Final Report on
Systematic Studies of Dynamic Triggering at Volcanic and Geothermal Sites

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Technical Report

For dynamic triggering studies, there has been continuous development over the years on how to identify positive triggering cases. In the earliest studies, researchers looked for elevated seismicity during or immediately following the surface waves of remote, large earthquakes using the standard regional catalogs or visual inspection [*Hill et al*., 1993; *Gomberg et al*., 1997;]. One major problem with this approach is that many possibly triggered events would be buried within the surface wave train of remote earthquakes due to the small magnitudes. Since the introduction of the matched filter technique [*Shelly et al*., 2007; *Peng and Zhao*, 2009; *Shelly et al.*, 2013], it has been applied to recover those possibly triggered events following remote, large earthquakes. However, many such studies only focus on short time windows (e.g., several hours) around large earthquakes because the template matching is very computationally intensive. As a result, the statistical analysis is not reliable due to either small number of events or significant fluctuations of seismicity, especially at geothermal and volcanic areas. Last but not least, most studies look for dynamic triggering following one large earthquake at several locations or at one location following several large earthquakes. Such results lack generality.

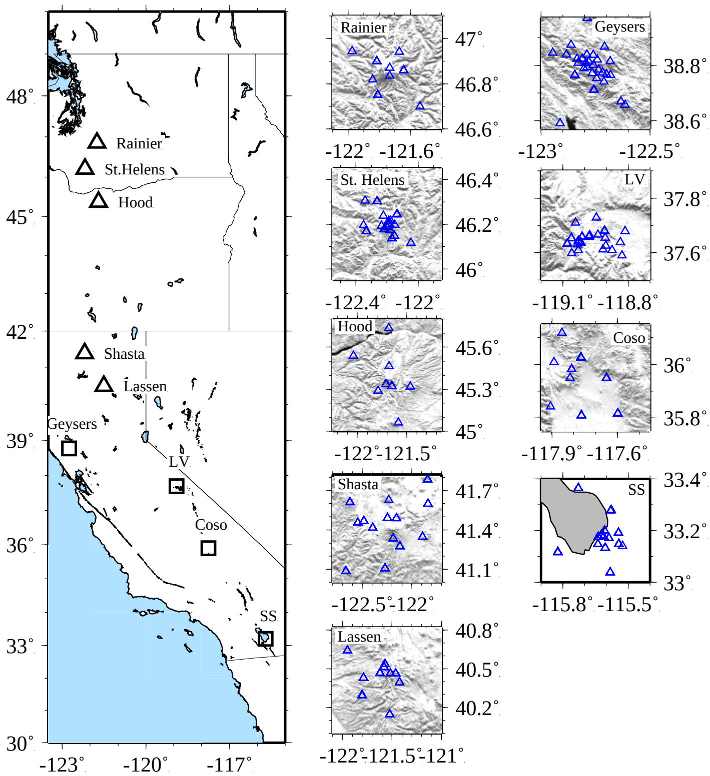

Figure 1. (Left) Map of all targeted Cascade volcanoes (triangles) and geothermal fields in California (square). **(Right)** Maps of all targeted sites. Blue triangles denote seismic stations used for detection. Red dots denote template events.

A. Detection of local events at geothermal and volcanic areas

We systematically study dynamic triggering at well-instrumented volcanic and geothermal sites along the west coast of United States. We select four geothermal fields in California (i.e., The Geysers, Coso, Long Valley and the Salton Sea) and five Cascade volcanoes (i.e., Mount Rainier, Mount St. Helens, Mount Hood, Lassen Peak and Mount Shasta) (Figure 1), because of the dense instrumentation and ample background earthquakes (Table 1). At each target site, we select ~50 M>6 earthquakes since 1990 that generate the largest peak dynamic stresses. We include earthquakes from all distance ranges (i.e., from near- to far-field), as it is important to investigate how frequency content and duration of seismic waves affects triggering. To effectively detect local microearthquakes that might be masked by the surface waves of the large mainshocks, we use earthquakes from regional catalogs as templates and search for similar waveforms in continuous data from one day before to one day after the mainshocks, using the matched filter technique. All seismograms are band-pass filtered between 2 and 15 Hz to remove noise and low frequency energy from distant mainshocks. We require at least six channels used for detection, and the detection threshold is 15 times the median absolute deviation.

Table 1. Number of seismic stations and templates used for detection

	Rainier	**St. Helens**	**Hood**	**Shasta**	**Lassen**	**Geysers**	**Long Valley**	**Coso**	**Salton Sea**
No. of stations	9	19	8	17	12	34	35	13	15
No. of templates	3642	5374	651	337	2773	3000	2913	3000	2838

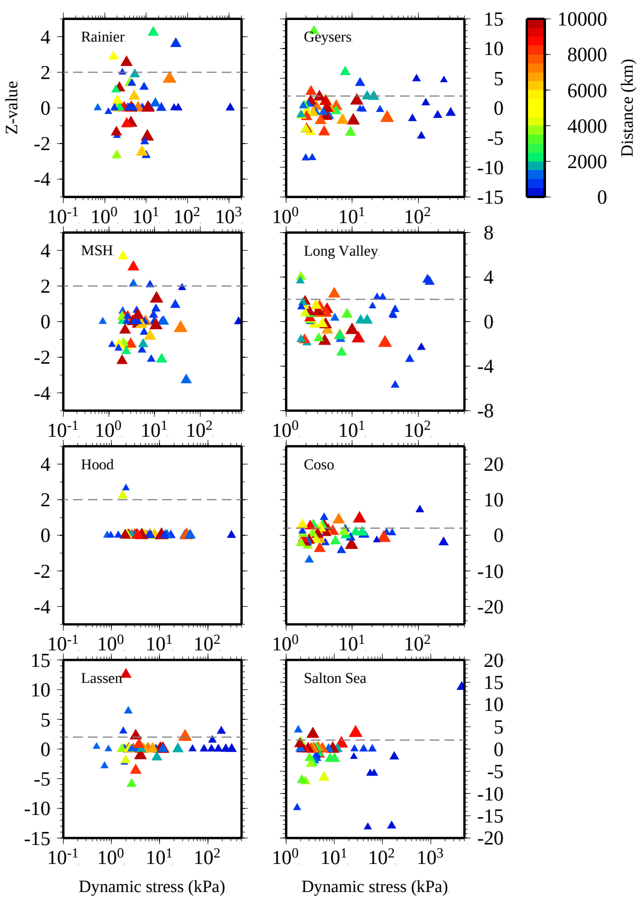

Figure 2. Z-value within one-day versus peak dynamic stresses for all cases at each target site, color-coded by distance. The size of the triangles denote magnitude.

B. Identification of possible triggering cases

Following the earthquake detection, we quantify seismicity rate changes using a statistical test (i.e., Z-value) [*Aron and Hardebeck*, 2009].

$$Z = \frac{N_a * T_b - N_b * T_a}{\sqrt{N_a * T_b^2 + N_b * T_a^2}}$$

where T_b and T_a are time windows before and after the mainshock, N_b and N_a are number of events within T_b and T_a, respectively. Z-values larger than two suggest the seismicity rate increase is statistically significant, which indicates a potential triggering case. Overall, we identify 17 potential triggering cases at four Cascade volcanoes and 28 potential triggering cases at four geothermal fields in California. As peak dynamic stresses are the primary triggering criterion used in previous studies [*Hill and Prejean*, 2015], we examine the correlation between Z-values and peak dynamic stresses (Figure 2). As a result, we do not observe any correlation between Z-values and peak dynamic stresses. That is, there is no apparent triggering threshold at any target site (peak dynamic stresses as small as ~2 kPa appear to trigger), and mainshocks with largest peak dynamic stresses do not necessarily promote local earthquakes. Moreover, there are a similar, if not more, number of cases that seismicity rate significantly decreased following large mainshocks (i.e., Z-values less than -2). Unlike static triggering, dynamic triggering can only excite local seismicity, therefore significant rate decrease can be only explained by the natural fluctuations of seismicity level. For example, if an intense earthquake swarm occurs during the day before the large mainshocks, we would observe significant rate decreases following the mainshocks. Therefore, we need to be extra cautious while identifying positive triggering cases with large Z-values, as significant rate increase could also be caused solely by earthquake swarms occurring during the day after the mainshocks.

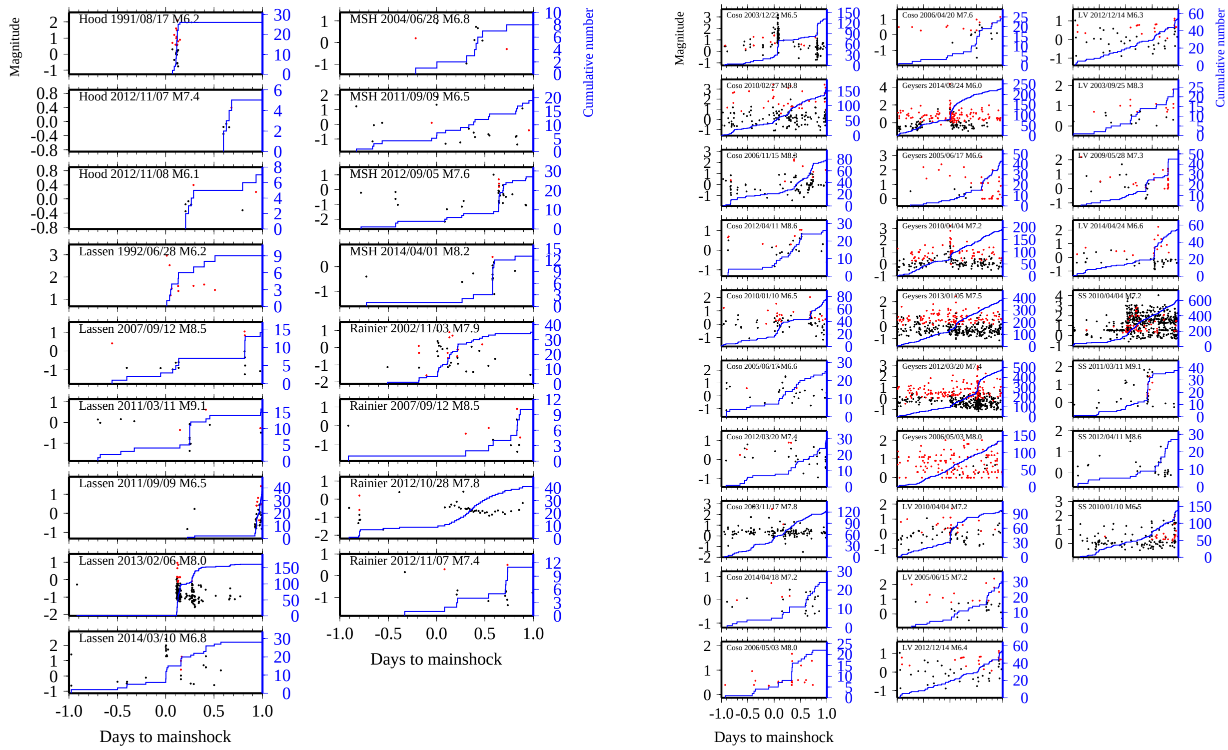

Figure 3. The evolution of seismicity for all potential triggering cases for Cascade volcanoes (left) and geothermal fields in California (right). Red and black dots denote template and detected events, respectively. Blue lines denote the cumulative number of earthquakes.

Next, we examine the evolution of seismicity closely (Figure 3) and confirm that for many cases, the significant rate increases are indeed caused by one or a few bursts of earthquake swarms following the large mainshocks (e.g., 2003/12/23 M6.5 San Simeon at Coso), instead of consistent elevation of seismic activity (e.g., 2010/04/04 M7.2 El Mayor-Cucapah at SS). At current stage, it is not clear whether the swarms are related to large mainshocks, as we do not know how often such swarms occur. then, we extend the detection time window to a much longer period (10 days before and after the mainshocks) for all potential triggering cases, in order to obtain a more stable background seismicity level. Finally, we compute Z-values in many different combinations of T_b and T_a, ranging from 10 hours to 10 days, to obtain more reliable statistical significance (Figure 4). As a result, for 15 out of 45 potential triggering cases, the Z-values become insignificant or even smaller than -2 (i.e., significant rate decrease) when T_b is extended to several days before the mainshocks.

In conclusion, we identify 45 potential dynamic triggering cases at four Cascade volcanoes and four geothermal fields in California. We do not see any correlation between the significance of seismicity rate increase and peak dynamic stresses. Moreover, we find that in many cases, the significant rate increases are caused by earthquake swarms, which may not be caused by large mainshocks. Using a variety of time windows could improve the reliability of the statistical analysis. The underlying physics of dynamic triggering is still elusive, mostly due to our limited knowledge on how to identify positive triggering cases.

Until one can reliably identify triggering cases, interpretation of the physical model of dynamic triggering will always be a challenge.

C. Student Support and Involvement

This work described above was primarily performed by postdoctoral researcher Xiaofeng Meng, under the guidance of Prof. John Vidale. Meng is in the process of wrapping this up as a peer-reviewed publication.

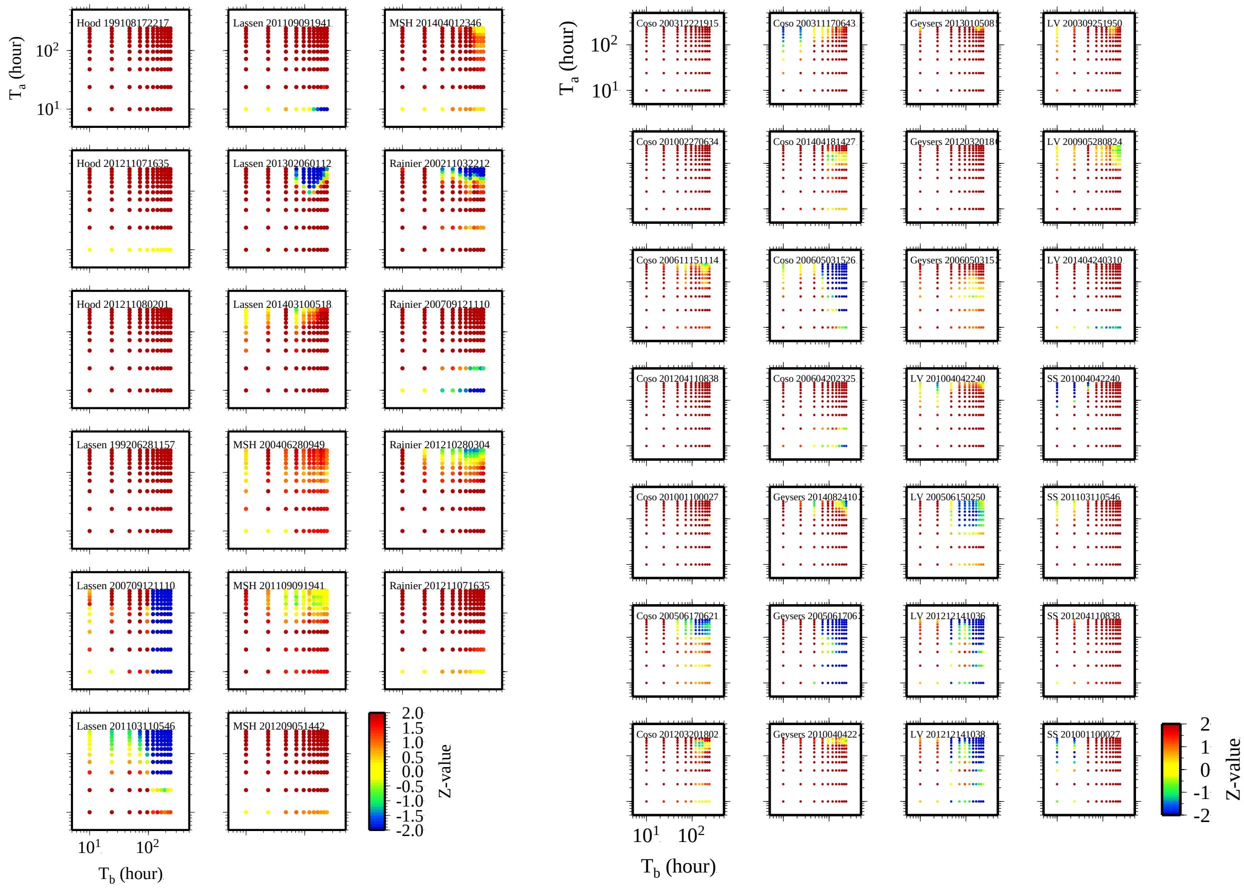

Figure 4. The Z-values of positive triggering cases for Cascade volcanoes (left) and geothermal fields in California (right), using different T_b and T_a.

D. References

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