EGU23-15982

DETECTING AND MAPPING THE INDUCED SEISMICITY OF A PLANNED EGS IN HELSINKI/ESPOO, FINLAND

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INTRODUCTION TO THE EGS

The energy company ST1 Oy planned to construct an Enhanced Geothermal System (EGS) using two boreholes drilled down to ca. 6 km depth under the Aalto University campus Otaniemi, Espoo. In order to achieve a water reservoir and circulation between the boreholes, the company conducted two high pressure stimulations, a larger 49-day main stimulation in June-July 2018 and a smaller 16-day counter-stimulation in May 2020. These stimulations induced tens of thousands of small earthquakes (Kwiatek et al., 2019, Leonhardt et al., 2021). Both stimulation periods were monitored by a dense network of over 100 stations consisting of Institute of Seismology (ISUH) operated permanent seismic stations, temporary stations installed by ISUH and borehole stations operated by the company ST1; while the interim and the post-stimulation periods were, and still are, monitored with a sparser, but still a relatively dense, seismic network consisting of ~20 stations (Hillers et al., 2020; Rintamäki et al., 2022). Outline of the monitoring networks, and the location of the EGS can be seen in Figure 1.

TEMPLATE MATCHING WITH A VARIABLE NETWORK

In order to study relatively weak seismicity with a dense but temporally variable seismic network, we have developed a template matching event detector based on EQCorrscan (Chamberlain et al., 2017). The detector is run on a continuous waveform archive using templates created from existing event catalogues inserted into a NorDB database (Veikkolainen et al., 2021). The four-stage detector – templating, detection, event filtering, and [re]location – is able to run on a variable station configuration and handle other intermittent issues such as gaps in the data. To quickly examine the results of the template matching, we have also developed a visualisation tool which can be used to analyse results and fine-tune the parameters (Figure 2).

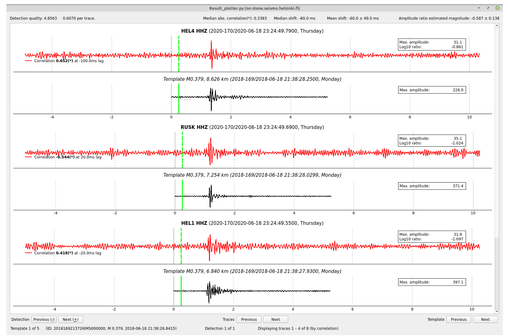

Figure 2. Interactive result plotter. The event detected is a M_L -0.6 on 2020-06-18 23:24:48.6 (UTC) at 60.1963N 24.8361E and a depth of 5.4 km. Event occurred 2 years after the template.

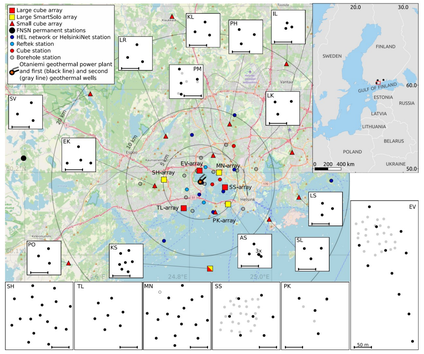

Figure 1. Map of the various monitoring networks. The detailed configuration of the 2020 & 2018 arrays are displayed in subplots. Adapted from Rintamäki et al. (2022).

Figure 3. Frequency-magnitude distributions (FMD) for the catalogues. The FMD diagrams show the number of induced earthquakes for each magnitude bin. Preliminary magnitudes of completeness estimated using the maximum curvature method (Wiemer & Wyss, 2000) are -0.4 for IMS and -0.5 for ISUH.

PARAMETERS AND PRACTICE

The template matching detector suite has 152 configuration parameters. If we exclude the input/output/visual parameters we are are left with ~100 parameters ranging from template length & frequency band to minimum number of detecting arrays and P-pick repick window. Thus, the results depend heavily on the parameters chosen, some of which are drawn from recent studies of the Otaniemi EGS (see e.g. Eulenfeld et al., 2023)

We ran the template matching from the beginning of the stimulation in June 2018 to the end of 2022 using 3 template catalogues: IMS2018 with automatic picks by IMS (Gal et al. 2018), ISUH2018 and ISUH2020. Template catalogues & detector runs are summarised in Table 1. Preliminary detector sensitivity analysis for the results of the 2018 catalogues is in Figure 3. The events of a combined catalogue are shown in Figure 4.

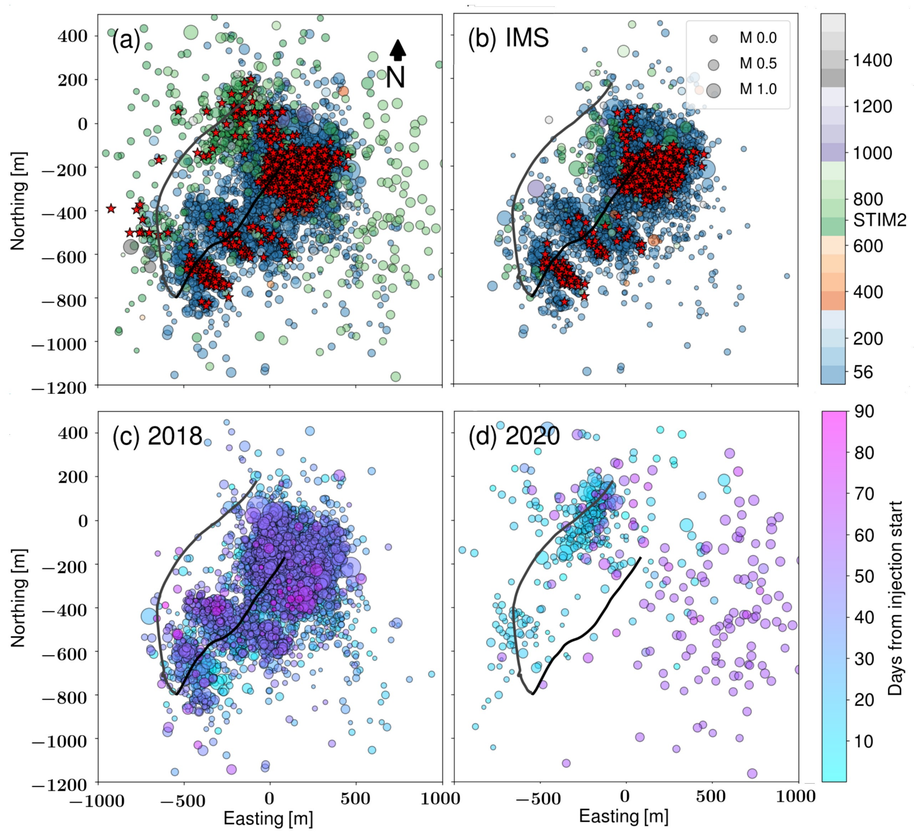

Figure 4. Top-down view of the detected seismicity. The black lines are the ST1 borehole trajectories, red stars represent the template events, circles are detections: size tells the estimated magnitude and colour shows the days from the start of the stimulation. Top row plots (a) & (b) display the seismicity from 2018 to the end of 2022, while (c) & (d) focus on the 2018 & 2020 stimulations. Figures (a), (c) & (d) show the events detected using all the possible templates, while (b) focuses on the events found using the IMS CCLoc-picked templates (Gal et al., 2021, IMS2018). The displayed event counts are (a) 7268 (b) 6067 (c) 6606, (d) 505; see also Table 1.

Catalogue	Templates	Detections	Per template
IMS2018	379	6361	17
ISUH2018	230	5828	25
ISUH2020	27	2795	104
POSTSTIM	32	3364	105
TOTAL	668	18348	27

Table 1. Summary of the detections by the available template catalogues. **POSTSTIM** catalogue refers to template events that happened outside the stimulation stages of the EGS. It also includes a selection of post-stimulation events that were detected by detector runs using the other template catalogues. This catalogue is not publicly available yet.

Note: The differences in numbers to Figure 4 are mostly explained by duplicate events and events that could not be properly re-located.

DISCUSSION AND INSIGHTS

We present here the first complete view of the induced seismicity in the Otaniemi EGS from the beginning of the stimulation, June 4th 2018 to the end of 2022. As is visible from Figure 4, most of the seismicity is focused on the stimulation periods and their immediate vicinity. Outside of the 90 days from the stimulation start, the number of detected events is 157. Compare that to the 7101 events within the time windows.

The 2020 results show apparent noise detections. One reason is the coincidental station geometry which picks near surface events that are most likely not related to the stimulation. Another complication are data issues with some of the stations, which – for some reason – show a simultaneous spike across a sub-network leading to a faulty detection that correlates well with the templates.

The results of the IMS automatically picked catalogue show two things. First, the detector with filtering is constrained by the events and most of the 2020 events are not detected by the **IMS2018** templates. Secondly, the large number of fully picked events allows to map the structure of the stimulation better than using catalogues which are not as comprehensively picked.

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Rintamäki, et al., 2022. *A seismic network to monitor the 2020 EGS stimulation in the Espoo/Helsinki Area, Southern Finland.* Seismological Research Letters, 93(2A), pp.1046-1062.
Veikkolainen, et al., 2021. *The Finnish national seismic network: Toward fully automated analysis of low-magnitude seismic events.* Seismological Research Letters, 92(3), pp.1581-1591.
Wiemer, S. and Wyss, M., 2000. *Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the western United States, and Japan.* Bulletin of the Seismological Society of America, 90(4), pp.859-869.
Eulenfeld, T., et al., 2023. *Induced earthquake source parameters, attenuation, and site effects from waveform envelopes in the Fennoscandian Shield.* JGR Solid Earth, preprint, JGRB56220, DOI: 10.1029/2022JB025162

TEMPLATE CATALOGS
IMS2018 – *IMS waveform, time and location data products from stimulations of deep geothermal wells in Espoo in 2018* DOI:10.23729/6d15a5ea-7671-4bab-88a1-71f4ed962276
ISUH2018 – *ISUH waveform, time and location data products from stimulations of deep geothermal wells in Espoo in 2018* DOI:10.23729/39cfac4f-4d0d-4fb4-83dc-6f67e8ba8dce
ISUH2020 – *ISUH waveform, time and location data products from stimulations of deep geothermal wells in Espoo in 2020* DOI:10.23729/cdfd937c-37d5-46b0-9c16-f6e0c10bc81f

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