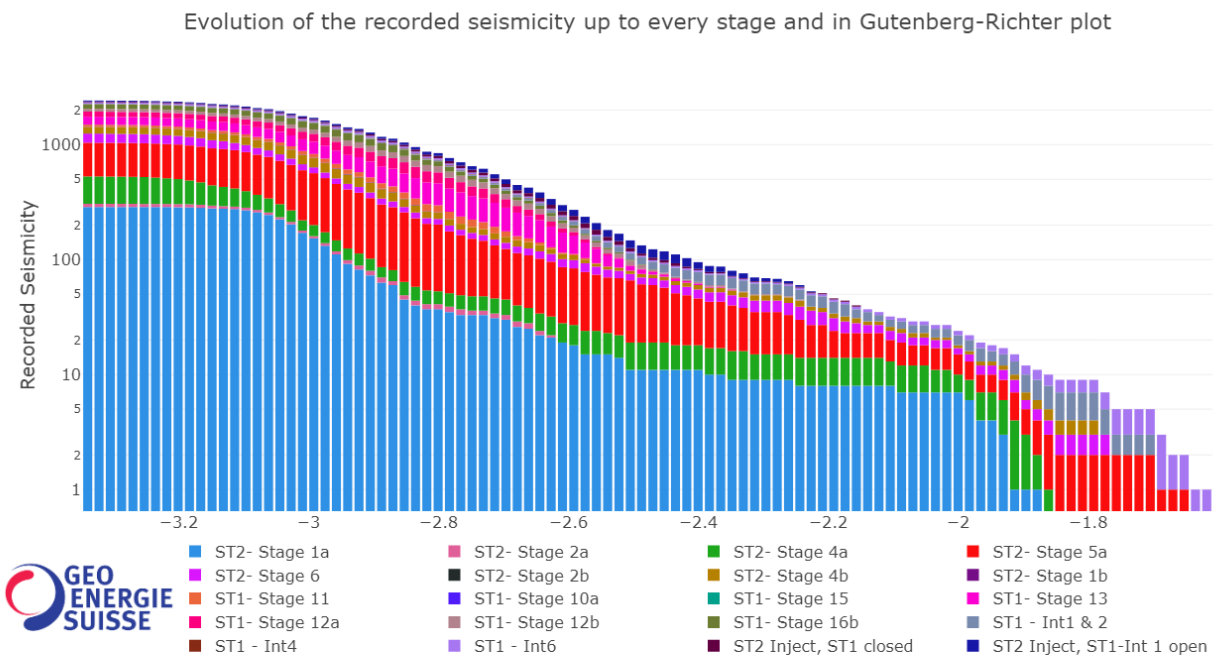

Figure 5. Distribution of magnitudes for the recorded microseismicity

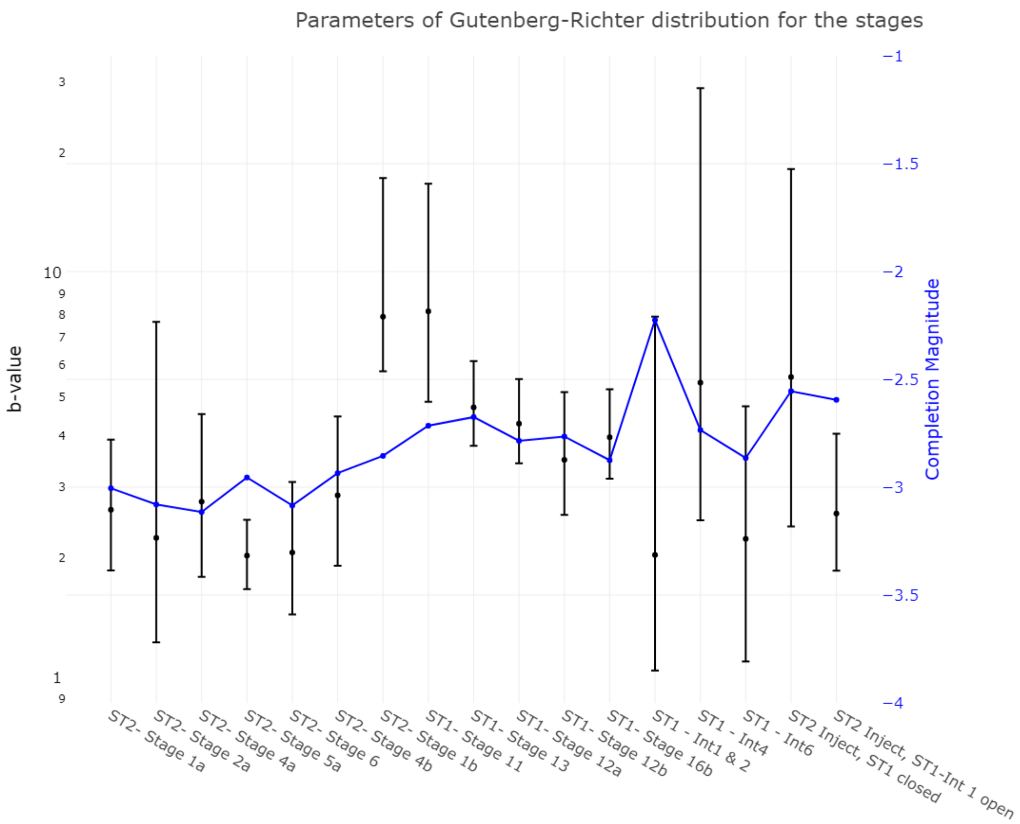

Figure 6. Evolution of the b-value and of M_c with stages

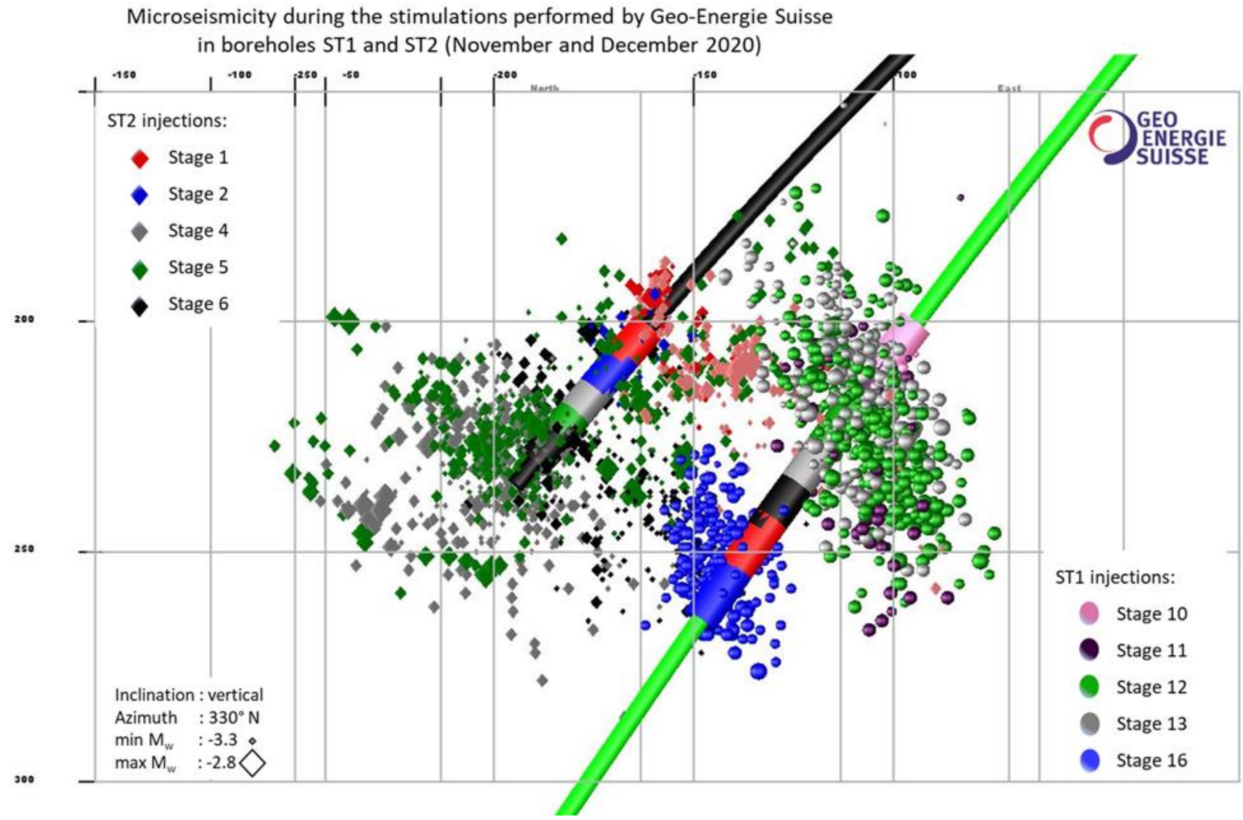

Figure 7. Sideview of the observed microseismicity during the stimulation of wells ST2 (November, 2020) and ST1 (December, 2020) in stages.

6. RESULTS AND CONCLUSIONS

The multi-stage hydraulic stimulation concept proposed by Geo-Energie Suisse, based on lessons learned from the Basel EGS project, was successfully demonstrated in 2020 and 2021 at the Bedretto underground rock laboratory in the granite of the Swiss Alps at a depth of 1100 m. The three main success criteria were met: first, a significant increase in flow rates and thus an increase in the energy output of an EGS project; second, detailed monitoring and mitigation of induced seismicity; and third, validation and qualification of advanced multi-stage stimulation devices from the oil and gas industry for geothermal applications.

The increase in flow rates predicted in 2016, using numerical modeling by factors between 3 and 6 for the multi-stage stimulation concept compared to single-stage stimulation was demonstrated in Bedretto in-situ at a reservoir scale of 1:3. Scaling the results from the field work to a deep EGS project such as Haute-Sorne in the Swiss canton of Jura yields a range of flow rates from 78 to 160 l/s. This value significantly exceeds the success criteria set at 65 l/s for the Haute-Sorne project. This is also a positive result given the inherent uncertainties. Applied to practice, this means that the electrical power of an EGS project can be increased from about 1.5 MW - if a single stimulation stage is carried out over the entire borehole reservoir section - to about 4.5 to 6 MW if a multi-stage stimulation approach is used.

Real-time monitoring and mitigation of induced seismicity and associated risks - the second main criterion for proving success - was also successfully demonstrated. The maximum moment magnitude of -1.6 within the stimulated rock volume was lower than naturally occurring seismicity (up to a magnitude of 0.0) at greater distances of about 1000 m from the stimulated reservoir.

Finally, the oil and gas industry's advanced multi-packer system for zonal isolation along the 400 m borehole for multi-stage stimulation of a crystalline geothermal reservoir worked flawlessly. The operation of the valves between the packers also worked reliably. Instrumentation of the multi-packer system with fiber optic lines for DAS, DTS and HPM (Heat Pulse Measurement) provided very useful data for identifying flowing fractures between packers before, during and after stimulation. Fiber optic instrumentation also provided important information on operational aspects such as valve opening or closing and possible packer bypass. This is important for a deep EGS project where the valves are located at a depth of 3000 to 7000 m and the mechanical valve movement of only a few decimeters at the surface cannot be controlled.

A worldwide unique multilevel EGS reservoir has been created in the last few years with great personnel, technical and financial effort, equipped with high-resolution and state-of-the-art measurement technology. This now offers the unique opportunity to investigate the complex behavior of coupled processes in an EGS reservoir in a long-term test, and thus to validate and optimize existing engineering approaches that have so far only been derived from uncalibrated numerical models.

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