High-resolution analysis of seismicity patterns in microearthquake sequences using waveform similarity methods

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Current challenges

One of the unsolved challenges for deep geothermal projects is how to migitate **large magnitude induced earthquakes** (**LMIE**).

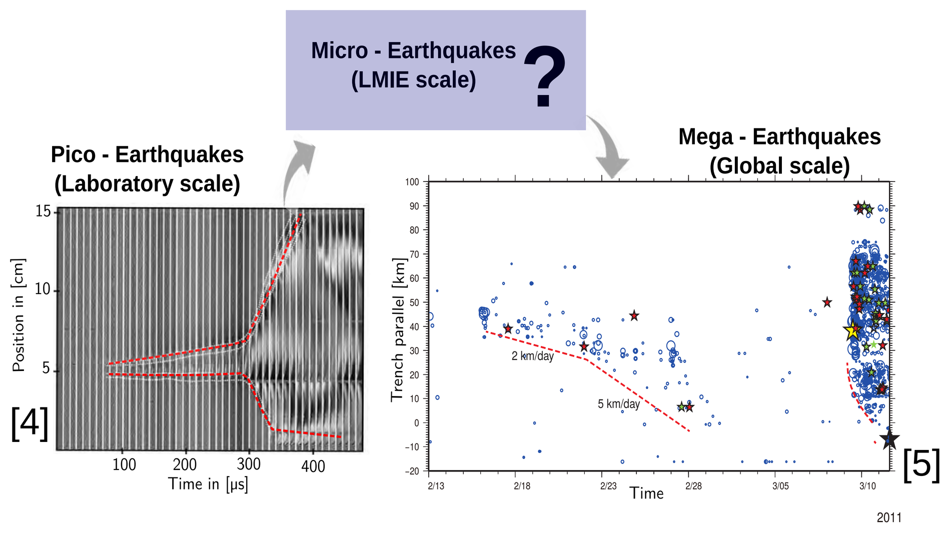
Forcasting LMIE potential and occurence is limited by:

1. Geological and hydromechanical conditions in the sub-surface cannot be mapped sufficiently well with current technology
2. Processes underpinning induced seismicity and earth-quake nucleation in general are still not understood due to i.e.
   - insufficient sensitivity of routine seismic catalogs
   - incomplete catalogs for small magnitudes

   that impede to resolve precursory patterns

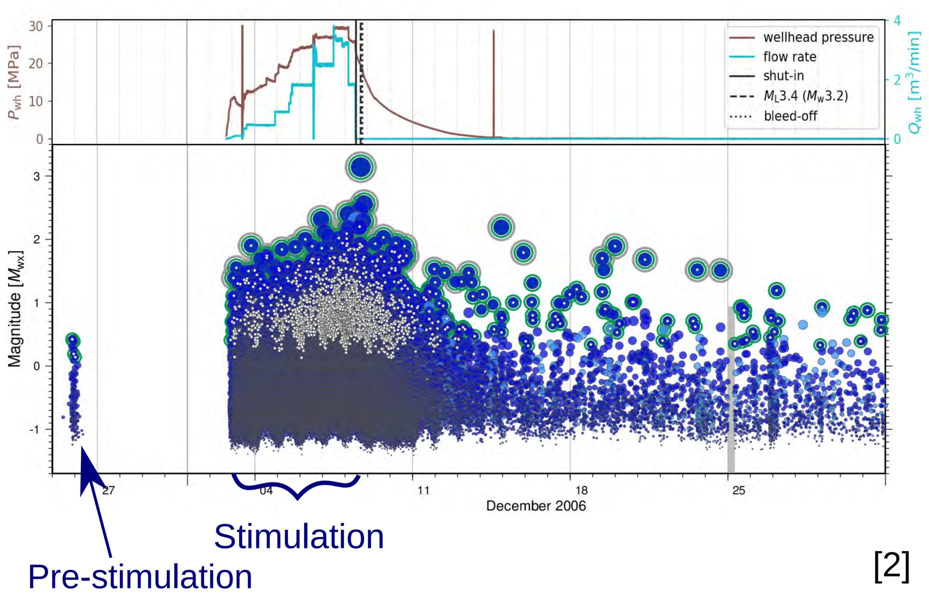
LMIE rarely exceed magnitudes M4

→ precursory seismicity that could improve our under-standing of LMIE physics and the migitation of LMIE cannot be resolved in detail



Example: Basel EGS site

- Stimulation of a reservoir for an Enhanced Geothermal System (EGS)
- Fluid injection into crystalline rock below city of Basel in december 2006
- M_L 2.6 and M_L 3.4 earthquake after 6 days
  → well opened and seismicity decayed
- Project canceled in december 2009
- Template matching scan with deepest installed borehole station (2.7 km) which is located ≈ 2 km from the ≈ 4.5 km deep reservoir



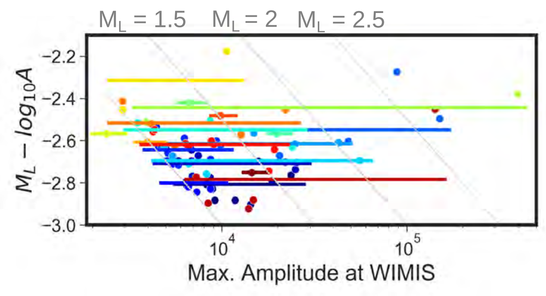
Advantages of the workflow

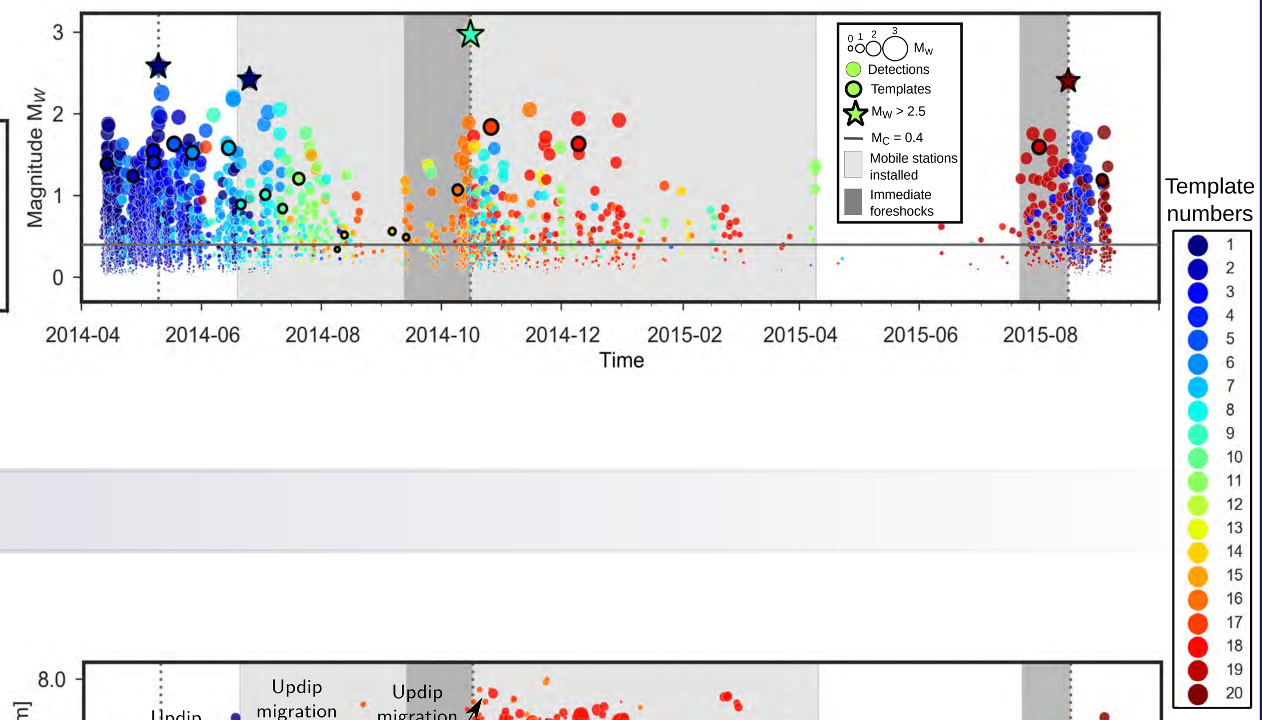
- An unexpected seismic response to a geothermal operation could be detected and located much faster.
- High station network around geothermal sites would allow to resolve precursory patterns even better than in natural earthquake sequences.
- The background seismicity could be evaluated with higher certainty before the start of a geothermal reservoir development and exploration.
- We will take advantage of the high similarity of natural and induced sequences and will further develop our workflow on natural earthquake sequences in Switzerland.
- Real-time application is currently implemented in the frame-work of the RAMSIS-RT project at SED.

Analysis workflow for induced and natural earthquake sequences (shown for the natural earthquake sequence of Diemtigen)

Template matching → improve detection sensitivity and magnitude consistency

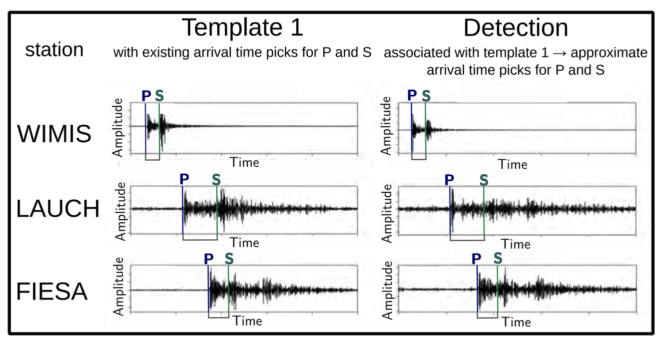
- Start: Routine catalog of the Swiss Seismological Service (SED) with located events of the sequence
- Dynamically assemble a template set to perform a matched filter analysis on the station with best SNR.
- TM-scan: Available recording history with SDSnet standard: since 2002.
- Allows to detect events with several orders of magnitude below the SED catalog detection threshold
- Magnitudes are determined by amplitude-magnitude regression for each template group using the SED catalog events.

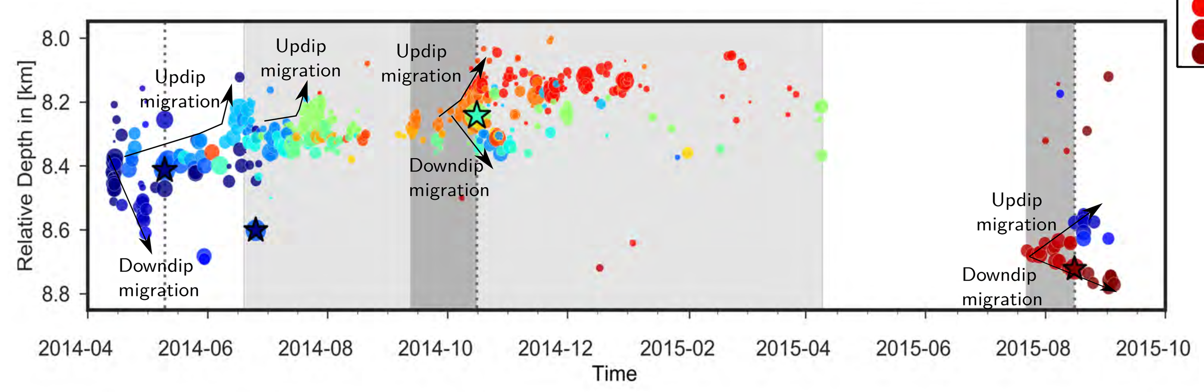




Relocation → improve location precision

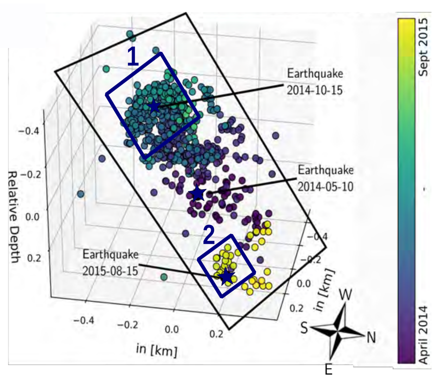
- Double difference relocation with subset of the detections above configurable magnitude and SNR threshold.
- Differential arrival times
- Earthquake relocation depends on a minimum number of arrival time picks from at least 4 stations
- Detections from template matching do not have arrival time picks
  → Waveform similarity assures a good approximation of the expected arrival time
  → Time-shift of arrival-time pattern of the template to the associated detections
- Fine adjustment of approximate arrival-time picks by cross-correlation with SNR and cycle skipping quality check
- HypoDD-software [3]

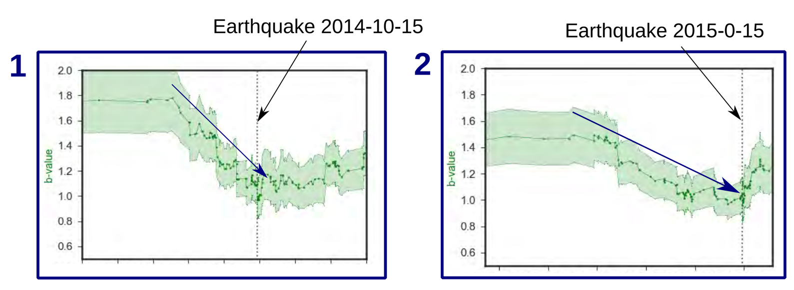


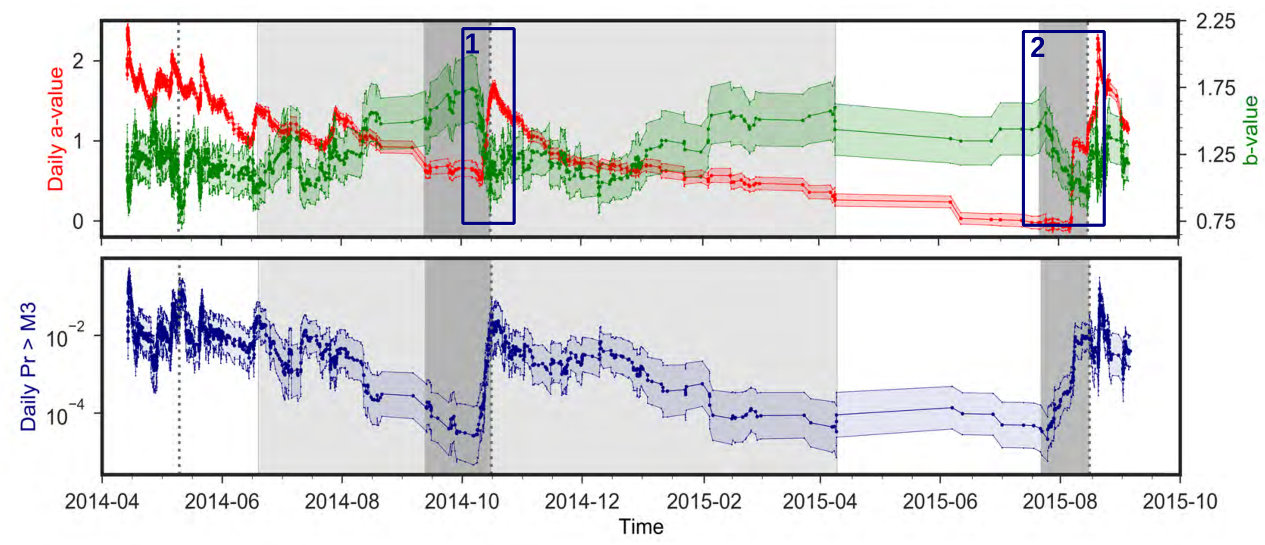


Statistical Analysis

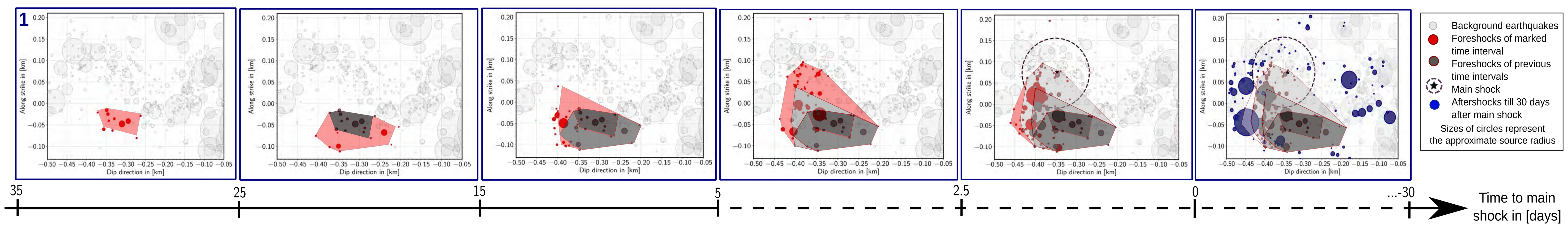
- Temporal variation of a- and b-values and earthquake probabilities
- Window length of 50 events moves through whole catalog event by event
- Take the decrease in b-value before main shocks as a starting point to study the spatial variation of immediate foreshocks





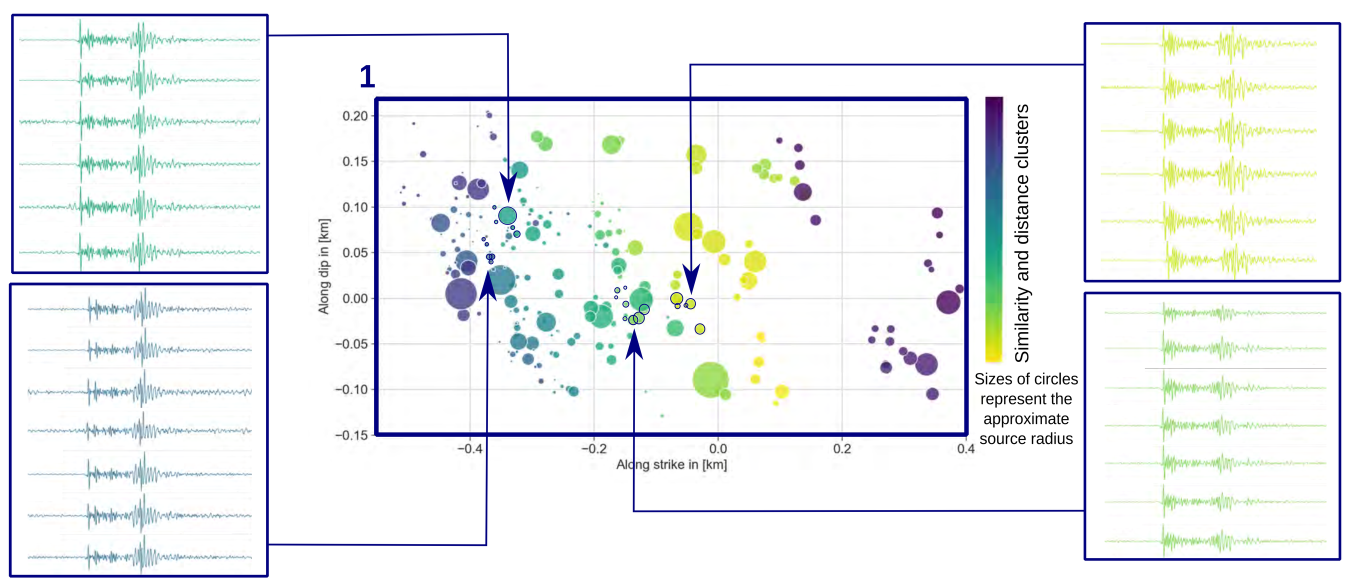


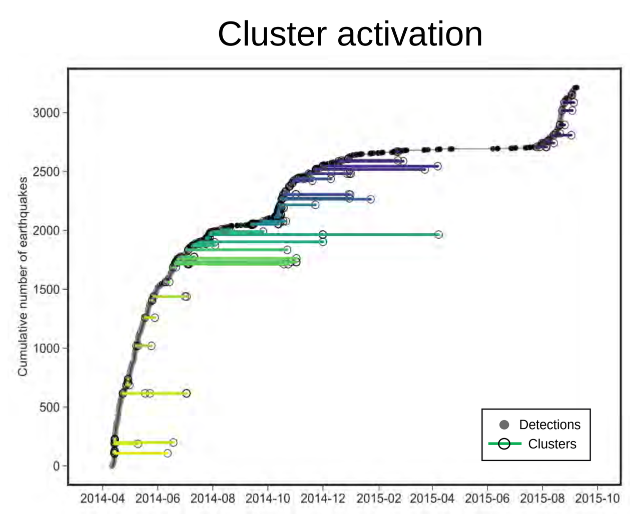
Spatial evolution of immediate foreshocks



Repeating earthquake analysis

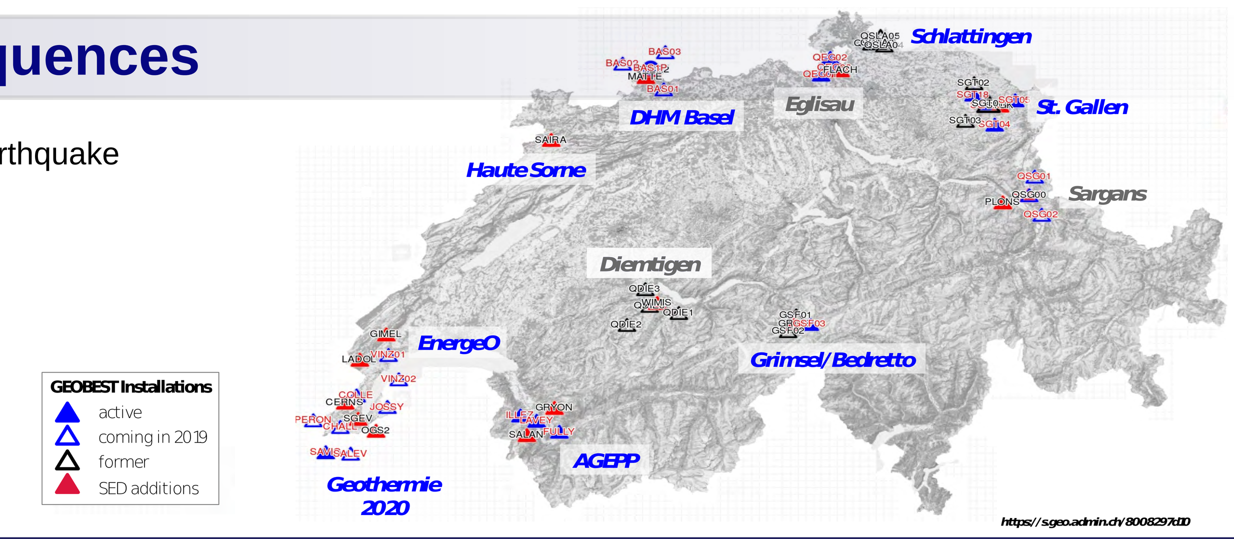
- Waveform similarity > 0.9
- Hypocenter separation < 40 m (which corresponds to our estimated location error)
- Ideally overlapping source radius
- Estimation of interevent times
- The analysis may help us to:
  → quantify loading by aseismic slip
  → discriminate between different forcing types (e.g. injection vs. earthquake-earthquake inter-action)





Systematic classification of Swiss earthquake sequences

- Systematic characterization of induced (e.g. Basel, St. Gallen, Schlattingen) and natural earthquake sequences
- Systematic analysis of Swiss catalog earthquakes of last 15 years
- Identification of seismicity patterns and their correlation with geology and seismotectonics
- Benefit from dense network: GEOBEST-CH



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