2014 SCEC Project Report

"Seismicity cluster anomalies in relation to different loadings and large earthquakes"

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ABSTRACT
The project aimed on clarifying the dynamics of seismicity in relation to large earthquakes and different types (e.g., tectonic vs. human induced) loadings. A key focus of the work was to indentify and separate seismicity clustering effects associated with steady tectonic loading, premonitory effects that may indicate likely approaching times of large damaging earthquakes, and anomalies associated with human induced loadings related to oil and gas exploration activities. The study utilized recent results of the PIs on robust non-parametric methodology for identification and classification of different types of seismicity clusters and correlations between clustering and properties of the crust. The previous SCEC projects by the PIs have established the existence of several different basic types of seismic clusters (burst-like, swarm-like, and singles) of small-to-medium magnitude earthquakes in southern California, and demonstrated that the cluster type is related to the properties governing the effective viscosity (indicated primarily by heat flow) of a region. The results of this project suggest that (i) the cluster properties systematically evolve in time, according to several robust cluster measures, in the spatio-temporal vicinity of the largest earthquakes in southern California, and (ii) seismic clustering differs, and probably can be used to discriminate between the regions dominated by tectonic vs. human-induced seismicity. The project resulted in the following ***major findings***:

- The distribution of seismic cluster properties, such as cluster size, average leaf depth (measure of “swarminess”), etc. is significanty different within the spatio-temporal regions around the large (M6.5) earthquakes in southern California and outside of such regions (**Figure 1**)
- The seismic clustering increases (according to several robust measures, like the average leaf depth, the number of large clusters, number of aftershocks, etc.) several years prior to large earthquakes in California when analysis is done in regions around the epicenters of large events with the linear size comparable with the rupture of the impending event (**Figures 2, 3**)
- Seismic clustering is different in regions dominated by tectonic vs. human-induced earthquakes. One of the differences is slower temporal decay of the offspring events away from the parent in tectonic regions.

INTELLECTUAL MERIT The study combines novel approaches to earthquake cluster identification/classification and high quality earthquake catalogs from different environments toward improved understanding of seismicity in relation to large events and human-induced earthquakes. An ability to track the evolving response of the crust to different loadings may be used to monitor the build up of stress in a region. The developed tools and results can have transformative impact on analysis of seismic hazard in active tectonic environments, oil and other production areas, and regions containing both, such as California.

BROADER IMPACTS The addressed problems on natural/induced seismicity and seismic anomalies preceding large events have critical societal and economic importance. The developed cluster framework can be applicable to other processes that develop in space-time-energy domains (e.g., river/subsurface flows, aerosol dynamics, chemical reactions, and fires).

TECHNICAL REPORT

1. Background and previous results

This study relied on the results obtained by the PIs in the previous SCEC projects. They are briefly summarized below together with relevant background information.

1.1 Earthquake distance: Consider an earthquake catalog, where each event i is characterized by its occurrence time t_i, hypocenter (ϕ_i, λ_i, d_i), and magnitude m_i. The distance between earthquakes i and j is asymmetric in time and is defined as $\eta_{ij} = t_{ij}(r_{ij})^d 10^{-bm_i}$ [*Zaliapin et al.,* 2008; *Zaliapin and Ben-Zion,* 2013a]. Here, $t_{ij} = t_j - t_i$ is the intercurrence time, $r_{ij} \geq 0$ is the spatial distance between the earthquake hypocenters, and d is the dimension of the earthquake hypocenters. For each earthquake j, we identify its nearest neighbor i and the corresponding nearest-neighbor distance η_{ij}. Consider the normalized space and time distances between the nearest neighbors:

$$T_{ij} = t_{ij} 10^{-qbm_i}; R_{ij} = (r_{ij})^d 10^{-pbm_i}; q + p = 1.$$

It is readily seen that $\log \eta_{ij} = \log T_{ij} + \log R_{ij}$. The observed seismicity exhibits a prominent bimodal joint distribution of (log T, log R). One mode corresponds to *background events* (similar to a Poisson process); the other consists of a large subpopulation of events located considerably closer in time and space to their parents, we refer to this population as *clustered events*.

1.2 Cluster identification: Each parent link is assigned strength inversely proportional to the corresponding nearest-neighbor distance η. If one removes the "weak" links that correspond to events from the *background mode***,** seismicity is decomposed into a set of significant clusters of earthquakes – all events within a cluster are now connected to their parents by "strong" links.

1.3 Existence of clusters of distinct types: *Zaliapin and Ben-Zion* [2013a] demonstrated that the seismicity clusters in the southern California earthquake catalog of *Hauksson et al.* [2012] can be represented as a combination of clusters of three main types: (i) *Singles* – clusters consisting of one event; a significant part of singles cannot be explained by catalog artifacts (incompleteness, existence of the lowest reported magnitude, etc.) and may reflect certain crustal processes and conditions; (ii) *Burst-like clusters* characterized by small topological depth (small number of offspring generations), decreased foreshock and aftershock productivity, and smaller spatio-temporal extent, and (iii) *Swarm-like clusters* characterized by high topological depth (large number of offspring generations), increased foreshock and aftershock productivity, and higher spatio-temporal extent. The cluster type can be quantified by a simple scalar measure – average topological depth $<d>$ of the leaves in the tree that represents the cluster in the time-space-energy domain. Notably, the ETAS model only produces the burst-like clusters; the number of singles in the observed catalog is statistically higher than in the ETAS model with parameters estimated for southern California.

1.4 Cluster type is related to the physical properties of a region: The clusters of different types have distinct preferred geographic locations. Burst-like clusters occur predominantly within areas with decreased levels of heat flow and fluid content and thicker seismogenic zone (high effective viscosity). Swarm-like clusters occur predominantly in the areas with increased levels of heat flow and fluid content, high geothermal activity, and thinner seismogenic zone (decreased effective viscosity).

Next, we describe this year's project findings.

2. Seismic clustering increases in the vicinity of large events

This section describes the results focused on the spatio-temporal changes of clustering with relation to large events (M6.4) in southern California.

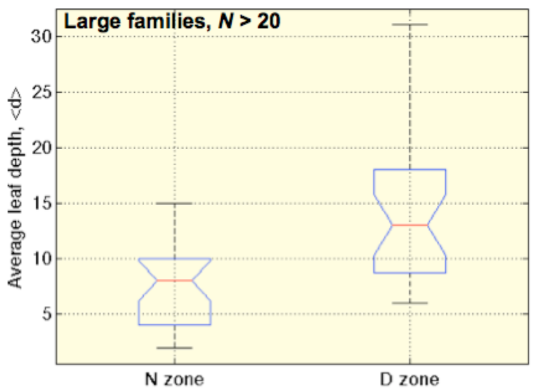

Figure 1: Change of earthquake clustering in the vicinity of a large earthquake. Comparative distribution of the average leaf depth for the families with mainshock magnitude $m > 3$ and number of events $N > 20$ within N and D zones. Increased leaf depth within D zones indicates more swarm-like clusters before large events, that is preference of premonitory small events to occur in relatively hot and/or deeper regions

<u>*Static approach (ND zones):*</u> We have demonstrated that earthquake clustering in spatio-temporal vicinity of some large events is statistically different from that at other times and locations. This has been done using the so-called ND-zone approach.

Specifically, consider the spatio-temporal volume ***S*** to be analyzed (southern California during 1981-2013). We define the *X*-zone for a particular large event as the spatio-temporal cylinder with radius *R* around the event's epicenter and within time T_X after its occurrence. The union of all *X*-zones is denoted by ***X***. The *D*-zone is defined as the intersection of the spatio-temporal cylinder with radius *R* around the event's epicenter and within time T_D prior to its occurrence and the space-time volume outside of the X-zones: **S\X**. The union of all D-zones is denoted by ***D***. The ***N***-zone is finally defined as the set difference ***S\X\D***. The analysis consists of statistical comparison of various cluster properties between ***D*** and ***N*** zones. We have shown (i) The average leaf depth <*d*> for all clusters with $m>3$ is significantly larger in ***D***-zones. (ii) The average leaf depth <*d*> for large families (number of events $L>20$) with $m>3$ is significantly larger in ***D***-zones (see **Figure 1**). These two results indicate preference of preceding small events to occur in relatively hot and/or deeper regions. (iii) The proportion of families (multi-event clusters) among all $m>3$ clusters is significantly larger in ***D***-zones. (iv) The proportion of large families ($L>5$) among all families ($L>1$) with $m>3$ is significantly larger in ***D***-zones. These results suggest that the *clustering increases in the vicinity of a large earthquake*, possibly reflecting acceleration of processes in regions with relatively low viscosity and near the bottom of the seismogenic zone that lead to the nucleation of large ruptures.

<u>*Dynamic approach:*</u> We have also demonstrated that earthquake clustering is changing in time around the epicenters of selected impending large events, within regions of linear size up to to that of the earthquake rupture length.

El Mayor Cucapah Earthquake, M7.2: Figure 2 shows an example of premonitory changes prior to the El Mayor Cucapah earthquake of April 4, 2010, M7.2. The figure demonstrates that the number of large families (more than 5 events, average leaf depth greater than 1) in the vicinity of the earthquake epicenter in significantly increasing several years prior to the event. The observed increase is unique within the 30-year observation span. The increase in observed for any size of the region around the epicenter, as soon as the region size is smaller than or comparable with the earthquake rupture length. The effect vanishes for very large regions (circles with radius above 200 km, not shown).

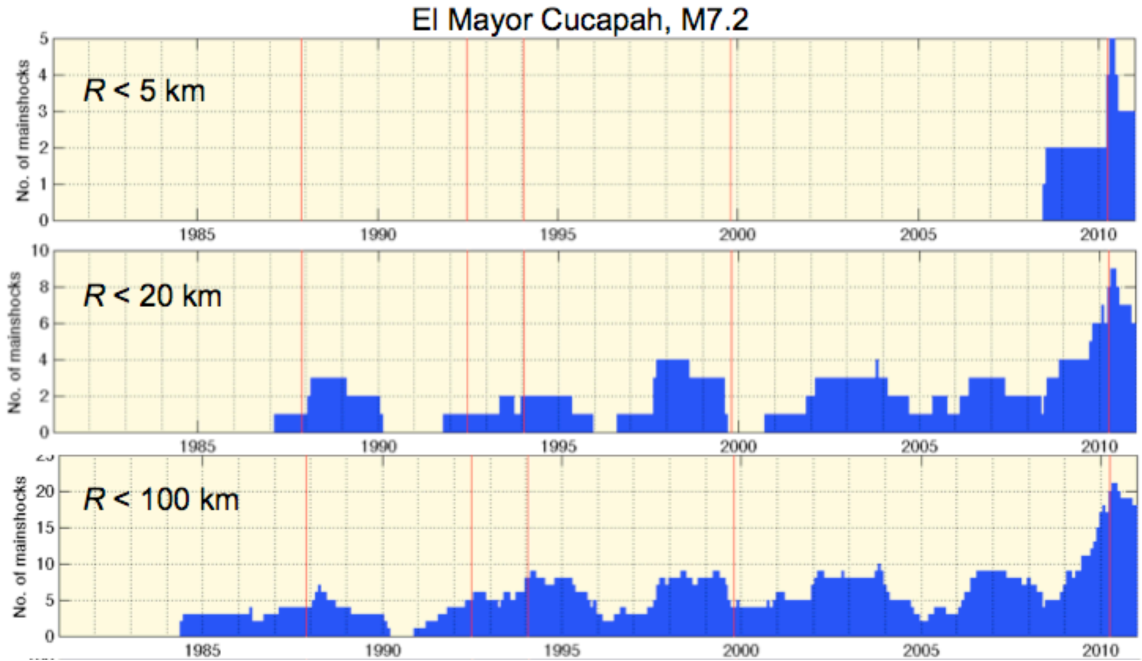

Figure 2: Premonitory activity in the spatio-temporal vicinity of El Mayor Cucapah earthquake, M7.2. The earthquake instant is marked by the rightmost red vertical line; the other lines mark the temporal occurrence of other M6.5 events in southern California. The figure shows the number of mainshocks with average leaf depth greater than 1 and number of events greater than 5, in a moving time window. Different panels correspond to different regions (circles with radius *R*) around the El Mayor Cucapah epicenter.

Parkfield Earthquake, M6.0: Figure 3 illustrates a similar analysis done for Parkfield earthquake using the relocated catalog of *Thurber et al.* [2006]. The top panel shows the number of mainshocks in a moving window; the lower panel shows the number of aftershocks. Both statistics clearly increase in the temporal vicinity of the Parkfield epicenter, with no comparable peaks during the 20 years of observations reported in the catalog. We have also observed (not shown) that the number of large families and the average leaf depth are increasing prior to the Parkfield epicenter. These observations are consistent with what we had observed in southern California using the relocated catalog of *Hauksson et al.*

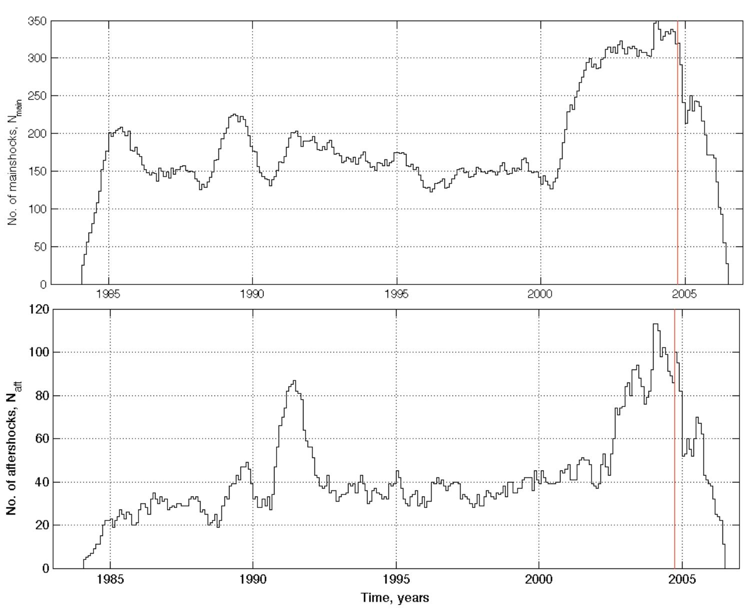

Figure 3: Premonitory activity in the spatio-temporal vicinity of Parkfield earthquake, M6.0. Top panel: Number of mainshocks. Bottom panel: Number of aftershocks. The analysis uses the catalog of *Thurber et al.* [2006]

3. Toward discriminating clustering properties of tectonic vs human-induced earthquakes

The project documented substantial differences between the clustering styles of earthquakes in regions of tectonic vs. human-induced seismicity. Specifically, we considered six regions that present clear-cut examples of tectonic and induced seismicity, as well as a mixture of both. The well-documented geothermal production or mining activity (or absence of such) together with availability of high quality catalogs and detailed geological/geochemical studies makes the examined regions a good natural laboratory for testing hypothesis about possible similarities and differences between the natural and induced seismicity: (a) The Geysers geothermal field in Northern California, dominated by induced events. (b) The TauTona golden mine in South Africa, dominated by induced events. (c) The Coso geothermal field in the eastern portion of central California that has a mixture of tectonic and induced events. (d) The Salton Sea geothermal field in southern California that has a mixture of tectonic and induced events. (e) The Coso region excluding the Coso geothermal field. This region is dominated by tectonic events. (f) San Jacinto fault – one of the best-studied regions with high level of seismicity and no geothermal or mining activities. This region is dominated by tectonic events.

We found several differences between seismic clusters within regions dominated by tectonic vs. induced seismicity. (i) First, we observed that the relative position of the clustered and background populations of seismicity (see Sect. 1.1 for definitions) is different for tectonic and induced seismic regions. (ii) The extent of the clustered mode along the T-axis (rescaled time) is larger for tectonic events than for the induced ones, with the mixed regions presenting an intermediate situation. (iii) The proportion of events in the background mode within the regions of induced seismicity is much higher than in the other examined regions. In addition, we found that (iv) the rate of temporal decay of the offspring events away from the parent differs in tectonic vs induced seismic regions. This last observation is illustrated in **Figure 4.**

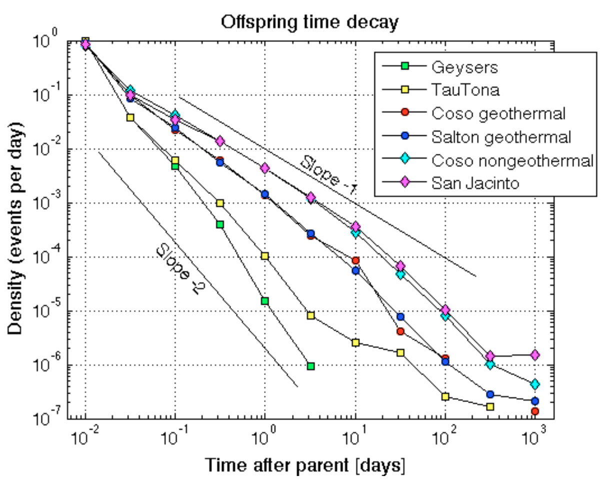

Figure 4: Temporal decay of the offspring intensity in the six examined regions. The figure shows the normalized daily density of events as a function of time. Different symbols correspond to different regions (see legend). The density decay is closely approximated by a power law in the form (density) $\propto$ (time)$^{-p}$ with index p decreasing from about 2 for induced earthquakes (Geysers and TauTona) to 1.5 for mixed seismicity (Coso and Salton Sea geothermal fields) to 1 for tectonic earthquakes (Coso non-geothermal and San Jacinto).

PROJECT PRESENTATIONS

1. Zaliapin, I. and Y. Ben-Zion (2014) Robust Quantification of Earthquake Clustering: Overcoming the Artifacts of Catalog Errors. Abstract S53D-4557 presented at 2014 Fall Meeting of AGU, San Francisco, California, December 15-19, 2014.
2. Zaliapin, I. and Y. Ben-Zion (2014) Robust quantification of earthquake clustering: Overcoming the artifacts of catalog errors. *Proc. of Southern California Earthquake Center (SCEC) 2014 Annual Meeting, Palm Springs, CA, September 6-10, 2014,* Vol. XXIV, p.189, poster 163.
3. Zaliapin, I. and Y. Ben-Zion (2014) Earthquake Clusters: Identification, Classification, and Relation to the Physical Properties of the Crust. Poster presented at the 30th IUGG Conference on Mathematical Geophysics, Merida, Yucatan, Mexico, June 2-6.
4. Zaliapin, I. and Y. Ben-Zion (2014) Spatio-temporal evolution of seismic clusters in natural and induced seismicity. Annual Meeting of Seismological Society of America, Anchorage, AK, 30 April – 2 May, 2014. *Seismol. Res. Lett*., 85(2), 487.

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