Detection and characterization of fluid-driven earthquake clusters

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Natural earthquake clusters are often related to a mainshock, which triggers the sequence by its induced stress changes. These clusters are called mainshock-aftershock sequences and statistically well explained by earthquake-earthquake interactions according to the Epidemic Type Aftershock Sequence (ETAS) model. Additionally, aseismic processes such as slow slip, dike propagation or fluid flow might also play a role in the initiation and driving of the earthquake sequence. Earthquake swarms, which lacks a dominant earthquake, are often believed to indicate such transient aseismic forcing signals. However, swarm-type clusters can also occur by chance in ETAS-simulations and thus not necessarily related to aseismic drivers. Thus, more sophisticated quantification of the space-time-magnitude characteristics of earthquake sequences are required for discrimination. Migration patterns are one of those properties which can be indicative for aseismic triggering. We suggest simple measures to identify and quantify migration patterns and test those for synthetic data, data from fluid injection experiments, and natural swarm activity related to fluid flow in NW Bohemia and Long Valley caldera. We analyze their potential to discriminate from ETAS-type clusters and compare it with those of time-magnitude characteristics of the activity such as seismic moment ratios and skewness. Our results are finally used to discriminate earthquake clusters in California and elsewhere.