On the variability of the seismic response during multiple decameter-scale hydraulic stimulations

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To improve the understanding of seismo-hydro-mechanical coupled processes associated with deep-geothermal reservoir creation, a decameter-scale In-situ Stimulation and Circulation (ISC) experiment was conducted at the Grimsel Test Site (GTS) in the central Swiss Alps. The stimulation tests included two phases: hydraulic shearing (HS) of pre-existing structures and hydraulic fracturing (HF) in intact rock.

Prior to the hydraulic stimulations, an extensive geological and stress-field characterization campaign of the targeted crystalline rock mass was performed. The geological characterization identified two large-scale fault structures: the S1 shear zone striking North-East South-West and the S3 shear zone striking East-West (Fig. 1). The in-situ stress field was estimated as being different in the southern, relatively unfractured part of the rock mass away from the shear zones (i.e., σ_1 ~13.8 MPa plunging to the East with 30°-40°, σ_3 ~8 MPa sub-horizontal NS oriented), compared to a progressive reduction of σ_3 to ~3 MPa and varying direction at the shear zones (Gischig et al., 2018; Krietsch et al., 2017).

During the first hydraulic stimulation phase, six borehole intervals intersecting shear zone S1 or S3 were pressurized, with the goal to introduce slip along these structures (HS experiment series). In the second stimulation phase, five intervals were chosen in intact rock to initiate new fractures (HF experiment series). For both parts of the stimulation phase, repeatable injection protocols were followed. Monitoring of deformation, pressure and seismicity was ensured using a dense and versatile sensor network. Deformation was continuously monitored in three boreholes intersecting the rock mass using fiberoptic-based measurement techniques as well as three tilt meters. Four boreholes were used for monitoring pressure evolution during injection. Seismicity during stimulation was continuously recorded with a dense network of highly sensitive piezo-electric acoustic emission sensors (green cones in Fig. 1), installed in the surrounding tunnels and four monitoring boreholes in close proximity (5-25 m) to the injection intervals. Five piezo-electric sensors in tunnels were complemented by calibrated accelerometers (red cones in Fig. 1).

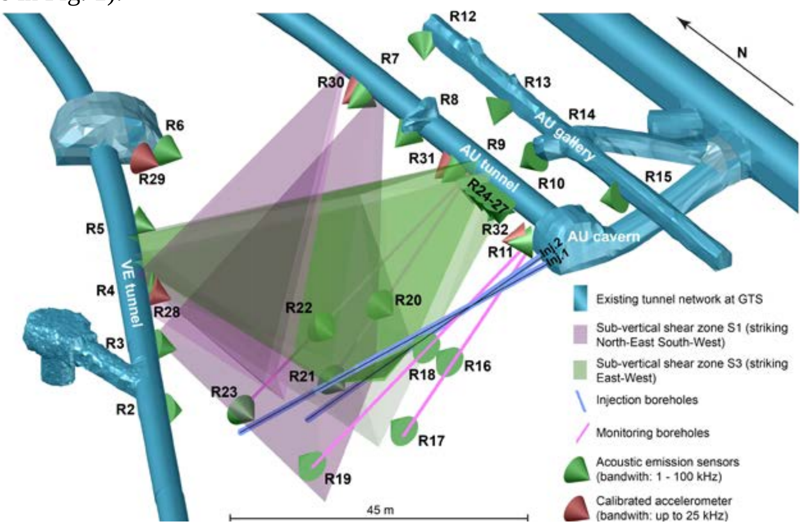

Fig. 1: Overview of the experimental site at GTS: Main structures shear zones S1 and S3 were accessed and stimulated using two injection boreholes. The seismic monitoring network consisted of sensors surrounding the injection intervals

First analysis of the experiments shows a high variability in injectivity gain, whereby final injectivities remain, for HS as well as for HF experiments, on the same order of magnitude, even if initial injectivities vary over many orders of magnitude (Table 1). The number of seismic event detections vary strongly and a higher gain in injectivity does not necessarily reflect in a higher number of detected seismic events. However, injections into shear zone S3 show a significantly higher number of events than S1 injections, indicating that the brittle-ductile S3 shear zone may be more seismogenic than the purely ductile S1 shear zone. However, care has to be taken when comparing the number of detected seismic events for different experiments, as network sensitivity changes from experiment to experiment. Estimating reliable event magnitudes and the seismically released portion of energy during deformation is work in progress.

Table 1: Overview of all performed hydraulic stimulation experiments

Experiment	**HS02**	**HS04**	**HS05**	**HS03**	**HS08**	**HS01**	**HF03**	**HF02**	**HF05**	**HF06**	**HF08**
Structure	S1	S3	S3	S1	S1, S3	S1	-	-	-	S1	-
Initial injectivity [l/min/MPa]	0.018	0.9	0.086	0.004	0.002	0.001	3.8e-13	3.1e-13	1.4e-13	-	3.1e-13
Final injectivity [l/min/MPa]	1.62	0.9	0.4	1.7	0.54	1.11	0.88	3.69	0.16	2.77	0.2
Injected volume [l]	797	1253	1211	831	1258	982	893	816	1235	943	1501
Detected events	**1203**	**5606**	**2452**	**314**	**3703**	**560**	**1997**	**2204**	**1969**	**94**	**722**

Apart from the number of seismic events, the tempo-spatial evolution of seismicity can give important insights into fluid migration, reservoir generation, and seismic potential. As an example, Fig. 2 shows the 1000 events with the highest detection-quality of experiment HS04. The located events coalesce into distinct clusters of small spatial extent (0.5 to 5 m) in relatively short distance to the injection interval (max. ~ 5 m). Also, larger magnitude events seem to occur in close proximity to the injection interval.

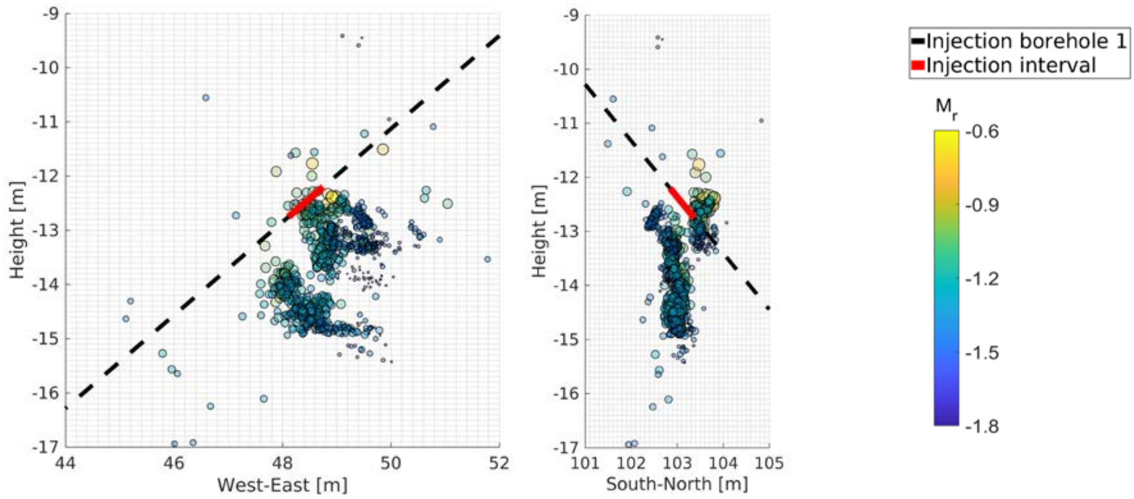

Fig. 2: Location of seismic detections based on P-wave arrivals of experiment HS04 using an isotropic and homogeneous velocity model with a P-wave velocity of $5150\ \frac{m}{s}$. The plot to the left represents the view towards north and the plot on the right shows the view towards west. Diameter and color of the shown events are scaled according to determined relative magnitudes M_r.

Detailed processing of the seismic, as well as the deformation and pressure monitoring data for all eleven experiments is ongoing. Pressure data show indications of both non-linear pressure diffusion and heterogeneous flow channeling, and rock deformation data clearly show slip on some pre-existing structures and opening of new fractures during the experiments. Especially the integration of deformation and seismic measurements will be key for understanding the seismo-hydro-mechanical response of the rock at the GTS. Our results will be used to test, calibrate and validate numerical models, in order to improve the capability of modelling reservoir stimulation at any scale.

References

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