SIAMIS-GT

Improvement of SeIsmological Analysis Methods to better support cantonal authorities in questions related to Induced Seismicity in deep GeoThermal projects

Report

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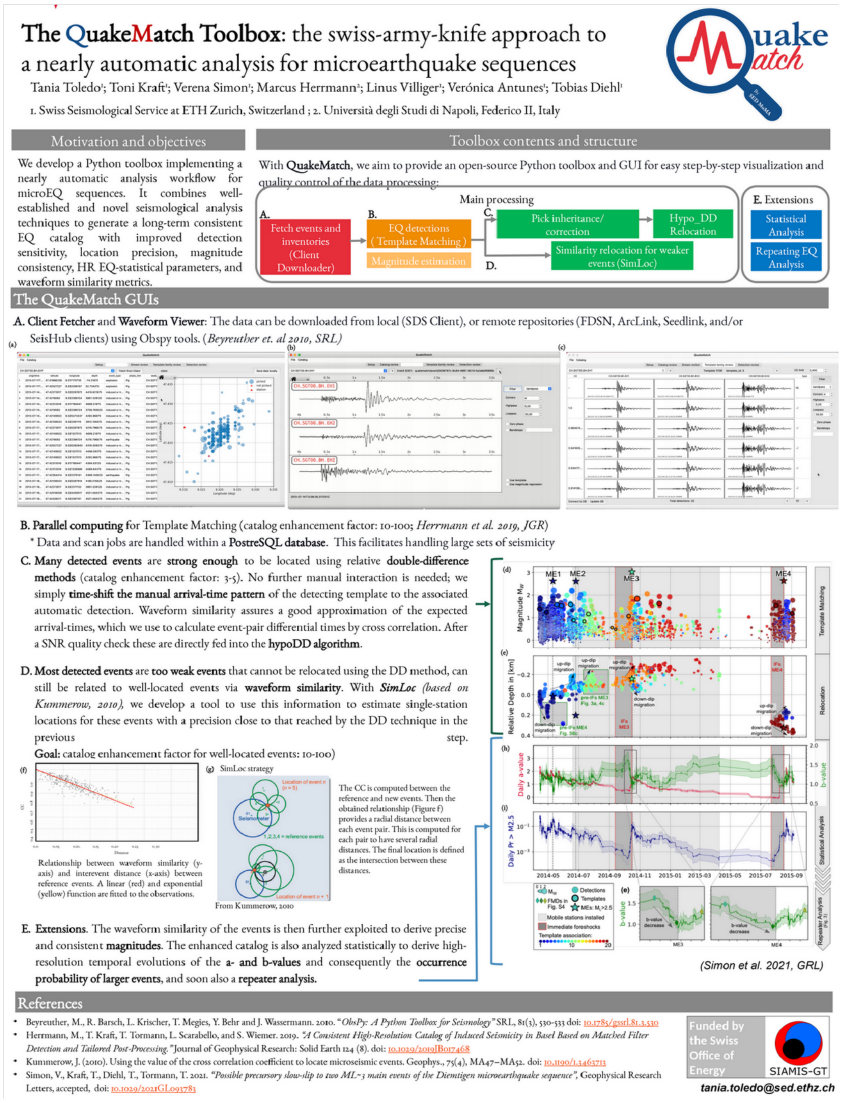

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Zusammenfassung

Das Projekt hat das Ziel seismologische Auswertemethoden zu verbessern, um den SED in die Lage zu versetzt, kantonale Behörden und Projektbetreiber schneller und gezielter über das Auftreten von unerwünschten seismischen Reaktionen des Untergrundes auf geotechnische Eingriffe (hier Tiefengeothermie) zu informieren. Im Vordergrund stehen dabei Methoden der Ähnlichkeitsanalyse die in der Seismologie zur Erkennung und Auswertung von Wiederholungsbeben eingesetzt werden, um so ein besseres Verständnis der physikalischen Vorgänge am Erdbebenherd zu gewinnen. Hier wurden diese Verfahren auf die induzierte Seismizität angewandt, die sich durch einen grossen Anteil an Wiederholungsbeben auszeichnet. Ziele sind neben der besseren Detektion, Lokalisierung und Charakterisierung von induzierten Erdbeben, eine bessere Unterscheidung von natürlicher und induzierter Seismizität zu ermöglichen. Ausserdem soll versucht werden aseismische Veränderungen des Untergrundes in Echtzeit zu erkennen, die mit klassischen seismologischen Verfahren nicht auflösbar sind.

Résumé

Le projet vise à améliorer les méthodes d'analyse sismologique pour permettre au SED de fournir des informations plus rapides et plus spécifiques aux autorités cantonales et aux opérateurs de projets en cas de réactions sismiques indésirables du sous-sol à une opération géotechnique (ici : géothermie profonde). L'étude se concentrera principalement sur les méthodes d'analyse de similitude qui sont utilisées en sismologie pour détecter et analyser les séismes répétés afin de mieux comprendre les processus physiques agissant à la source du séisme. Ici, nous prévoyons d'appliquer ces méthodologies à la sismicité induite, qui se caractérise par la présence de nombreux séismes répétés. L'objectif est non seulement d'améliorer la détection, la localisation et la classification des tremblements de terre, mais aussi d'améliorer la discrimination des tremblements de terre naturels et induits. De plus, nous voulons essayer de surveiller en temps réel les changements asismiques dans le sous-sol qui ne sont pas détectables avec les méthodes sismologiques classiques.

Summary

The project aims to improve seismological analysis methods to enable the SED to provide faster and more specific information to cantonal authorities and project operators in case of an undesired seismic responses of the underground to a geotechnical operation (here: deep geothermal). The study will mainly focus on similarity analysis methods that are used in seismology to detect and analyze repeated earthquakes to gain a better understanding of the physical processes acting at the earthquake source. Here, we plan to apply these methodologies to induced seismicity, which is characterized by containing many repeated earthquakes. The goal is not only to improve earthquake detection, location and classification, but also to improve the discrimination of natural and induced earthquakes. Further we want to try to monitor aseismic changes in the subsurface in real time that are not detectable with classical seismological methods.

Take-home messages

- The developed template matching (TM) approach enables the creation of consistent, decade-long earthquake catalogs for a geothermal site with constant, high detection sensitivity and precise magnitude estimation.
- The resulting TM catalog allows a high-resolution statistical analysis of the geothermal site's natural and induced seismicity to improve seismic hazard and risk estimates and earthquake forecasting models.
- The workflow and analysis toolbox developed in this project allows a largely automatic relative relocation of the TM-catalog earthquakes. This technique enables mapping the seismogenic structures with high precision and resolution, improving the discrimination of natural and induced earthquakes and allowing a detailed characterization of the geothermal reservoir.
- The developed analysis workflow can be applied repeatedly in short intervals to allow the automatic, near-real-time processing of the seismic data. This technique enables an improved safety monitoring of geothermal projects and builds the basis for future advanced Traffic Light Systems to mitigate unacceptably-large, induced earthquakes.
- The toolbox provides algorithms to identify and map repeating earthquakes, widely accepted proxies for aseismic faulting. Mapping these processes on a routine basis will improve the understanding of reservoir development and can contribute to improved future geothermal project safety and development.

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1 Goals of the Project

In this project, we improved seismological analysis methods used for monitoring induced seismicity by taking advantage of the waveform similarity observed in these earthquake sequences. The project is organized in the following subtasks:

Improvement of microearthquake detection

Building on template matching techniques, developed in recent years for natural seismicity, we expect to improve the detection threshold for induced earthquakes to 1-2 orders of magnitude below the detection threshold of classical energy based detectors.

High precision active faults detection

We plan to couple template matching with high-precision relocation techniques. This will allow to identify active fault planes in the geothermal reservoirs and to build more realistic thermo-hydromechanical reservoir models.

Single station similarity location of microseismicity

The majority of the events detected by template matching will be too small to be detected on more than one seismological station. We will develop a similarity location algorithm that takes advantage of the fact the closely spaced earthquakes have very similar seismograms. Once calibrated, the algorithm only relies on waveform comparisons at a single station.

Detect aseismic changes with high spatiotemporal resolution

In recent years ambient seismic noise techniques have claimed the potential to resolve tiny changes in subsurface properties. These methods often have the problem of not being able to locate the source of the observed change with much certainty or even to distinguish between a change in the ambient seismic noise field and a real change in the medium. To overcome these problems we plan to apply coda wave interferometry to repeating induced earthquakes.

2 Methods

2.1 Template Matching Detection Module

Template matching is an earthquake detection method based on waveform crosscorrelation, which proved to lower the detection threshold by about one magnitude unit compared to conventional methods (e.g., like the energy-based short-term average/long-term average technique) and can often recover ten to hundred times more events. Template matching has the potential to detect events with signal amplitudes even below the noise level and at times of high event rates when waveforms overlap.

The method takes advantage of the high waveform similarity observed within seismic sequences. Seismic waves that originate from a similar source region caused by a similar source mechanism travel a similar path in the medium and will have similar waveform shapes at a receiver. Hence, with a waveform of a known event, one can search for more events that have a similar, or the same, source. To find them, a matched filter continuously measures the similarity between the waveform of a known event and the available continuous data. It provides a cross-correlation (CC) trace that spans the extent of the available data. A peak in the CC trace that exceeds a defined threshold triggers a new detection. A very high CC value indicates a repeating source, but the value degrades (i.e., the waveforms decorrelate) with growing separation distance, increasing noise level, increasing frequency bandwidth of the signal, differing magnitude, and due to deviations in the focal mechanism and source-time function.

We developed a Python-based framework which can perform the workflow presented in this study (e.g., template selection, waveform preprocessing, matched filter detection, post-processing, and result plotting). It was particularly designed for the single-station approach, because our interest was to use only the most sensitive station for earthquake detection. For waveform management and processing, we made use of obspy (Beyreuther et al., 2010) but replaced some of its routines for performance considerations (e.g., filtering and resampling in the frequency domain).

For performing event detection with thousands of templates over more then ten years of data in manageable time, we parallelized our matched filter routine to enable high-performance computing involving hundreds of processors. We made use of MPI (Message Passing Interface) and implemented a master/slave configuration, where one master process controls as many slave processes as processors are available. Each slave process either (1) reads waveform data from an archive and preprocesses it or (2) performs a match filter detection on preprocessed waveform data with one template. To avoid idle slave processes, the master process optimizes resource sharing and balances the computational load. The performance scales with the number of processors because the processing of the chunk-template pairs are independent from each other.

A first version of the detection module was finalized in 2019 and published on the SED gitlab repository: https://gitlab.seismo.ethz.ch/microEQ/TM

> *SEISMATCH*
>
> *A software framework to search for (i.e., detect) similar earthquakes in a waveform archive using a catalog of known events. The detection method is called template matching, or matched filter analysis, and is based on waveform cross-correlation. seismatch is designed to perform the detection at a single seismometer station (typically the most sensitive one), which can have multiple channels. Template matching proved to lower the detection threshold by about one magnitude unit compared to conventional methods and can thus often recover 10 times more≳ events. seismatch also features basic analysis and post-processing steps like waveform clustering, magnitude calculation, plotting of waveforms & timelines, and more to come.*

seismatch is implemented in Python and was originally developed for this study:

Herrmann, M., T. Kraft, T. Tormann, L. Scarabello, and S. Wiemer (2019) "A Consistent HighResolution Catalog of Induced Seismicity in Basel Based on Matched Filter Detection and Tailored Post Processing. J. Geophys. Res., 124(8), doi:10.1029/2019JB017468.-

Because of the development history of seismatch starting as a research tool, the internal data handling and the user interaction have turned out to be unsuitable for further developing the software into a toolbox that integrates modules from other work packages. Therefore, we decided to re-code the software from scratch and base internal data handling on an SQL-database, waveform handling on established standards (i.e., QuakeML, FDSN-WS), and user interaction on graphical user interfaces. This decision greatly simplified the toolbox development and ensures its sustainability.

> *QUAKEMATCH*
>
> *is an open source, stand alone research toolbox that allows a step-by-step visualization and computation of template matching detections and subsequent microseismic analysis. Like seismatch, QuakeMatch detects events using a single*

station template matching approach, estimates their magnitudes, and plots timelines of the analyzed sequences.

QuakeMatch, however, addresses some of the limitations of seismatch such as handling different seismic data formats like ASDF (used in lab-scale settings), and querying event and waveform data from different data center repositories. In this regard, QuakeMatch uses more standard Python tools to allow its use for different applications and users outside the SED.

Additionally, QuakeMatch introduces a PostreSQL data base structure for an easier handling of the computation processes and for bookkeeping large sets of seismicity. The latter is a limitation of seismatch, where the results are kept in large ASCII files. In QuakeMatch, general event information (time, location, and magnitude) is kept within a SQL data base and detailed information (e.g. picks) are stored in quakeml fomat. This new structure allows a faster and easier filtering and querying event information to continue with calculations such as new amplitude estimations, highprecision relocations, similarity location, event classification, repeater analysis, etc.

The current version of the re-coded toolbox QuakeMatch will be published on gitlab (https://gitlab.seismo.ethz.ch/microEQ/QM). At present, access to the repository is restricted to the core developers but will open access after some further testing soon.

2.2 Relative Relocation / Waveform Similarity Location

Beside the basic template matching module, QuakeMatch also implements relocation techniques. We us a pick-inheritance method to perform a nearly automatically relocate TM detections using the double-difference (DD) method (Waldhauser & Ellsworth, 2000). Earthquakes that are to weak to be relocated by the DD method, may be relocated by a single station waveform similarity approach.

For the pick-inheritance/DD-relocation module, we make use of the results of Geller & Mueller (1980) and assume - because of waveform similarity - that the templates and their associated detections are located very close to each other. Consequently, we inherit the arrival time pattern (Nicholson, 2002) of the body-waves of the template events to their detections by time-shifting, using the corresponding cross-correlation lag time of the TM analysis. In this way, we get reliable estimates of the expected body-wave arrival times for the detections at all stations. Using these estimates, we calculate differential body-wave arrival times for all possible event pairs at all stations using all recording stations of the Swiss national network around the sequence. Further, we calculate high-precision differential arrival times by cross-correlation analysis (e.g., Deichmann & Garcia-Fernandez, 1992) for all arrival pairs. We only keep those pairs that pass the cycle-skipping test described by Diehl et al. (2017). With a minimum of six catalog and six differential arrival time observations, we invert relative earthquake locations using the double-difference technique (Waldhauser & Ellsworth, 2000) and the 1D velocity model of Diehl et al. (2005).

For Similarity Location, we implemented a hierarchical clustering method to re-associate the detection from the Template Matching module in a stand-alone module. In a next step, we started to implement a prototype version of the simloc module in Python. The module builds on the result of the clustering module to establish a cluster-familiy-based relationship between waveform similarity and interevent distance (Fig.1). These relationships are then used to estimate the epicentral distances, Dj, of the earthquake to be located with a number of reference earthquakes, j. The reference earthquakes are chosen form the clusters established in the previous step and should be evenly distributed over the seismic cloud of the seismic sequence. The SimLoc prototype estimates the epicentral location by minimizing the difference between the sum of the estimated interevent distances and the observes ones: MIN(ABS(SUM(Djcal)-SUM(Djobs))) using a grid search algorithm (Fig.2).

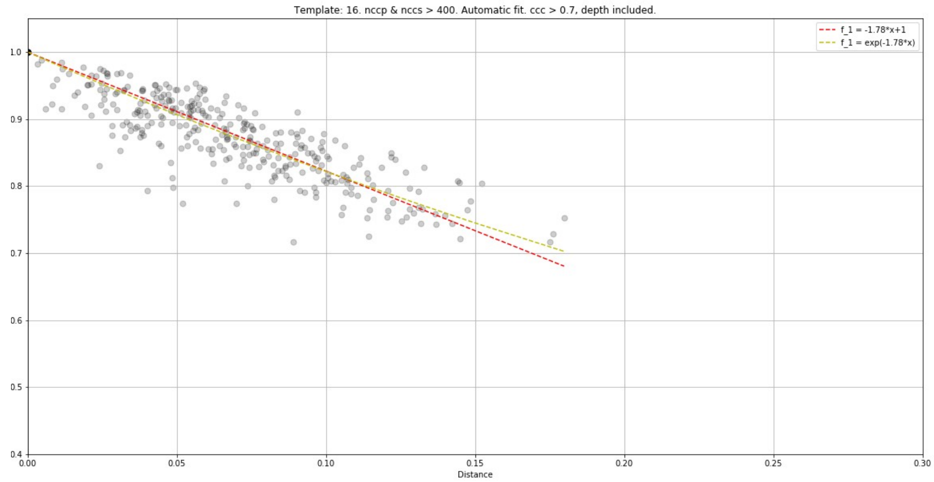

Fig. 1) Raltionship between waveform similarity (y-axis) and interevent distance (xasis). A linear (red) and exponetial (yellow) function are fitted to the observations.

First result for the 2014/15 Diemtigen earthquake swarm are promising. However, they also highlight problems with the current implementation of the SimLoc prototype that have to be solved over the run of the last project year. Among these issues are: improve sensitivity of Dj to waveform similarity; go from 2D distance to 3D distance; optimize selection of reference events.

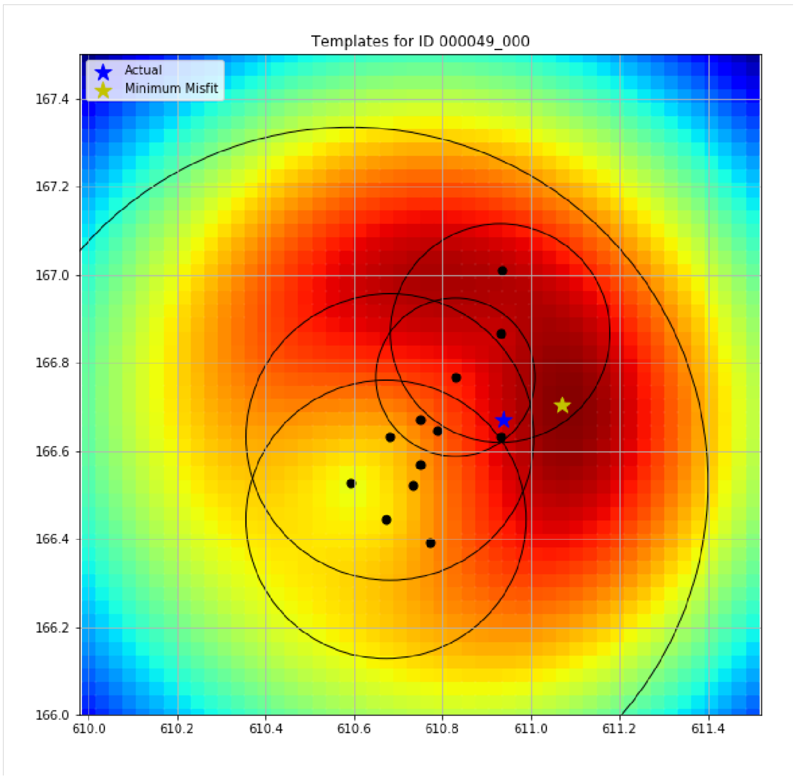

Fig. 2) Location result of SimLoc prototype. Background color: heat map of earthquake location probability density; blue star: reference DD-location; yellow star: maximum likelihood SimLoc location; black dots: locations of reference earthquakes; black circles: individual interevent distance estimate based on waveform similarity.

2.3 Repeating Earthquake Analysis Module

Uchida & Bürgmann (2019) give the following description of repeating earthquakes:

> *"Repeating earthquakes are identical in location and geometry but occur at different times. They appear to represent recurring seismic energy release from distinct structures such as slip on a fault patch. Repeaters are most commonly found on creeping plate boundary faults, where seismic patches are loaded by surrounding slow slip, and they can be used to track fault creep at depth. [...] While true repeaters should have identical seismic waveforms, small differences in their seismograms can be used to examine subtle changes in source properties or in material properties of the rocks through which the waves propagate. Source studies have documented the presence of smaller slip patches within the rupture areas of larger repeaters, illuminated earthquake triggering mechanisms, and revealed systematic changes in rupture characteristics as a function of loading rate."*

We have implement the hierarchical clustering method to group detection from the Template Matching module by similarity (see 2.2). In the course of this work, we looked into repeating earthquake occurrence in the Diemtigen sequence to better understand the cause of the precursory phenomena observed (Fig. 3&4).

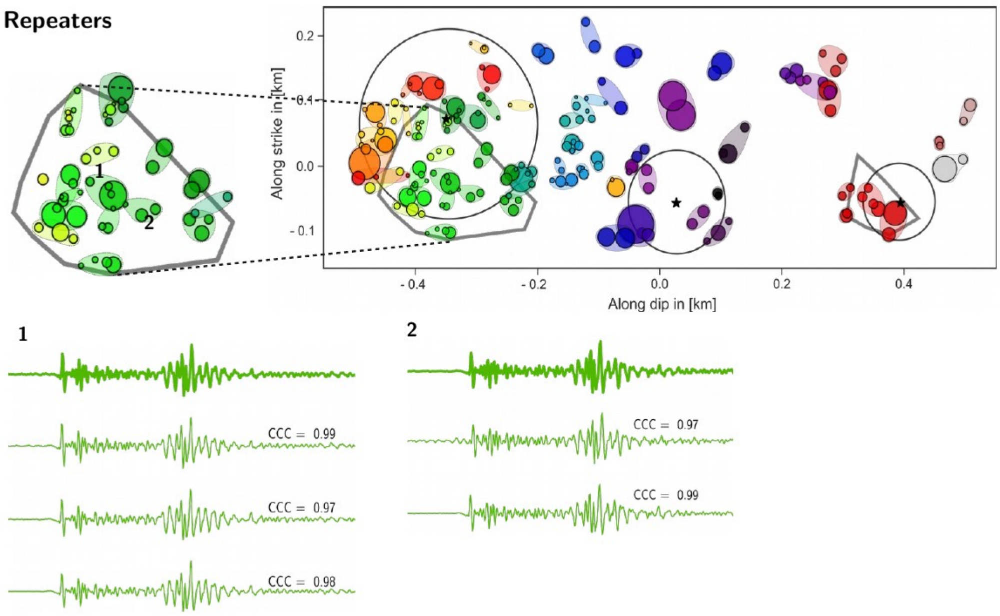

Fig 3) Top right: Repeating earthquake clusters projected onto the Diemtigen swarm fault plane. Colors and convex hulls indicate association to different repeater clusters. Top left: zoom into the Immediate Foreshock Zone of the ML3.2 mainevent of the sequence where the repeaters concenrate. Bottom: seismogram examples for two repeater clusters with four and three members (location indicated in top left figure). Modified from Simon et al., 2021.

The results of the analysis of the Diemtigen swarm show that the similarity analysis methods developed in SIAMIS-GT can resolve seismicity patterns in unprecedented detail. The observed seismicity patterns are closely resembling the ones reported from laboratory scale experiments. From these observations we hope to derive how earthquake physical and fault zone condition parameters evolve over the course of the sequence. These results will hopefully allow to better understand the behavior of seimicity of the sequence.

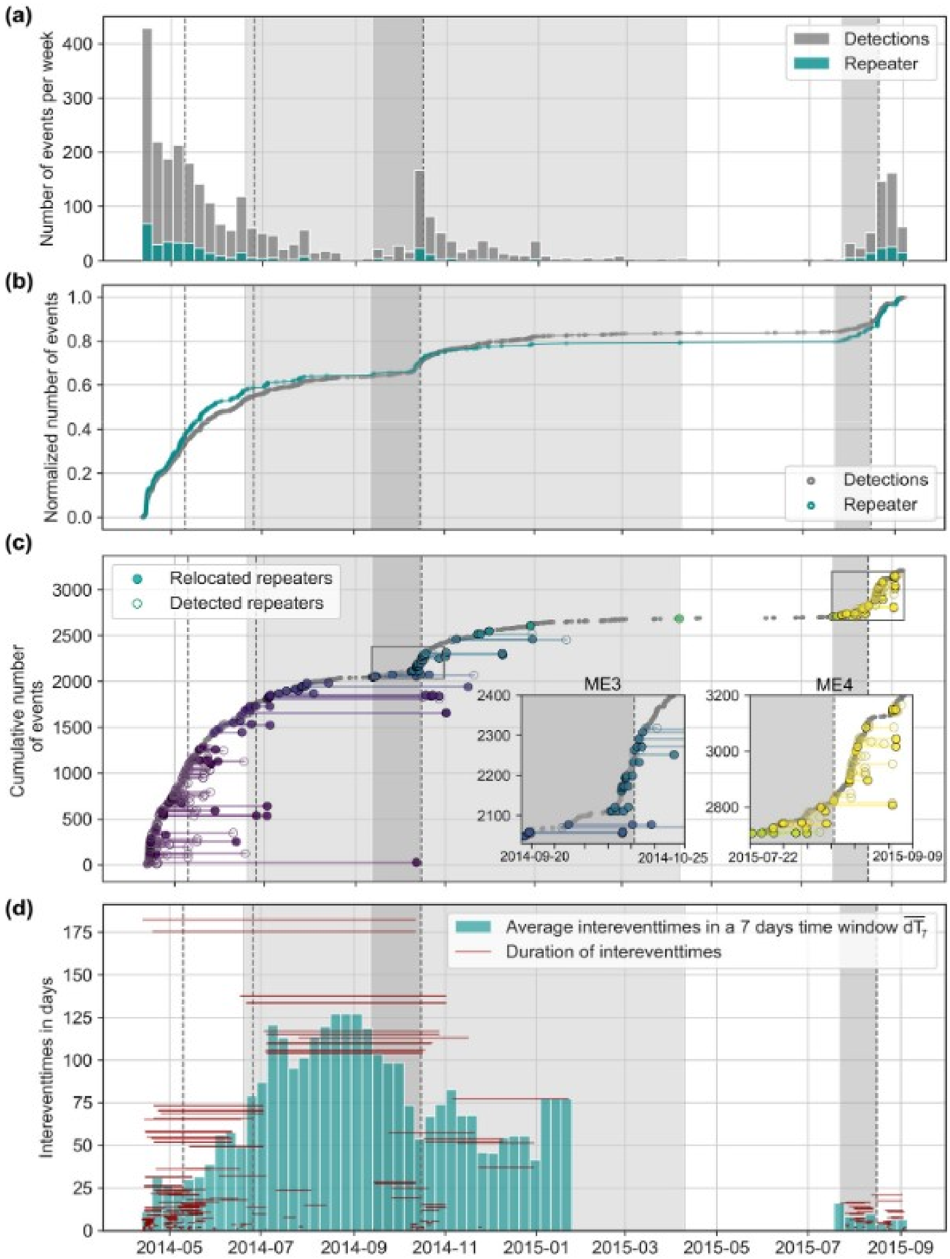

Fig 4) Overall repeater statistics of the 2014/15 Diemtigen sequence: Repeater families displayed here are joined only considering the waveform similarity criterium (CCC ≥ 0.95). Dark gray shading defines the IF phase of ME3 and ME4, light gray shading the time when mobile stations were installed. (a) Number of detections vs. number of repeaters per week. (b) Normalized number of detections vs. repeaters. (c) Temporal variation of the cumulative number of detections. The activation time of every repeater cluster is shown by dots and horizontal bars, starting with the first event in the family. Relocations are plotted by filled circles, detections by unfilled circles. Inserts show the repeater families around ME3 and ME4. (d) Average interevent times in a seven-day window in blue, duration of every interevent time displayed as red stripes. Modified from Simon et al., 2021.

In induced seismic sequences, analysis like the ones outlined above may allow to better tune injection parameters to optimize reservoir productivity and to minimize its seimic response to injection. Applications of the workflow developed in the SIMAIS-GT project on the way and are outlined in Section 4.

The results of the Diemtigen Analysis are summarized in paper in Geophysical Research Letters (Simon et al., 2021). Verena Simon and Tania Toledo have presented intermediate results of the QuakeMatch workflow at several scientific meetings (Simon et al., 2019a,b,c,d,e, 2021a,b,c,d, 2022; Toledo et al., 2021a,b, 2022).

3 Current applications of the developed tools

3.1 Performance analysis of GEOBEST baseline monitoring networks

In the framework of the GEOBEST2020+ project, the Swiss Seismological Service (SED) provides the baseline seismic monitoring for deep geothermal projects to the cantonal authorities. For this purpose, the SED usually installs 1-4 additional seismic stations close to a project site to optimize the network geometry of the Swiss national network. To evaluate the performance against ground-truth-seismicity catalogs, we have developed a method based on the template-matching module developed in the SIAMIS-GT project.

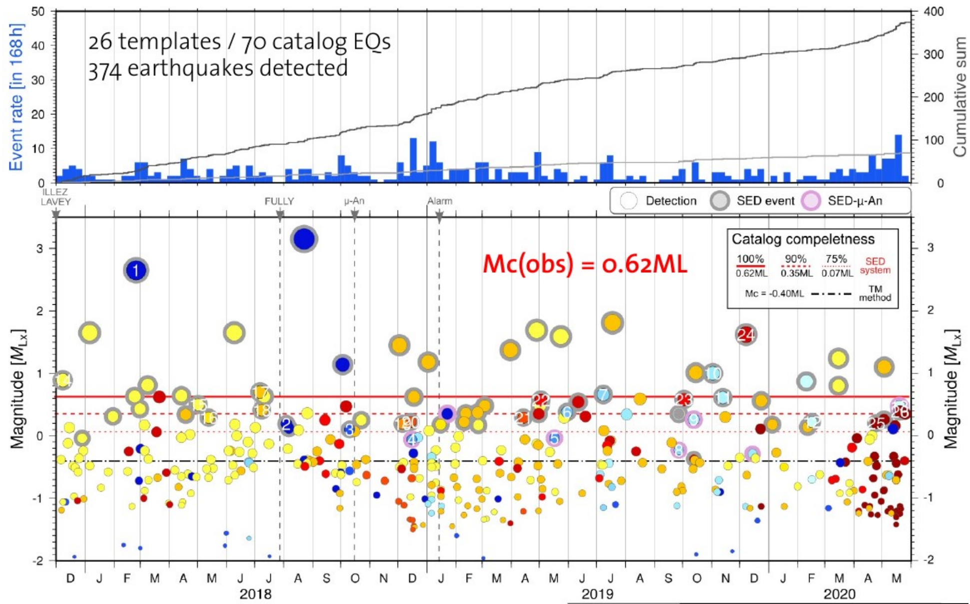

Fig. 5) Timeline of the 374 earthquakes detected by template matching (Herrmann et al., 2019) in the vicinity of the planned AGEPP drill site between Dec. 2017 and May 2020. Earthquakes are indicated as dots scaled by local magnitude (MLx) and color-coded by template association. Gray outline: SED catalog event; Pink outline: SED-μAn event (detected by the non-routine 3station-trigger algorithm). Their template numbers indicate the 26 template events. Horizontal lines indicate the observed completeness magnitudes of the SED catalog (solid red: ML0.62; dashed: 90% and 70% levels), and the TM catalog (from Kraft, 2020)

First, the SED catalog is enhanced by template matching, and the magnitudes of the detected events are calculated based on the template-family-based regression method developed by Herrmann et al. (2019). The enhanced catalog usually contains 10 to 50 times more events than the SED catalog and usually lowers the completeness magnitude (Mc) by at least one magnitude. By comparing the highly complete catalog to the original SED catalogs obtained with the old and new network geometry, it is possible to identify which events are missing in the latter catalogs, and their completeness level can directly be evaluated without using statistical model assumptions.

Fig. 5 shows the result of the network performance analysis for the AGEPP project near Lavey-lesBain/VD. The SED catalog recorded with the new baseline monitoring network reaches an observed completeness of Mc=0.62ML in the vicinity of the AGEPP project. This value agrees with the value estimated on a statistical model basis by the BMC method used for network planning purposes in the GEOEBST2020+ project. Also, notice that the statistically estimated completeness of the template matching catalog is Mc=-0.4ML.

3.2 Daily microseismic monitoring of the deep borehole Basel-1

The deep geothermal project in Basel induced an ML3.4 earthquake during a hydraulic stimulation in December 2006. Following a comprehensive risk analysis, the project was terminated, and the 5kmdeep borehole closed in April 2011. Subsequently, the wellhead pressure increased to about 80 MPa in early 2017, and seismic in the formally stimulated volume increased, reaching magnitudes up to ML1.8.

To better understand the observed seismicity, Herrmann et al. (2019) used an early version of the template matching and earthquake statistical analysis modules developed in the SIAMIS-GT project to enhance the catalog of induced earthquakes of the past 15 years. Several hundred thousand microearthquakes down to a magnitude of ML~-3.0 were detected and analyzed statistically. Based on Hermann et al.'s catalog, Wiemer et al. (2017) and Karvounis & Wiemer (2022) calibrated numerical reservoir seismicity models to test various scenarios to reduce the wellhead overpressure and reduce the level of induced seismicity.

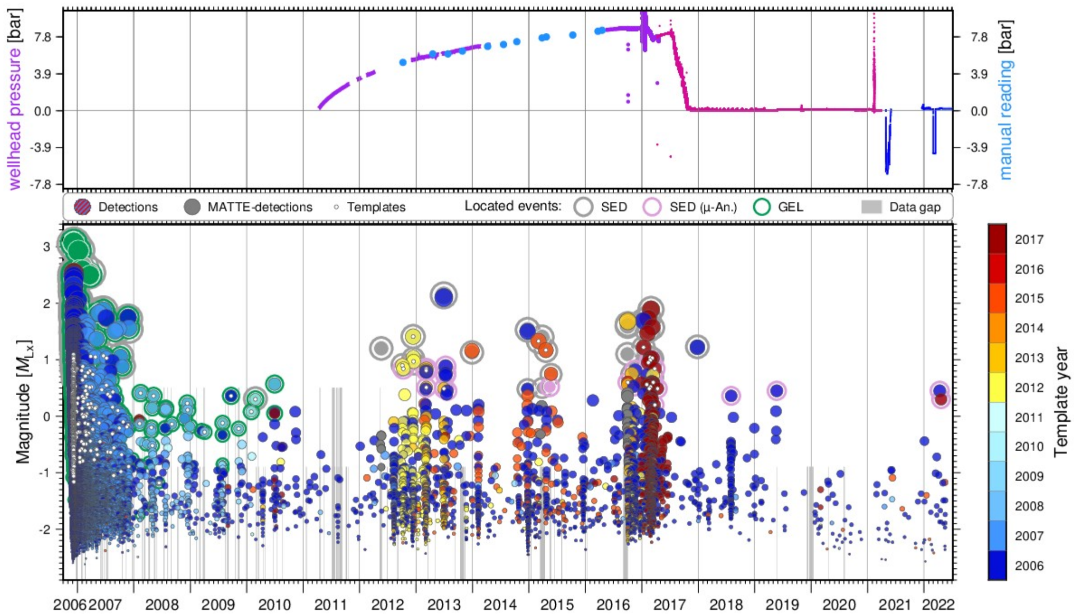

Fig. 6) Timeline of induced seismicity in hydraulically stimulated volume 5km below Basel detected by template matching (as displayed on the SED's internal web-page for canton and operator). The top panel shows the development of wellhead pressure.

In summer 2017, the wellhead pressure was reduced in a controlled step-wise procedure. For this procedure, an earthquake-rate and magnitude-based traffic light system (TLS) was developed by the operator of the borehole (Industrielle Werke Basel, IWB). Input to the TLS was provided by SED running an automated daily template-matching scan with 345 templates from 2006-2017 to detect induced microearthquakes down to magnitude ML-3.0. Results of the template-matching scan, the current alarm level, and near-real-time hydraulic data from the borehole were displayed on a web page with access restricted to the canton operator. The daily template-matching scan has since been operated continuously and also provided input to the TLS operated during a long-term production test in spring 2021 that investigated the potential of reducing the seismic hazard more rapidly by actively decreasing the reservoir overpressure by pumping.

In spring 2022, the daily template-matching scan helped to identify a slight increase in induced seismic activity potentially linked to a change of the wellhead assembly performed by the operator. The SED's rapid detection and report of the seismicity increase allowed the operator to intervene and slightly adapt the wellhead design quickly. After this intervention, the seismicity reduced again significantly.

3.3 Near-realtime monitoring of the BedrettoLab microseismicity

The BedrettoLab (Bedretto Underground Laboratory for Geosciences and Geoenergies) is a unique research infrastructure run by ETH Zurich, making it possible to examine the Earth's interior closely. It is located in the Swiss Alps 1.5km below the surface and in the middle of a 5km-long tunnel connecting the Bedretto Valley in Ticino with the Furka railway tunnel. The Bedretto Reservoir Project aims to scientifically investigate the development of a large-scale, deep reservoir for water circulation and the storage and extraction of geothermal energy.

Part of the safety infrastructure of the BedrettoLab is an enhanced seismic network in and around the tunnel that is streaming real-time data to the SED routine system. Earthquake alerts generated by SED's automatic earthquake analysis system contribute to the earthquake-magnitude and localground-motion-based traffic light system designed by the BedrettoLab team.

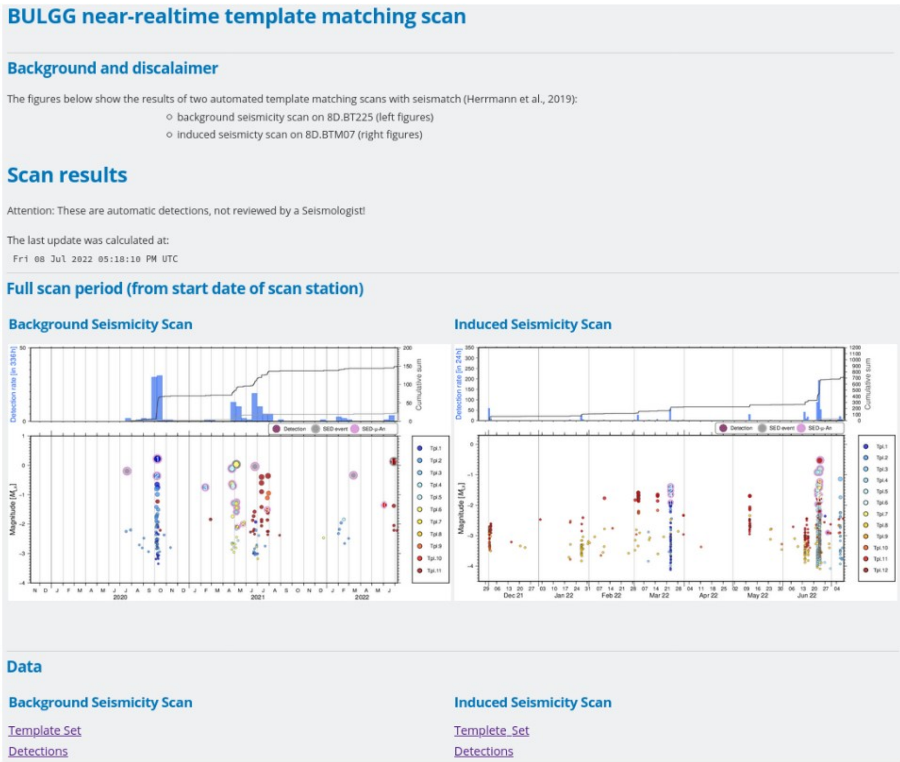

Fig. 7) Screen shot of the internal webpage displaying the results of two template matching scans for the BedrettoLab.

To enhance the detection sensitivity of the seismic monitoring system in periods when no hydraulic stimulations are performed in the BedrettoLab and to also capture the background microseismicity at some distance to the Bedretto tunnel, the SED's implemented two separate template matching scans for the BedrettoLab. Both scans are running fully automatic every hour and update information on an internal web page that the BedrettoLab team can access. The scans ensure a constant detection sensitivity for background and induced events for the whole operation period of the scanned seismic stations (background scan: Nov. 2020; induced scan: Dec. 2021).

So far, the scans' template sets are based on SED's routine system catalogs. Therefore, the detection sensitivity currently can not compete with the dedicated monitoring system for hydraulic stimulation operated by the BedrettoLab team. However, in periods when this system is not operational (i.e., when no hydraulic stimulation is performed), the scans dramatically improve the detection sensitivity of the SED routine system (down to magnitudes ML-4.0) and help to provide safety-relevant seismicity information to the BedrettoLab team.

SED's microseismic monitoring and analysis group (muma) currently assists the BedrettoLab team in implementing template matching routines developed in the SIAMIS-GT project (seismatch & quakematch) for direct use in the dedicated monitoring system for hydraulic stimulation. For this development, the teams can build on the experience and development from the application of the SIAMIS-GT tools to the data of the Grimsel "In-situ Stimulation and Circulation (ISC)" project (see below).

3.4 Repeater analysis of hydro-frack seismicity at the Grimsel Test Site

The Grimsel In-situ Stimulation and Circulation project aimed to understand better hydro-seismomechanical coupled processes associated with high-pressure fluid injections in a crystalline rock mass. The experiment was carried out at the Grimsel Test Site. In a stimulation phase, fault zones were pressurized until slip occurred, and the associated permeability creation, pore pressure propagation, deformations, and seismicity were monitored (Gischig et al., 2019).

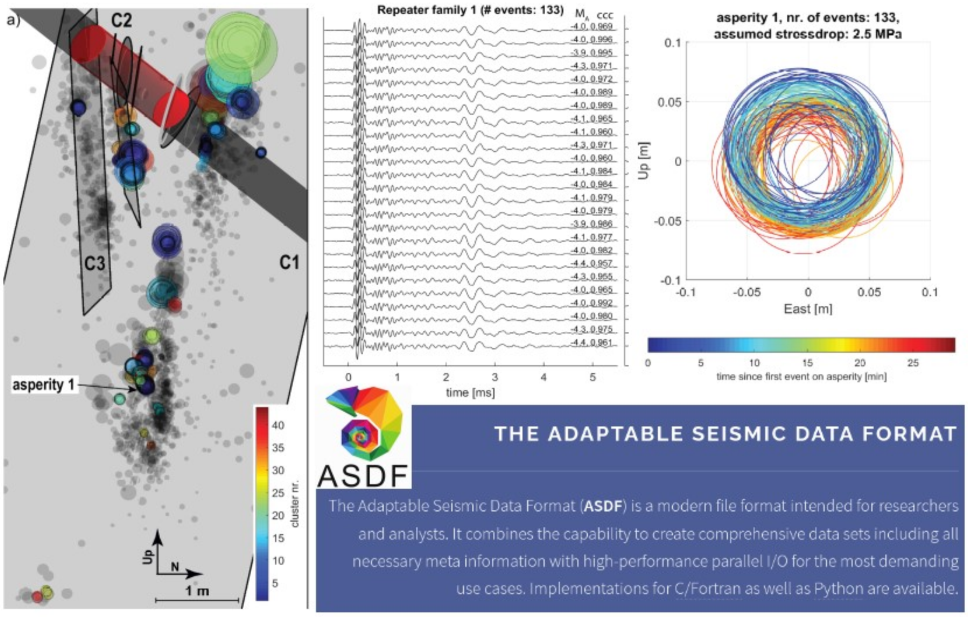

Fig. 8) Seismic monitoring results of hydraulic fracturing experiments performed in the Grimsel "In-situ Stimulation and Circulation (ISC)". Analysis tools developed in SIAMIS-GT were adapted to read ADSF format and helped to identify repeating earthquakes with overlapping rupture areas. (partly adapted form Villliger et al., 2021)

In the framework of SIAMIS-GT, the template matching tools seismatch and QuakeMatch were adapted to read and write the ADSF format (Krischer et al., 2016) used for storing the MHz-sampled seismic and acoustic emission data of the Grimsel ISC projects. (ASDF is also used for these data types in the BedrettoLab). With this adaptation, it was possible to use the template matching algorithms for the Grimsel data set and to ensure a constant detection sensitivity for the whole project period.

Cluster analysis techniques using waveform similarity implemented in the SIAMIS-GT project were used to find families of highly similar picoearthquakes. High-precision relocations based on cross-correlation improved differential arrival times confirmed that these families consist of events that repeatedly ruptured the same fault patch (Fig. 8). Such repeating earthquakes can indicate aseismic slip on the fault plane surrounding the repeater patches, and changes in their inter-event times can reveal changes in the external forcing acting on the repeater patches. Such changes can, e.g., be caused by stress redistribution from other nearby earthquakes and poroelastic effects from hydraulic fracturing. A detailed investigation into these aspects is underway.

3.5 Analysis of natural microseismic sequences in CH

The methods developed and implemented in SIAMIS-GT also help to improve the analysis of natural earthquake sequences. In her PhD-project, Verena Simon currently performs a systematic high-precision analysis of all earthquake sequences with mainshock magnitude ML>2.5 that occurred in Switzerland in the last 15 years. She starts by improving the existing SED catalog using template-matching. Then, perform a high-resolution statistical analysis of all sequences to study their temporal magnitude-frequency behavior. Finally, she derives high-precision relative locations to examine the spatio-temporal behavior of the sequences (Fig. 9).

The goal is to develop a systematic classification of seismicity patterns in Switzerland and study how they correlate with the seismotectonic and geological setting, source depth, and other parameters. We will also investigate the long-term behavior and driving mechanisms of the sequences, as well as the influence of external forcing (e.g., remote triggering, rainfall, earth tides). The data will also allow us to study earthquake nucleation and earthquake physics in general. As a community service, we plan to implement a fully automated analysis scheme for sequences of specific interest and to publish their highresolution earthquake catalogs via the SED internet data portal.

The experiences from the analysis of these natural sequences largely benefit the testing and implementation of the SIAMIS-GT tools and procedures for induced seismicity. Lessons learned from this analysis are also helping the development and improvement of new analysis modules of SED's routine analysis software SeisComP3 (Weber et al., 2007). Recent adaptations influenced by the SIAMIS-GT project results are the real-time double-difference location module (SCRTDD; github.com/ swiss-seismological-service/scrtdd; Scarabello et al., 2022) and the real-time template matching module (SCdetect; github.com/ swiss-seismological-service/scdetect; Armbruster et al., 2022).

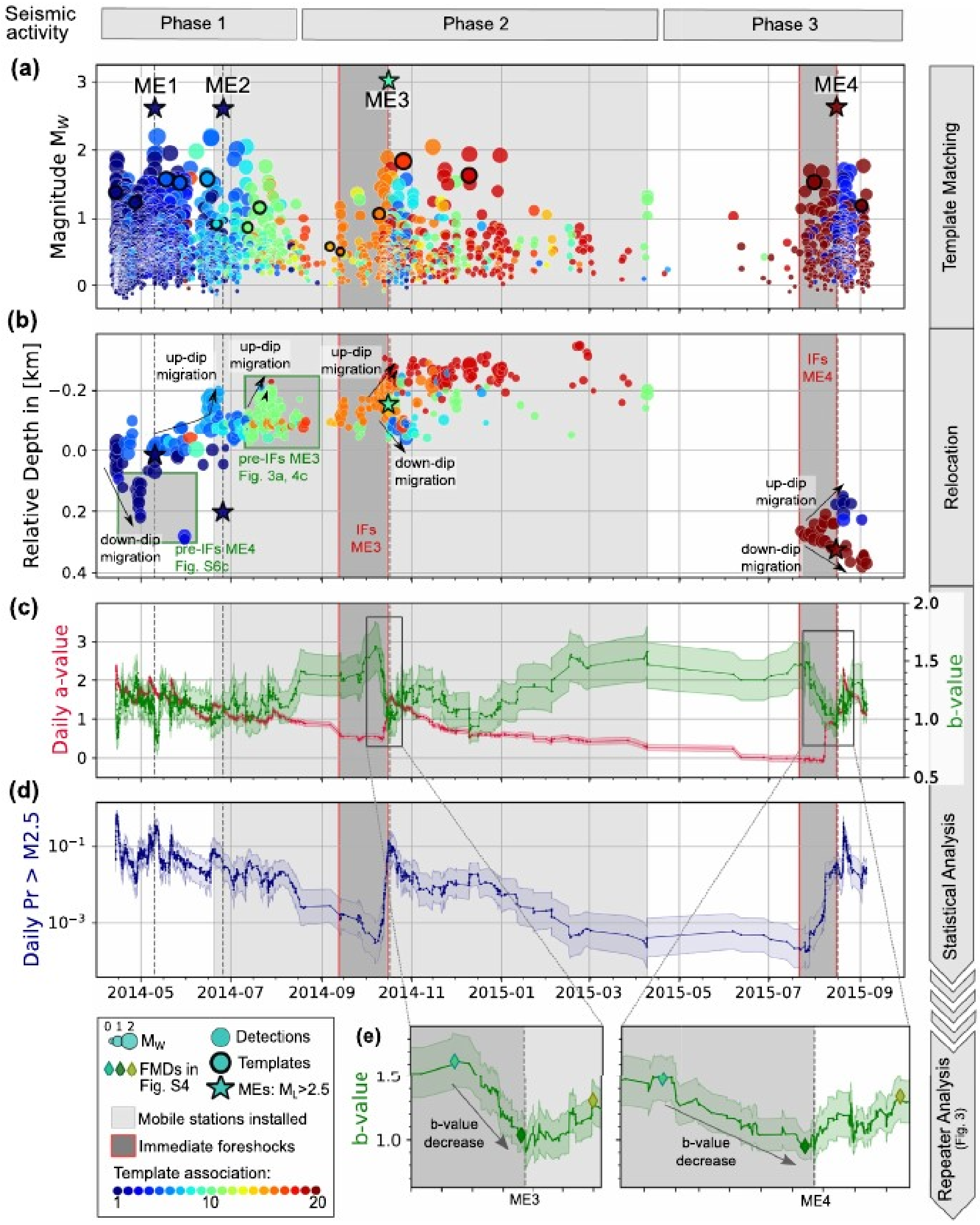

Fig. 9) Illustration of the analysis workflow developed with support of SIAMIS-GT at the example of the 2014/15 Diemtigen sequence (a) Temporal evolution: (a) Moment magnitudes (MW); colors indicate template associations. (b) Source depth (w.r.t. first event). (c) a- and b-value (MC = 0.4 MW); b-value change before ME3 and ME4 enlarged in (e). (d) Daily probability of a MW > 2.5 earthquake. (From Simon et al., 2021)

3.6 TM improves seismotectonic analysis of St.Ursanne/JU area

We used the template matching module in an seimotectonic analysis of the Saint-Ursanne/JU area in the Jura fold-and-thrust belt. The area hosts the Mont Terri rock laboratory and is close to the upcomming Haute-Sorne deep geothermal project of Geoenergie Suisse AG. The TM analysis allowed to use well-located event of the past few years with improved stations coverage, to detect past events starting from 2000 and contributed to a better understanding of the tectonic setting of the area.

Lanza et al. (2015) document the result in detail and give the following abstract:

> *"The interpretation of seismotectonic processes within the uppermost few kilometers of the Earth's crust has proven challenging due to the often significant uncertainties in hypocenter locations and focal mechanisms of shallow seismicity. Here, we revisit the shallow seismic sequence of Saint-Ursanne of March and April 2000 and apply advanced seismological analyses to reduce these uncertainties. The sequence, consisting of five earthquakes of which the largest one reached a local magnitude (ML) of 3.2, occurred in the vicinity of two critical sites, the Mont Terri rock laboratory and Haute-Sorne, which is currently evaluated as a possible site for the development of a deep geothermal project. Template matching analysis for the period 2000 - 2021, including data from mini arrays installed in the region since 2014, suggests that the source of the 2000 sequence has not been persistently active ever since. Forward modelling of synthetic waveforms points to a very shallow source, between 0 and 1 km depth, and the focal mechanism analysis indicates a low-angle, NNW-dipping, thrust mechanism. These results combined with geological data suggest that the sequence is likely related to a backthrust fault located within the sedimentary cover and shed new light on the hosting lithology and source kinematics of the Saint-Ursanne sequence. Together with two other more recent shallow thrust faulting earthquakes near Grenchen and Neuchatel in the north-central portion of the Jura fold-and-thrust belt (FTB), these new findings provide new insights into the present-day seismotectonic processes of the Jura FTB of northern Switzerland and suggest that the Jura FTB is still undergoing seismically active contraction at rates likely < 0.5 mm/yr. The shallow focal depths provide indications that this low-rate contraction in the NE portion of the Jura FTB is at least partly accommodated within the sedimentary cover and possibly decoupled from the basement."*

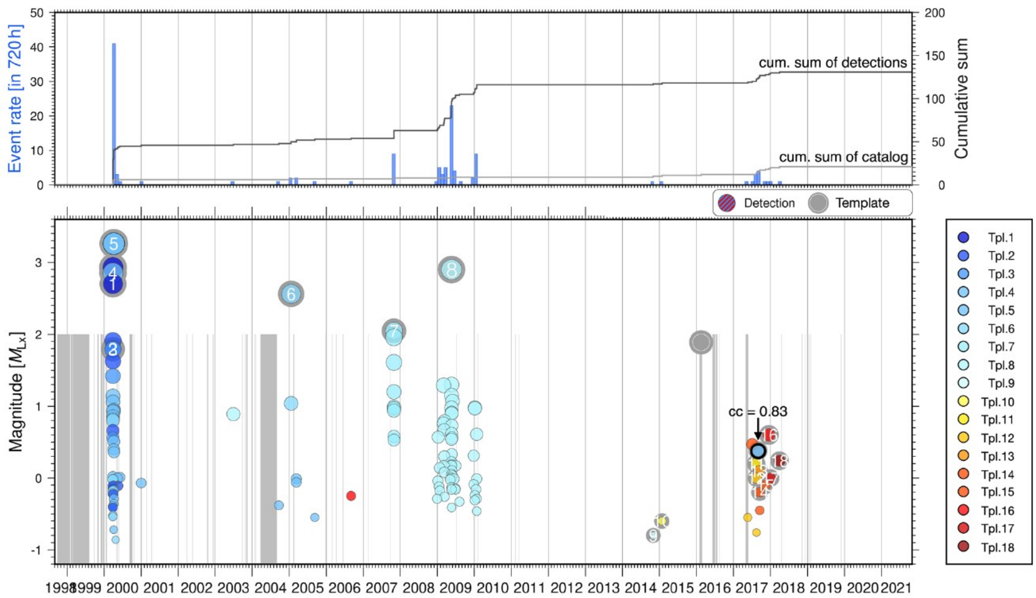

Fig. 10) TM earthquake detections timeline for the St Ursanne sequence at station BOURR using thresholds individually selected for each template family by visual inspection. Top panel: resolved event rate. Coloring of events indicates template association. Existing catalogue events are highlighted with a gray ring. Data gaps are indicated by vertical gray bars. Their height is a conservative estimate of the completeness magnitude of the SED catalog for the study area. Above this magnitude threshold earthquakes in the study area would have been detected without the template matching method. (Modified from Lanza et al., 2021)

4 Conclusions

The examples in Chapter 3 illustrate the significant contribution of the SIAMIS-GT project products to the improvement of seismic monitoring and operational safety for geothermal projects on the commercial and scientific levels. Applying the SIAMIS-GT products in the GEOBEST2020+ project context allows the SED better to inform the cantons on safety-relevant changes in seismicity and more accurately evaluate background seismicity and monitoring performance before the start and during the operation of a deep geothermal project. The examples of the near-real-time applications of the SIAMIS-GT products in Basel and the Bedretto-Lab further document their significant contribution to the operational safety of geothermal projects.

The SIAMIS-GT products are currently implemented as stand-alone analysis tools that are not part of the SED real-time routine analysis. However, real-time-capable modules for template matching detection and double-difference relocation (scdetect and scrtdd, see above) are currently being implemented for the SED routine analysis tool SeisComP3. They will also be available for real-time monitoring and alerting as part of GEOEBST2020+. The SIAMIS-GT stand-alone tools support this development as easy-to-use test benches that allow the SED to gain experience with the algorithms and further develop them on real-wolrd examples.

In the framework of GEOEBST2020+, the SIAMIS-GT products help to improve seismic analysis in all phases of a geothermal project to support decision-making on the cantonal level:

- Before the start of the project, they improve the evaluation of the natural seismicity near the project site and the performance of the project-dedicated seismic monitoring network (see Chap. 3.1).
- During the construction and operation phase, they improve seismic monitoring and alarming by regular (e.g., hourly, daily, weekly) semi-automatic reevaluation of the microseismicity near the project site (see Chap. 3.3). This procedure helps to identify even small changes in the seismic response of the underground to the geothermal operations and enables the canton and the operator to take timely mitigation measures if necessary. In case of unusual seismic activity, the SIAMIS-GT tools are used to evaluate the seismicity in great detail and consistently to better understand the causative mechanisms (see Chap. 3.4, 3.5, and 3.6).
- After the end of a project, the SIAMIS-GT products assure the continuation of the seismic monitoring at a high-sensitive level even when network coverage may be reduced (Chap. 3.2).

Even though we were not able to finish all work packages within the project's lifetime due to the impact of the COVID-19 pandemic, the main goal of the SIAMIS-GT project (i.e., the "Improvement of SeIsmological Analysis Methods to better support cantonal authorities in questions related to Induced Seismicity in deep GeoThermal projects") has been achieved and demonstrated in practical applications.

5 Publications

Simon, V., T.Kraft, T. Diehl & S. Wiemer (2019a). *Systematic classification of seismicity patterns in microearthquake sequences in Switzerland*. EGU Annual Meeting, Vienna, Austria, 7–12 April 2019.

Simon, V., T.Kraft, T. Diehl & S. Wiemer (2019b). *High-resolution Analysis of Seismicity Patterns in Swiss Microearthquake Sequences*. Repeating Earthquake Workshop, ENS Paris, 3-4 July, 2019.

Simon, V., T.Kraft, & T. Diehl (2019c). *High-resolution Analysis of Seismicity Patterns in Swiss Microearthquake Sequences*. SISM@lp-Swarm Workshop, ISTerre Grenoble, 21 May 2019.

Simon, V., T.Kraft, T. Diehl & M. Herrmann. (2019d). *Analysis of seasonality in microseismic sequences.* Hydro-Seismo-Tectonics Workshop, UNIFR, Fribourg, 18. Oct. 2019.

Simon, V., T. Kraft, T. Diehl, T. Tormann, M. Herrmann & S. Wiemer (2019e) *High-Resolution Imaging of Foreshock Patterns in Microearthquake Sequences in Switzerland*. AGU Annual Meeting, San Francisco, 8.-12. Dec. 2019.

Simon, V., T. Kraft, T. Diehl, & T. Tormann (2021a). Indication for precursory slow slip to two mainevents (M_L3.2 and M_L2.7) of the Diemtigen microearthquake sequence in Switzerland. doi.org/10.1029/2021GL093783

Simon, V., Kraft, T., Diehl, T., & Tormann, T. (2021b). *High-Resolution Imaging of Foreshock Patterns in Microearthquake Sequences in Switzerland*, Presentation at Workshop for Machine learning and the physics of earthquake faulting in Rome, Italy.

Simon, V., Kraft, T. (2021c). *High-resolution analysis of the recent onset of seasonal microseismicity in the Mt. Blanc Massif*. Poster at Swiss Geoscience Meeting, Session: Cryospheric Sciences.

Simon, V., Kraft, T. (2021d). *High-resolution Analysis of the Recent Onset of Seasonal Microseismicity in the Mt. Blanc Massif (France/Italy/Switzerland)*. Poster at AGU Fall Meeting, Session: Influence of Environmental Stress Changes on the Seismic Cycle.

Simon V., Toledo T. (2022). High-Resolution Analysis of Microearthquake Sequences in Switzerland and the QuakeMatch Toolbox. Presentation at Seismo-Mechanics Seminar at GFZ Potsdam.

Toledo, T., Kraft, T., Simon, V., Herrmann, M., Villiger, L., Antunes, V., Diehl, T. (2021a): *The QuakeMatch Toolbox: the swiss-army-knife approach to a nearly automatic analysis for microearthquake sequences*. 19th Swiss Geoscience Meeting, Geneva.

Toledo, T., Kraft, T., Simon, V., Herrmann, M., Villiger, L., Antunes, V., Diehl, T. (2021b): *The QuakeMatch Toolbox: the swiss-army-knife approach to a nearly automatic analysis for microearthquake sequences*. ERC – TECTONIC Workshop "The physics of earthquake faulting: machine learning to illuminate earthquake precursors and predict laboratory earthquakes".

Toledo, T., Kraft, T., Simon, V., Herrmann, M., Villiger, L., Antunes, V., Diehl, T. (2022a): *The QuakeMatch Toolbox using waveform similarity to enhance the automatic analysis for microearthquake sequences*. Summer School "Passive Imaging & Monitoring in Wave Physics: From Seismology to Ultrasound" Institut D'Études Scientifiques de Cargèse, Corsica, France.

Toledo, T., Simon, V., Kraft, T., Herrmann, M., Villiger, L., Antunes, V., Diehl, T. (2022b): *Using waveform similarity to enhance the analysis of microearthquake sequences: the QuakeMatch Toolbox and its application to Swiss geothermal projects*. SSA Latin American and Caribbean Seismological Commission Meeting. Quito Ecuador (Oct 2022) --submitted

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