Properties and dynamics of different types of seismicity clusters in southern California

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Technical Report

We document space-dependent clustering properties of earthquakes with \( m \geq 4 \) in the 1975-2015 worldwide seismic catalog of the Northern California Earthquake Data Center (Section 1.1). Earthquake clusters are identified using a nearest-neighbor distance in time-space-magnitude domain (Section 1.5). Multiple cluster characteristics are compared with the heat flow level (Section 1.2) and type of deformation defined by parameters of the strain rate tensor (Section 1.3). The analysis suggests that the dominant type of seismicity clusters in a region depends strongly on the heat flow (Figs. 1,2), while the deformation style and intensity play a secondary role. The results show that there are two dominant types of global clustering: burst-like clusters that represent brittle fracture in relatively cold lithosphere (e.g., shallow events in subduction zones) and swarm-like clusters that represent brittle-ductile deformation in relatively hot lithosphere (e.g., mid-oceanic ridges). The global results are consistent with theoretical expectations and previous analyses of earthquake clustering in southern California based on higher quality catalogs. The observed region-specific deviations from average universal description of seismicity provide important constraints on the physics governing earthquakes and can be used to improve local seismic hazard assessments.

1.1 Earthquakes

We work with the global catalog produced by the Northern California Earthquake Data Center (NCEDC, 2015). The examined catalog covers the period 1/1/1975 to 6/9/2015 and contains 256,993 events. The minimal magnitude used in the analysis is \( m_{\text{min}} = 4 \). This magnitude is higher than the completeness magnitude in many examined regions, in particular during the earlier times. We demonstrated (Zaliapin & Ben-Zion, 2013a, Auxiliary Sections D,E) that the cluster structure estimated by our technique (Sect. 3) is insensitive to the catalog incompleteness as well as to the minimal reported magnitude. Accordingly, some cluster statistics, like the total number of clusters and partition of events into mainshocks, foreshocks, and aftershocks (see Sect. 3.6 for definitions) are fairly robust with respect to the magnitude incompleteness.

1.2 Heat flow

The employed surface heat flow data is taken from Bird et al. (2008). The heat flow within the seismically active areas is mapped in Fig. 2. The distribution of the heat flow over the entire Earth surface is shown in Appendix A, Fig. A1. The heat flow production is prominently high along the oceanic spreading ridges, reaching 0.3 W/m².

1.3 Strain rate tensor

We use the global strain rate field modeled by Kreemer et al. (2014). Specifically, we consider the second invariant \( I_2 \) of the strain rate tensor \( \boldsymbol{\varepsilon} \):

\[
I_2 = \sqrt{\left(\dot{\varepsilon}_{00}\right)^2 + \left(\dot{\varepsilon}_{00}\right)^2 + 2\left(\dot{\varepsilon}_{00}\right)^2}
\]

(2)

and the tensor style \( S \) defined by Kreemer et al. (2014) as:

\[
S = \frac{e_1 + e_2}{\max(|e_1|,|e_2|)}.
\]

(3)

Here \( e_i \) are the eigenvalues of the strain rate tensor. The strain rate tensor style \( S \) can be used to roughly quantify the type of displacement into contraction (\( S < -0.5 \)), strike-slip (\( 0.5 < S < -0.5 \)), and extension (\( S > 0.5 \)).
1.4 Δ-analysis

Any cluster analysis of earthquakes is affected by the existence of the catalog lower cutoff magnitude $m_{\text{min}}$ (which may be smaller than the completeness magnitude $m_c$). For instance, if we analyze earthquakes with $m \geq m_{\text{min}} = 4$, then an earthquake of $m = 4$ cannot have recorded aftershocks of a smaller magnitude, while an $m = 6$ event may have aftershocks with magnitudes $4 \leq m \leq 6$. To equalize the magnitude ranges for potential fore/aftershocks of mainshocks with different magnitudes, we sometimes perform Δ-analysis that (i) only considers mainshocks with magnitude $m \geq m_{\text{min}} + \Delta$ and (ii) only considers fore/aftershocks with magnitude within $\Delta$ units below that of a mainshock. The fore/aftershocks detected by this analysis are called Δ-fore/aftershocks. The conventional analysis that considers all events is referred to as regular analysis.

1.5 Generalized earthquake distance

Consider a catalog where each event $i$ is characterized by its occurrence time $t_i$, hypocenter $(\phi_i, \lambda_i, d_i)$, and magnitude $m_i$. We define the proximity $\eta_{ij}$ of earthquake $j$ to earthquake $i$ following Baiesi and Paczuski (2004) as:

$$\eta_{ij} = \begin{cases} t_j (r_j)^d 10^{-bm} , & t_j > 0; \\ \infty , & t_j \leq 0. \end{cases}$$

(4)

Here, $t_{ij} = t_j - t_i$ is the event intercurrence time, which is positive if event $j$ occurred after event $i$; $r_{ij} \geq 0$ is the spatial distance between the earthquake hypocenters; $d$ is the (possibly fractal) dimension of the hypocenters or epicenters, and $b$ is the parameter of the Gutenberg-Richter law (1). The motivation for and properties of this proximity measure are discussed in Zaliapin and Ben-Zion (2013a, 2015, 2016). In particular, the proximity to the nearest neighbor is inversely related to the seismic intensity. It is intuitive that the distance between events is smaller in a high-intensity process where a larger number of events occupy the same space-time volume; see Zaliapin et al. (2008) for formal derivations and Zaliapin and Ben-Zion (2013a) for simulation results.
Figure 1: Heat flow in the seismically active regions. A point is included in this graph if the circle of radius 100km centered at the point contains 5 or more earthquakes of magnitude $m \geq 5$. The heat flow values are clipped at $H = 0.2$ (the maximal reported value is 0.3)
Figure 2: Global spatial distribution of selected earthquake cluster statistics. (a) Proportion $p_S$ of singles among regular clusters. (b) Proportion $p_F$ of foreshocks among foreshocks and aftershocks. (c) Average leaf depth corrected for cluster size, $d_N$, for families with size $5 \leq N \leq 20$. 