Report for SCEC3 funded project

"Correlation between seismic clustering properties and regional physical conditions"

Principal Investigators:

Ilya Zaliapin
Department of Mathematics and Statistics
University of Nevada, Reno NV 89557
Phone: (775) 784-6077, Fax: (775) 784-6378
E-mail: zal@unr.edu

Yehuda Ben-Zion
Department of Earth Sciences
University of Southern California
Los Angeles, CA 90089
Phone: (213) 740-6734, Fax: (213) 740-8801
E-mail: benzion@usc.edu

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SCEC3 Science Objectives: A9, A2, A4, A10

Special Project: WGCEP

SUMMARY

SCEC3 major research findings:

- *Statistical methodology and software for cluster analysis of seismicity*. We have developed a non-parametric method for identifying statistically significant earthquake clusters; the method is based on a bimodal distribution of earthquake distance in the space-time-magnitude domain. Accordingly, the cluster identification is not based on apriori cluster parameters or ad-hoc assumptions about the seismic flow.
- *Universality of earthquake clustering.* The analysis of several regional (California, Nevada, Japan, New Zealand) and the global NEIC catalog has shown a universal character of the bimodal distribution of the earthquake distance, and hence a universal character of seismic clustering (with region-dependent cluster parameters).
- *Asymmetric distribution of early aftershocks on bimaterial faults.* We have analyzed the relations between spatial symmetry properties of earthquake patterns along faults in California (CA) and local velocity structure images to test the hypothesis that ruptures on bimaterial faults have statistically preferred propagation directions. We have found strong asymmetric patterns in early-time spatially-close aftershocks along large faults with prominent bimaterial interfaces (e.g., sections of the San Andreas fault), with enhanced activity in the directions predicted for the local velocity contrasts, and absence of significant asymmetry along most other faults.
- *Classification of earthquake clusters.* We have shown the existence of two dominant types of earthquake clusters in southern California: *aftershock-dominated sequences* and *swarms*. The identification and quantitative analysis of the cluster types is done via the network representation of clusters. The topological cluster properties are highly coupled with a dozen of examined conventional metric cluster statistics (duration, area, fore/aftershock number, *etc.*).
- *Coupling between cluster type and physical properties of the lithosphere.* We have shown that the two dominant types of earthquake clusters have distinct preferred spatial locations. Swarms tend to occur in the regions with low level of effective viscosity (high heat flow, geothermal activity, increased fluid content) – Coso and Salton trough. The aftershock-dominated sequences tend to occur in the regions with high level of effective viscosity (low heat flow, mild-to-no geothermal activity) – e.g., Mojave, San Bernardino, Ventura.

Broader impact:

Our studies have developed and applied improved statistical methods for deriving high-resolution information from earthquake catalogs that are related to specific properties of fault zones and the crust. The results provide important information for developing refined seismic hazard assessments, and constraining the physics of earthquake ruptures and dynamics of seismicity. The PIs organize a special session at the 2012 Annual SSA meeting related to the research initiated in this project.

Student involvement:

Jennifer Bautista (BSc student at UNR); Andrew Hicks (MSc student at UNR); Maggie Michalowski (MSc student at UNR); Zachary Ross (PhD student at USC)

Project publications:

The project has resulted in 4 peer-reviewed papers/preprints, 2 student theses, and 10 conference presentations.

Technical Description

1. Introduction

Earthquake clustering is an essential aspect of seismicity, with signatures in space, time and size (e.g. magnitude) domains that provide key information on regional earthquake dynamics. Clustering is the most prominent form of the existing variety of structures and patterns of earthquakes, understood in the broadest sense of various deviations from a time-stationary space-inhomogeneous marked point process. Clustering in space is exemplified by the concentration of earthquakes along the boundaries of major tectonic plates and regional fault networks. Clustering in time is best seen as a significant increase of seismic activity immediately after large earthquakes, leading to *aftershock sequences*. Earthquake *swarms*, *foreshocks*, *bursts*, *gaps*, and *switching* of seismic activity among different spatio-temporal domains, are other terms used to denote types of seismic clustering [*Ben-Zion*, 2008].

Despite the overall agreement on the existence of different types of seismic clustering, reflected by a well-developed cluster terminology (the italicized terms above), a formal definition of seismic clusters is lacking. This limits the ability of performing rigorous systematic cluster analysis. Even the most prominent type of clusters – aftershocks – does not have a commonly accepted definition. The existing cluster studies rely on various *ad-hoc* definitions and assumptions, which are well suited for answering particular focused questions, yet typically insufficient for general use. This study takes advantage of recent results on non-parametric statistical aftershock identification [*Zaliapin et al.*, 2008; *Zaliapin and Ben-Zion*, 2011], as well as recent empirical evidence [e.g., *Vidale et al.*, 2006a,b; *Enescu et al.*, 2009; *Holtkamp et al.*, 2011], to develop a comprehensive approach towards objective robust identification of various types of seismic clusters.

This project has achieved the following goals: (i) identify statistically significant earthquake clusters in southern California, (ii) classify the detected clusters into several main types according to their statistical properties, and (iii) establish connections between the cluster statistics and physical properties of the lithosphere.

2. Earthquake distance

The cluster detection is done using the earthquake cluster methodology of *Zaliapin et al.* (2008). Consider an earthquake catalog where each event i is characterized by occurrence time t_i, hypocenter (ϕ_i, λ_i, d_i) and magnitude m_i. Our initial goal is to identify for each earthquake j its possible parent, which is an earlier earthquake i that might have caused the occurrence of j. This motivates us to consider a distance that is asymmetric in time. Following *Baiesi and Paczuski* (2004), the distance between earthquakes i and j is defined as

$$\eta_{ij} = \begin{cases} t_{ij}(r_{ij})^d 10^{-bm_i}, & t_{ij} > 0; \\ \infty, & t_{ij} \le 0. \end{cases} \quad (1)$$

Here $t_{ij} = t_j - t_i$ is the intercurrence time, which is positive if earthquake i happened before earthquake j and negative otherwise; $r_{ij} \geq 0$ is the spatial distance between the earthquake hypocenters; and d is the (possibly fractal) dimension of the earthquake hypocenter distribution.

We represent the scalar distance η in terms of its space and time components normalized by the magnitude of the parent event i:

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

The developed analysis is based on a bimodal distribution of nearest-neighbor earthquake distances in a combined space-time-magnitude domain.

3. Bimodal distribution of the observed nearest-neighbor distance

The analysis of the observed seismicity in southern California reveals a prominently bimodal distribution of η as well as of the joint distribution of (T, R). Figure 1 shows the distribution of the nearest-neighbor distance η. The first striking observation is the existence of two modes: One is extended along and above the white diagonal line in Fig. 1a; this mode is reminiscent of the single mode of the distribution for a homogeneous Poisson process (not shown). We refer to this mode as *background*. The other mode is located closer to the origin and has horizontally elongated shape in the 2-D version. We call this mode *clustered*.

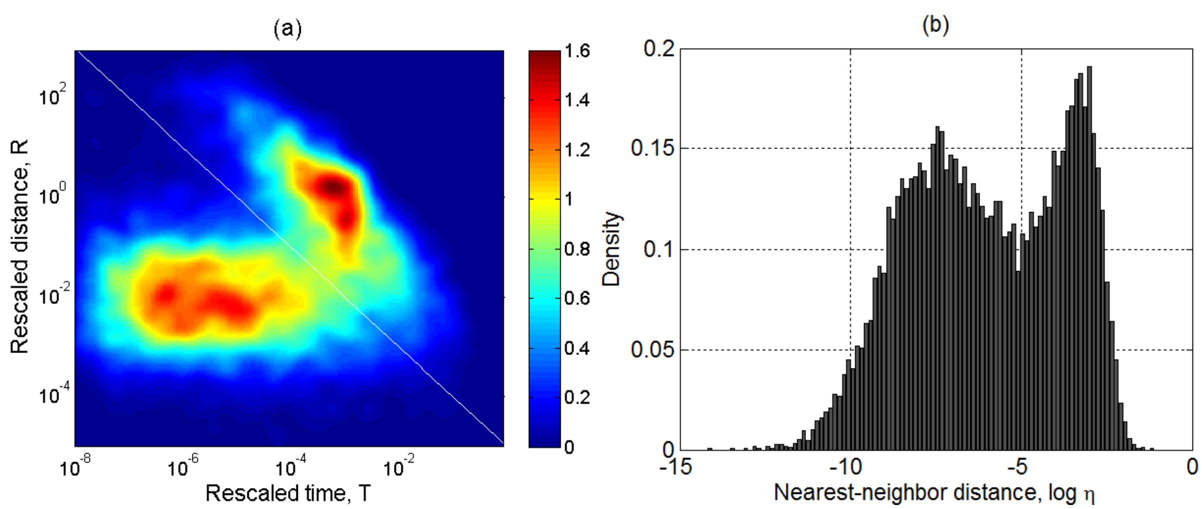

Figure 1: Distribution of the nearest-neighbor earthquake distance η in southern California using the relocated catalog of *Hauksson et al.* (2012). (a) The joint distribution of the rescaled time and space components (T,R). (b) Histogram of the nearest-neighbor distance η; the values are normalized to sum up to unity. The bimodal distribution is clearly seen in both panels. The line $\log R + \log T = -5$ that separates the two modes is shown in white in panel (a).

The bimodal distribution of the nearest-neighbor distance is a universal feature of the observed seismicity. *Hicks* (2010) used the NEIC catalog to report similar bimodal distribution for the world-wide seismicity, as well as the regional seismicity of Japan, New Zealand, and

Africa. *Bautista* (2010) has demonstrated a bimodal distribution for the seismicity of Nevada, using the catalog produced by the Nevada Seismological Laboratory.

Our research has shown, in particular, that the observed bimodal distribution cannot result from the marginal spatial or temporal clustering of earthquakes, and is fundamentally due to dependent space-time structures of seismicity, associated primarily with foreshock-mainshock-aftershock sequences. The observed bimodal distribution of earthquake distances provides a natural tool for partitioning an examined earthquake catalogs into separate *clusters*: events within each cluster are abnormally close to their nearest-neighbors, while events from distinct clusters are relatively far from each other.

The clusters are divided into *singles* that contain just one event, and *families* having multiple events that are sub-classified into *foreshocks, mainshocks, and aftershocks*. Families are the main object of the study and are further classified into classical *aftershock-dominated sequences* (with very few foreshocks and many first-generation aftershocks) and *swarms*. The two main detected family types differ significantly according to a dozen of examined cluster statistics. The family type can be most efficiently quantified by a scalar measure related to the topological structure of the earthquake family network (see Sect. 4 below). The topology of the family is shown to be significantly correlated with all the examined family statistics (see Sect. 5 below). The results are in line with traditional classification of different types of earthquakes (mainshocks, foreshocks, aftershocks) and event clusters (classical sequences vs. swarms). However, our methodology is based solely on non-parametric statistical properties of the observed seismicity and can be used to analyze consistently seismicity in different regions of space and time.

4. Two types of earthquake family clusters

Our research has demonstrated the existence of two dominant earthquake family types. One type corresponds to *aftershock-like clustering*; it is characterized by high branching number, small number of generations, and large magnitude difference between the mainshock and the largest fore/aftershocks. The other type corresponds to *swarm-like clustering*; it is characterized by low branching number, large number of generations, and small magnitude difference between the mainshock and the largest fore/aftershocks. To quantify the observed differences of the trees, we use the concept of *vertex depth* – the minimal number d of links that connects a given vertex (earthquake) to the tree root (the first earthquake in the family). A useful scalar measure that characterizes a tree is the *average leaf depth* $\langle d \rangle$ – the vertex depth d averaged over the tree leaves (vertices with no children). Importantly, various statistical properties of nearest-neighbor families strongly coupled with the average leaf depth $\langle d \rangle$. It has been shown that the aftershock-dominated sequences are characterized by low values of the average leaf depth while swarms are characterized by high values of the depth. The Table 1 below summarizes the coupling between the family type and various cluster statistics.

Table 1: Relation between examined earthquake cluster statistics and family type

Examined cluster statistic	Aftershock sequence	Swarm
Magnitude difference between mainshock and largest aftershock, Δ_m	High	Low
Magnitude difference between mainshock and largest foreshock, Δ_m	High	Low
Ave. no. of aftershocks per family, L_a	Low	High
Ave. no. of foreshocks per family, L_f	Low	High
Branching index, B	High	Low
Area of aftershocks, A_a	Low	High
Area of foreshocks, A_f	Low	High
Duration of aftershocks, D_a	Low	High
Duration of foreshocks, D_f	Low	High
Intensity of aftershocks, Λ_a	Low	High
Intensity of foreshocks, Λ_f	Low	High
Circular homogeneity, U	High	Low
Average leaf depth, $\langle d \rangle$	Low	High

Figure 2 illustrates the coupling between the average leaf depth $\langle d \rangle$ and the intensity of foreshocks and aftershocks per family. In this analysis we split all detected earthquake clusters into two groups according to the values of the average leaf depth. The analysis shows that (i) the absolute number of foreshocks and aftershocks is higher for deep families (swarms), (ii) the decay rate away from a mainshock for foreshocks and aftershocks is higher for shallow families (aftershock-dominated sequences).

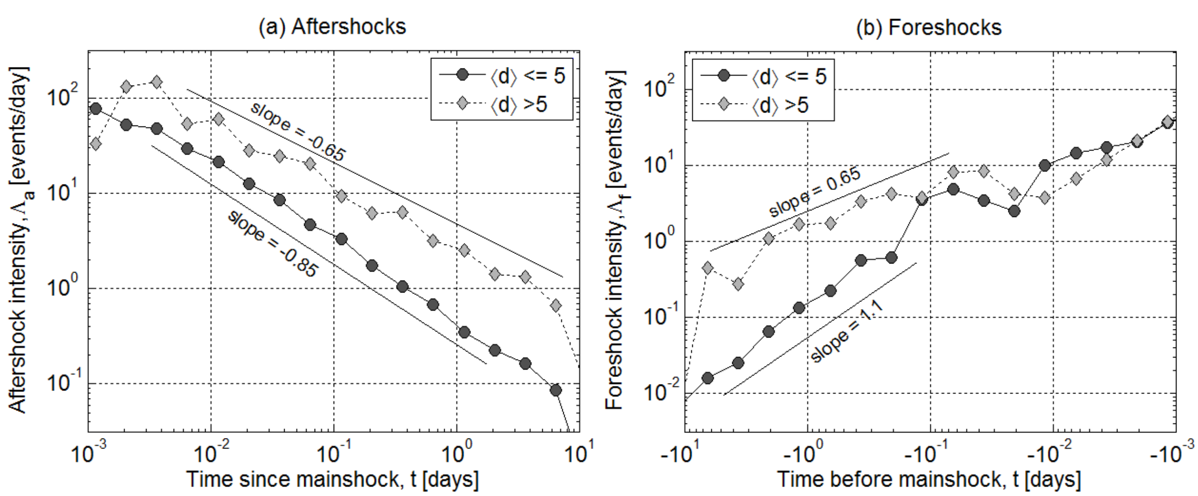

Figure 2: Fore/aftershock intensity. The figure shows estimated intensity of aftershocks (panel a) and foreshocks (panel b) in events per day in a single family for families with ‹*d*› ≤ 5 (solid line, circles) and ‹*d*› > 5 (dashed line, diamonds). The event decay away from the mainshock is more rapid in shallow families.

5. Spatial variations of cluster properties

Importantly, the two dominant types of earthquake families have distinct preferred spatial locations. The deep families (swarms) tend to occur in the regions with low level of effective viscosity (high heat flow, geothermal activity, increased fluid content) – Coso and Salton trough; while the shallow families (aftershock-dominated sequences) tend to occur in the regions with high level of effective viscosity (low heat flow, mild-to-no geothermal activity) – e.g., Mojave, San Bernardino, Ventura. Figure 3 illustrates this observation for the average leaf depth. Similar results are obtained for all the examined cluster characteristics.

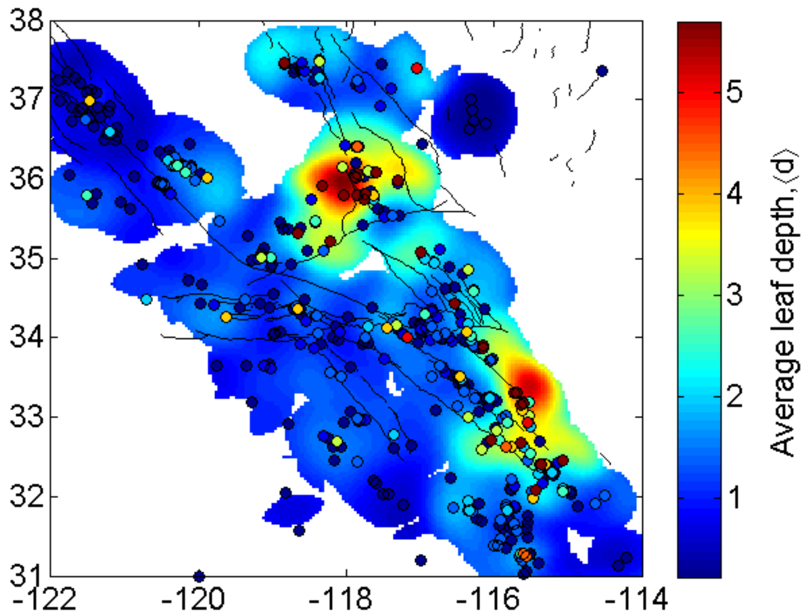

Figure 3: Spatial distribution of different types of earthquake families. The figure shows the average leaf depth ‹*d*› for *N* = 452 clusters with maximal magnitude $4 \le m < 6$ from the relocated catalog of *Hauksson et al.* (2012). Recall that the high (low) values of the average leaf depth ‹*d*› correspond to swarms (aftershock-dominated sequences). The high-depth families (swarms) are concentrated within the regions with low effective level of viscosity – Coso and Salton trough. The high-viscosity regions – e.g., Mojave, San Bernardino, Ventura – are characterized by the low-depth families (aftershock-dominated sequences).

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Project publications

A. Peer-reviewed papers

1. Enescu, B., S. Hainzl and Y. Ben-Zion, Correlations of Seismicity Patterns in Southern California with Surface Heat Flow Data, *Bull. Seism. Soc. Am.*, **99**, 3114-3123, doi: 10.1785/0120080038, 2009.
2. Zaliapin, I. and Y. Ben-Zion (2011) Asymmetric distribution of early aftershocks on large faults in California. *Geophys. J. Intl*., **185**, 1288–1304.

B. Preprints

1. Zaliapin, I. and Y. Ben-Zion (2012) Detection and classification of earthquake clusters in southern California. Preprint.
2. Zaliapin, I. and Y. Ben-Zion (2012) Relation between earthquake clustering and the physical properties of the crust in southern California. Preprint.

C. Theses

1. Hicks, A. (2010) *Clustering in Multidimensional Spaces with Applications to Statistical Analysis of Earthquake Clustering*. MSc Thesis, Department of Mathematics and Statistics, University of Nevada, Reno. August, 2012.
2. Bautista, J. (2010) *Nearest-Neighbor Analysis of Marked Point Fields with Applications to Cluster Analysis of Seismicity*. Undergraduate Honors Thesis, Department of Mathematics and Statistics, University of Nevada, Reno. May, 2012.

D. Conference presentations

1. Ben-Zion, Y. and I. Zaliapin (2011) Relations between properties of seismicity and regional heat flow in California. Abstract S34A-04 presented at 2011 Fall Meeting, AGU, San Francisco, California, 5-9 December.
2. Zaliapin, I. and Y. Ben-Zion (2011) Relations between properties of seismicity and regional heat flow in California. Proc. of Southern California Earthquake Center (SCEC) 2011 Annual Meeting, Palm Springs, CA, September 11-14, 2011, Vol. XXI, p. 252.
3. Ben-Zion, Y. and I. Zaliapin (2011) Observational tests of dynamic bimaterial effects on natural faults with along-strike symmetry properties of aftershocks. EGU General Assembly 2011, Vienna, Austria, 3-8 April, 2011. Geophysical Research Abstracts, Vol. 13, EGU2011-2797.
4. Zaliapin, I. and Y. Ben-Zion (2011) Correlations between clustering and productivity properties of seismicity in California and heat flow. Annual Meeting of Seismological Society of America, Memphis TN, 13-15 April, 2011. *Seismol. Res. Lett*., 82, 361.
5. Zaliapin, I. (2011) Hierarchical network approach to modeling natural complexities. Presented at *ENHANS International Workshop on Extreme Natural Hazards and Disaster Risk in Africa*, Pretoria, South Africa, 17-20 January. (Invited)

6. Hicks, A., I. Zaliapin, Y. Ben-Zion (2010) Worldwide seismic clustering and correlations with regional physical properties. Abstract NG44A-04 presented at 2010 Fall Meeting, AGU, San Francisco, California, 13-17 December.
7. Zaliapin, I. and Y. Ben-Zion (2010) Seismic Clustering and Regional Physical Properties: A Statistical Analysis, *Proc. of Southern California Earthquake Center (SCEC) 2010 Annual Meeting, Palm Springs, CA, September 11-15, 2010*, Vol. XX, p. 299.
8. Zaliapin, I. and Y. Ben-Zion (2010) Seismic clustering and regional physical properties: A statistical analysis. Poster presented at 28th IUGG Conference on Mathematical Geophysics, June 7-11, 2010, Pisa, Italy
9. Zaliapin, I. and Y. Ben-Zion (2010) Asymmetric properties of early aftershocks on faults in California. 2010 Annual Meeting of Seismological Society of America, Portland OR, 21-23 April, 2010. *Seismol. Res. Lett.*, 81(2), 366.
10. Zaliapin, I. and Y. Ben-Zion (2009) Correlations between seismic clustering and properties of the crust. *Proc. of Southern California Earthquake Center (SCEC) 2009 Annual Meeting, Palm Springs, CA, September 12-16, 2009*, Vol. XIX, p. 233.