Repeating earthquakes induced during decameter- to hectometer-scale hydraulic stimulation experiments

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Motivation and experimental setups

Repeating earthquakes (i.e., repeaters) are commonly interpreted as representing **repeated rupturing of the same fault patch at different times** loaded by slow aseismic slip on adjacent fault surfaces. Repeaters can therefore be used as **indicators of the spatiotemporal distribution of slow slip** (Uchida and Büurgmann, 2019). Identifying the slow slip behavior of fault systems may be one critical mechanism in earthquake nucleation processes and thus may offer the **possibility to advance earthquake forecasting** (Ellsworth and Beroza, 1995).

Repeaters are observed in various tectonic and nontectonic environments. We performed hydraulic stimulation experiments in crystalline rock, progressing from the decameter scale at the Grimsel Test Site (GTS) to the hectometer scale at the Bedretto Underground Laboratory for Geosciences and Geoenergies (BULGG), both situated in Switzerland. At both sites, seismic activity was monitored using a highly sensitive seismic network providing extensive spherical coverage, complemented by measurements of fluid pressure, rock mass deformation, and fault dislocation. For this contribution, we selected one experiment from each site (HS4 and Mzero_a) to identify repeating earthquakes and analyzed first-order seismicity catalogs using similarity-based hierarchical cluster analysis and master event relative relocation of the induced seismic events.

Method

Starting point for the GTS repeaters was a manually picked catalog consisting of 3100 events (M_max = -3.0 MA). In contrast, for the BULGG repeaters an automatically processed catalog with 9700 induced events (M_max = -0.4 MW) was utilized. **Cross-correlation between P-waves** was performed for all the events and all the recordings on highly sensitive acoutsic emission (AE) sensors to infer **correlation coefficients and lag times.** For the cross-correlation, the signal in a window of 0.1 ms pre and 2.4 ms post the pick were used per event and AE sensor. The signals were band-pass filtered between 2 - 15kHz (see example waveforms in Figure 2). The **network correlation coefficients** of all the 26 AE sensors for the GTS case and 39 AE sensors for the BULG case of one event pair were combined and weighted according to the product of the signal-to-noise ratios of the event pair:

$$ccc_{network} = \sum_{i=1}^{n} ccc_i \frac{SNR_i}{SNR_{tot}}$$

where ccc_i is the cross correlation coefficient of one event pair at a respective AE sensor, the SNR_i represents the signal-to-noise ratio product of this event pair at a respective AE sensor and SNR_{tot} represents the sum of signal-to-noise ratio products of a respective event pair in the network. Correlation based repeater families were extracted using **hierarchical clustering including single linkage, a distance criterion and a normalized cutoff at 0.85.** The normalized cutoff parameter was determined by trial and error (see Figure 4 for ccc evolution in RF1). Subsequently, t**he time differences at any station between all seismic event pairs belonging to a repeater family were optimized considering the cross-correlation based lag times.** Adjusted travel times were used to relocate the seismic events belonging to a repeater family relatively to a defined master-event.

HS4 - GTS

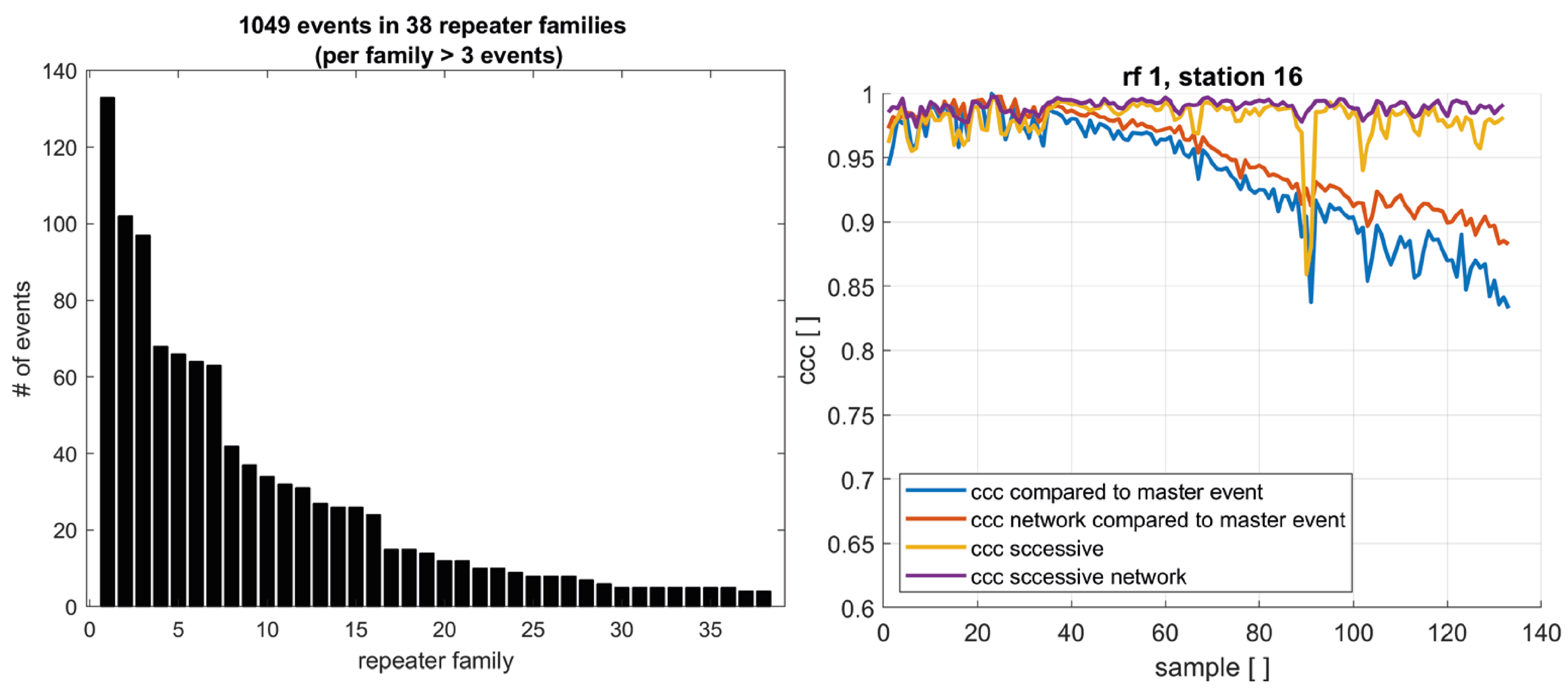

Figure 1: (left) # of repeater families found vs. # events in each repeater family. (right) evolution of cross correlation coefficients (ccc) of repeater family 1 (rf1) containing 133 events. Compared are station 16 ccc's in comparison to the master event in rf1, network determined ccc's compared to its master event, rf1 station 16 ccc's and rf1 network ccc's succesively in time.

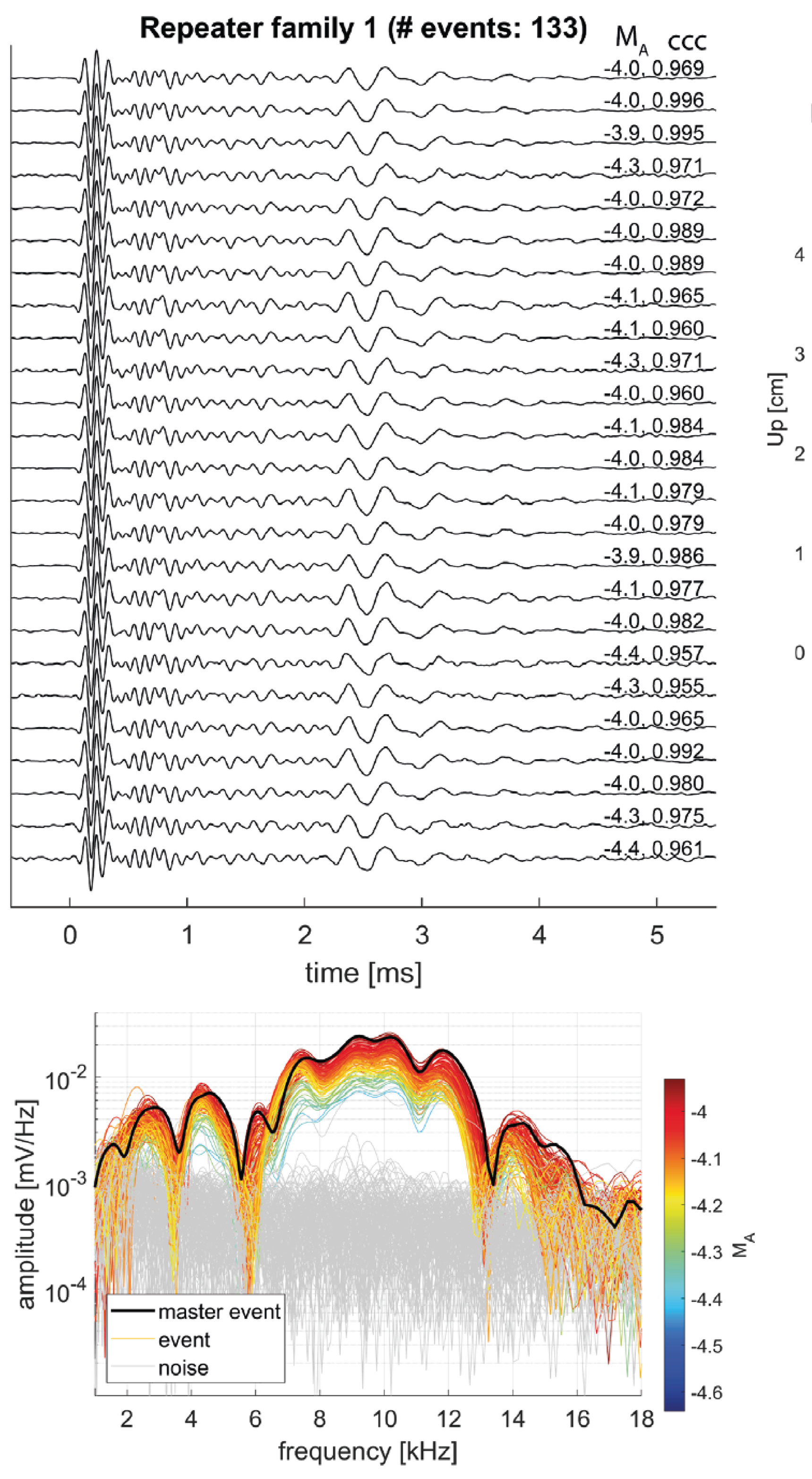

Figure 2: Recorded waveforms at AE sensor R16 aligned on the refined P-wave arrivals and MAs of the first 25 events belonging to repeater family 1 exhibiting 133 seismic events. And frequency domain representation of the P-waves of all seismic events in repeater familiy 1 along with the master event (black line) and the noise spectra (grey lines).

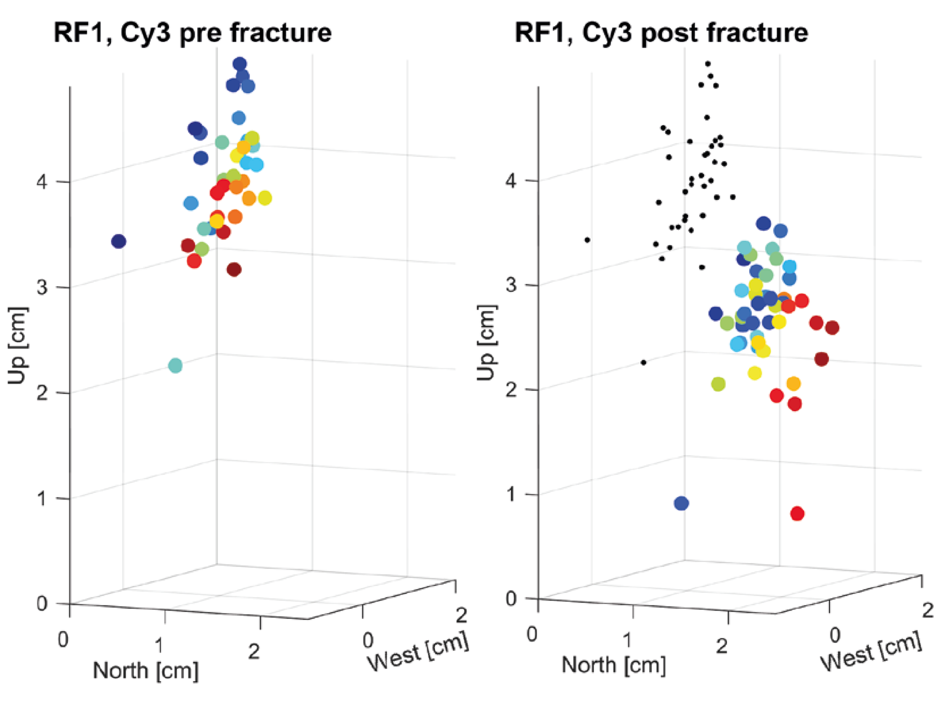

Figure 3: Evolution in 3D of the 133 hypocenters of repeater family 1 pre-, and post the induced fracture in cycle 3 of 4 (the events are color coded chronologically, previously induced events are colored in black).

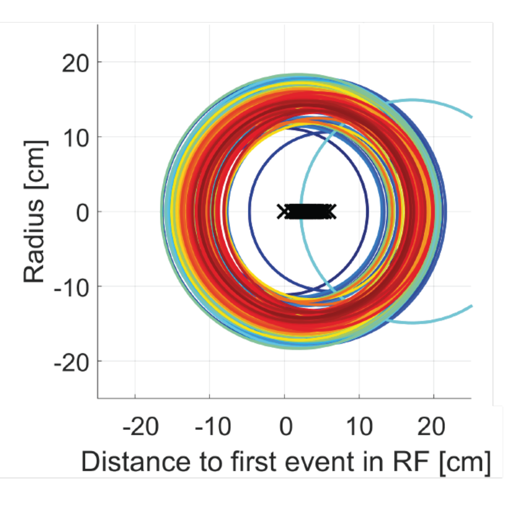

Figure 4: Estimated source areas of repeater family 1 (RF1, 133 events) based on Eshelby (1957) assuming a stress drop of 0.1 MPa, along with the hypocenter distance between the first event in the repeater family and each successive event (circles are again colored in chronological order).

BULGG - Mzero_a

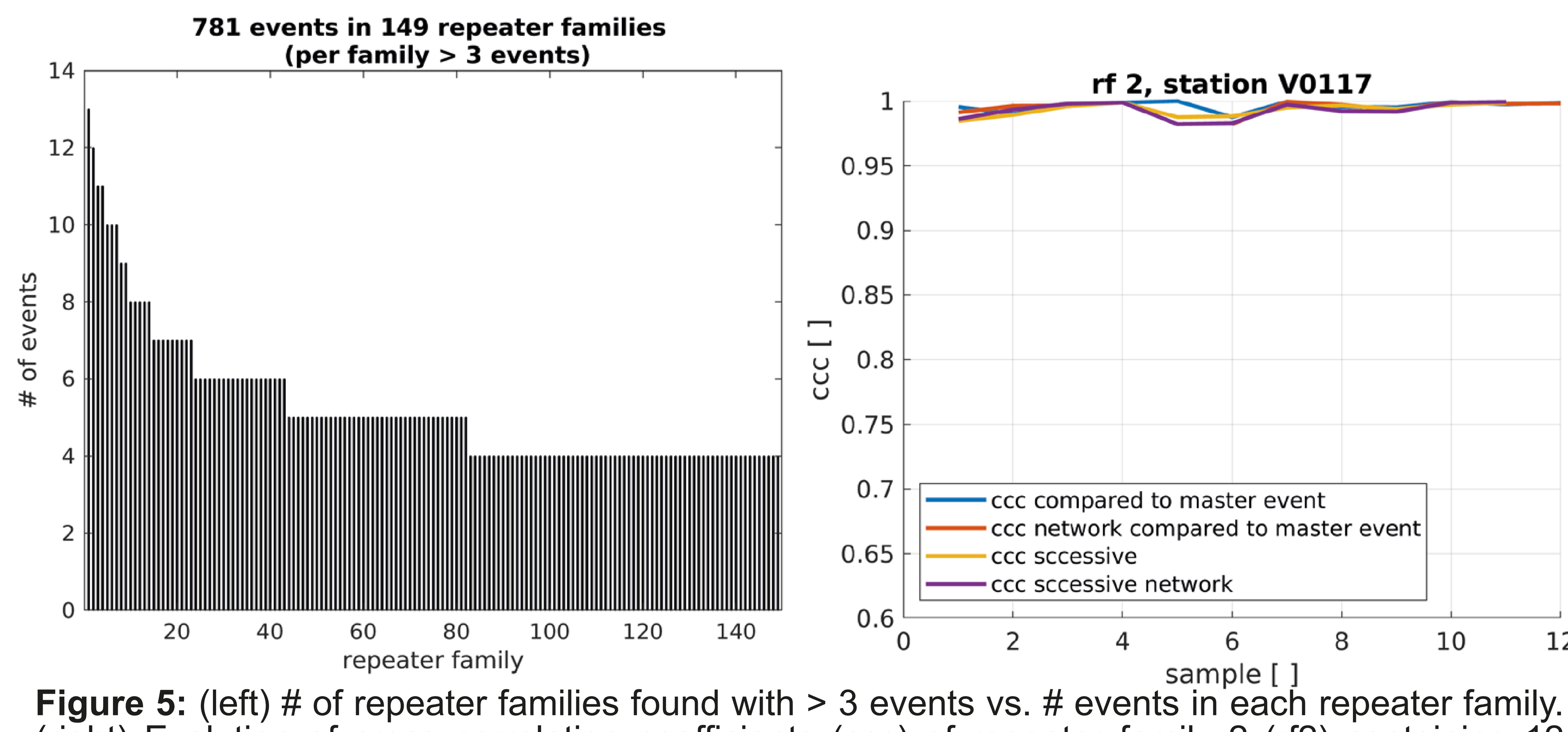

Figure 5: (left) # of repeater families found with > 3 events vs. # events in each repeater family. (right) Evolution of cross correlation coefficients (ccc) of repeater family 2 (rf2) containing 12 events. Compared are station V0117 ccc's in comparison to the master event in rf2, network determined ccc's compared to its master event, rf2 station V0117 ccc's and rf2 network ccc's successively in time.

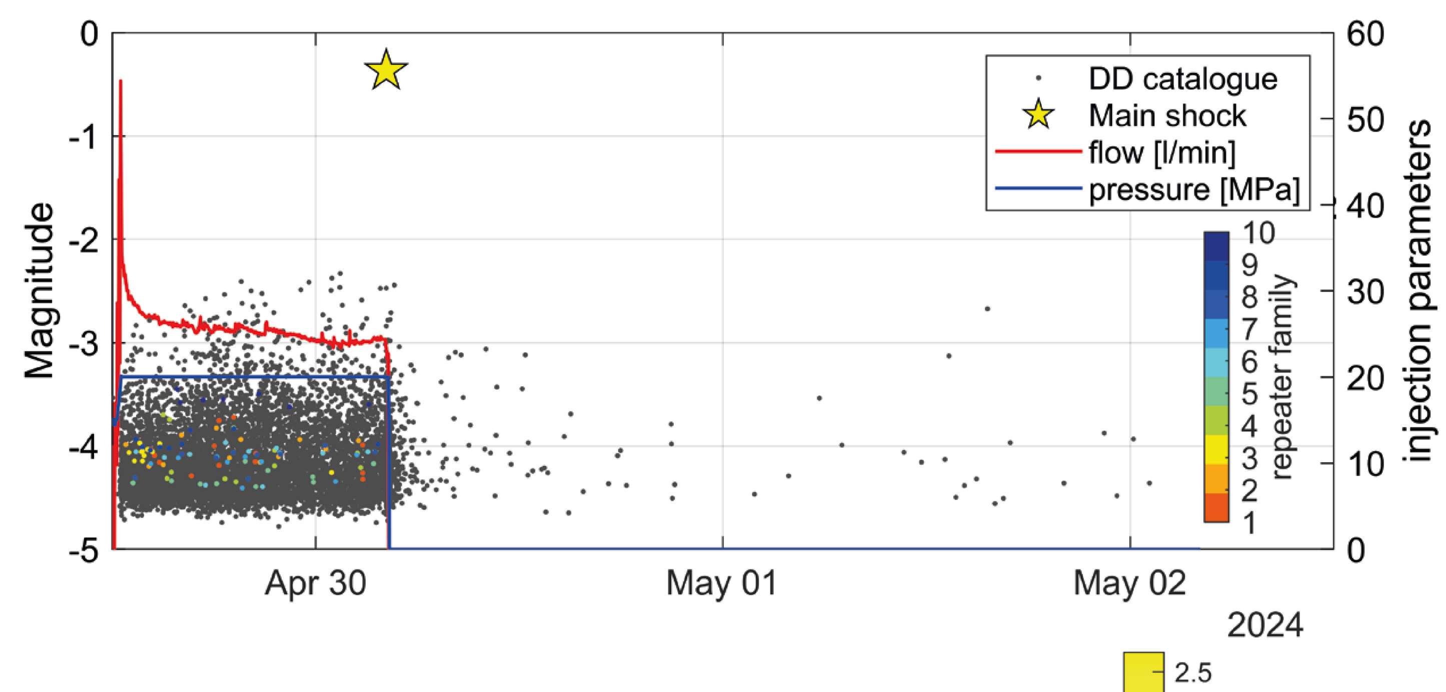

Figure 6: Mzero_a seismicity 12 hours before and 24 hours after the main shock, along with injection parameters and color-coded repeater families (1-10).

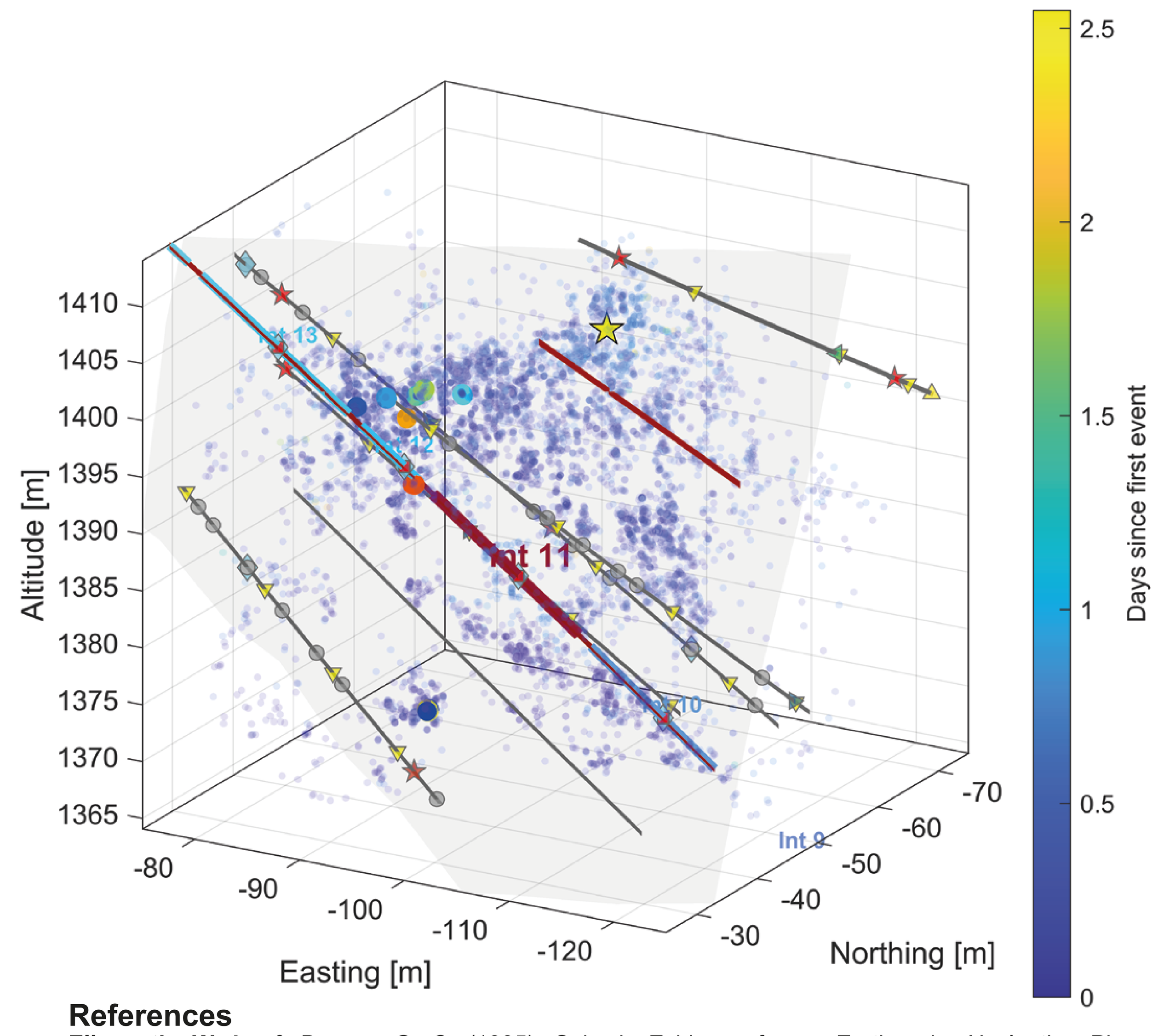

Figure 7: The same seismicity catalog compared to Figure 6 in 3D, including the color-coded repeater families, injection interval 11 of 18m length, surrounded by monitoring boreholes.

References

Ellsworth, W. L., & Beroza, G. C. (1995). Seismic Evidence for an Earthquake Nucleation Phase. Science, 268(5212), 851-855. https://doi.org/10.1126/science.268.5212.851 (Science)

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