Project report for SCEC award # 25231: Identifying seismicity bursts across California to probe fault-zone conditions

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Abstract

Earthquakes tend to cluster in space and time, developing into sequences driven by stress perturbations and transient fault-zone processes (Omori, 1894; King et al., 1994; Peng et al., 2025). The characteristics of earthquake sequences can vary depending on the driving process, and this variability challenges our ability to observe and distinguish these mechanisms at high resolution. This project systematically identified highly clustered seismicity bursts throughout southern California using new statistical methods (DeSalvio and Fan, 2023; Fan et al., 2021) and examined their causes using independent geophysical observations. Seismicity bursts were defined as statistically significant seismicity rate anomalies relative to the local background rate, an approach that is data-driven and depends on few earthquake occurrence assumptions. We found abundant seismicity bursts across the region, most frequently occurring along the San Jacinto Fault and in the Salton Sea and Coso geothermal fields. These seismicity bursts are highly compact in space and time, often encompassed by a 5 km radius with durations of less than 10 hours. Through analyses of magnitude-frequency distributions, spectral stress drops, spatiotemporal clustering, and stress ratios, we demonstrated that the seismicity bursts have systematically different characteristics from regional seismicity. These differences suggest that seismicity bursts are driven by transient fault-zone processes, including pore fluid pressure changes, aseismic transients, and stress-dependent cascading effects, acting frequently across fault networks.

Key Findings

This project developed and applied a new systematic, data-driven approach to identify seismicity bursts in southern California over a 10-year period (2008–2017) using the high-resolution Quake Template Matching (QTM) earthquake catalog (Ross et al., 2019). The identification method uses the β-statistic (Matthews and Reasenberg, 1988) to quantify seismicity rate changes and determine whether rate increases are statistically significant at the 95% confidence level, with site-specific background rate estimation that accounts for spatial heterogeneity in detection capability and seismicity rates across the region (DeSalvio and Fan, 2023; Fan et al., 2021).

We identified 2,045 seismicity bursts across 188 qualified spatial grids covering southern California. These bursts are remarkably compact: the median spatial extent is less than 5 km in radius (containing 85% of burst seismicity), and the median duration is less than 10 hours, with approximately 95% of the bursts lasting one day or less. The seismicity bursts are akin to swarms (Vidale and Shearer, 2006), with 91% having effective stress drops below 1 MPa (Fischer and Hainzl, 2017), and the majority lacking a clear mainshock (Båth, 1965). The burst earthquakes account for approximately 13.4% of the regional seismicity.

We compared the seismicity bursts with regional seismicity using multiple independent geophysical datasets, revealing the following characteristic differences:

(1) The seismicity bursts exhibit lower Gutenberg-Richter b-values (Gutenberg and Richter, 1944) (approximately 0.15 lower), indicating a relative enrichment in larger earthquakes within the bursts. This difference is robust across different magnitude ranges, is confirmed in the Southern California Earthquake Data Center (SCEDC) catalog, and is absent in a synthetic Epidemic-Type Aftershock Sequence (ETAS) catalog (Hardebeck, 2013), demonstrating that it is not a procedural artifact.

(2) The seismicity bursts have lower spectral stress drops (Shearer et al., 2022), with the median burst stress drop approximately 3 MPa lower than the regional median. This difference is statistically significant

as confirmed by a Kolmogorov–Smirnov test, a Fisher's permutation test (Fisher, 1951), and a bootstrap test (Moyer et al., 2018). The stress drop difference holds for earthquakes on natural faults after removing geothermal field events.

(3) The burst seismicity shows a higher degree of spatiotemporal clustering in nearest-neighbor diagrams (Zaliapin and Ben-Zion, 2013; Hsu et al., 2024) relative to the clustered mode of the regional seismicity.

(4) The seismicity bursts have different stress ratios (Warren-Smith et al., 2019) from the regional seismicity, with burst events generally trending toward a pure strike-slip stress state ($R = 0.5$). The stress ratio differences are robust, exceeding 10 times their uncertainties at the majority of grid locations. Focal mechanisms from Cheng et al. (2023) were inverted using the Spatial And Temporal Stress Inversion method (Hardebeck and Michael, 2006).

(5) The occurrence of seismicity bursts does not correlate with fault complexity metrics, including surface trace misalignment ratio, fault-trace density ratio (Chu et al., 2021), and focal mechanism diversity (Hardebeck and Hauksson, 2001), indicating that long-term fault geometry does not control burst activity.

New Insights

The systematic identification and characterization of seismicity bursts provides several new insights into fault zone processes and earthquake sequence behavior. The distinct characteristics of seismicity bursts relative to regional seismicity indicate that the bursts are not simply explained by standard earthquake-to-earthquake triggering (King et al., 1994; Kilb et al., 2000), but are instead controlled by transient fault-zone processes operating on kilometer and hour scales.

The analysis reveals that multiple driving mechanisms are likely responsible for the observed seismicity bursts, including pore fluid pressure changes, aseismic slip transients, and rate-dependent cascading processes (McLaskey, 2019; Noda et al., 2013). These mechanisms can act separately and in tandem. Pore fluid migration is supported by the swarm-like behavior (low moment release skew, lack of clear mainshocks), lower stress drops (Goertz-Allmann et al., 2011; Ross et al., 2020), and compact spatiotemporal patterns similar to fluid-driven earthquake sequences (Chen and Shearer, 2011; Ruhl et al., 2016; Sirorattanakul et al., 2022). Aseismic transients are supported by comparison with geodetically observed slip events in the Salton Sea region (Lohman and McGuire, 2007; Materna et al., 2022; Wei et al., 2015). However, the low b-values observed in the bursts are not fully consistent with either pore fluids or aseismic slip alone, as previous studies generally associate these mechanisms with higher b-values (Bachmann et al., 2012; Senatorski, 2020; Tormann et al., 2014; Yukutake et al., 2022). This discrepancy points to complex interactions between driving processes at seismogenic depths, where frictional stability heterogeneity (Cattania and Segall, 2021; Jiang and Lapusta, 2016) may cause aseismic creep to trigger earthquakes with different magnitude scaling (Ito and Kaneko, 2023).

The geographic heterogeneity in burst characteristics further highlights the importance of local fault conditions. For instance, the Salton Sea geothermal field (Brodsky and Lajoie, 2013) does not exhibit b-value or stress drop differences between burst and regional seismicity, suggesting that both populations may be influenced by pervasive fluid activity, with seismicity bursts potentially driven by surges of pore pressure (Moein et al., 2023). In contrast, the Coso geothermal field (Holmgren et al., 2025) and natural faults exhibit the characteristic differences observed in the regional aggregate. The lack of correlation between burst occurrence and regional geophysical models (e.g., V_p/V_s ratio, surface geology) further implies that the seismicity bursts are driven by transient geophysical processes acting over small spatiotemporal footprints (Atterholt et al., 2022; Ben-Zion et al., 1992; Lin and Fan, 2024). These findings demonstrate that the seismicity bursts provide a new and high-resolution dynamic window into fault zone environments, offering opportunities for case studies that can resolve transient processes at unprecedented spatiotemporal resolution.

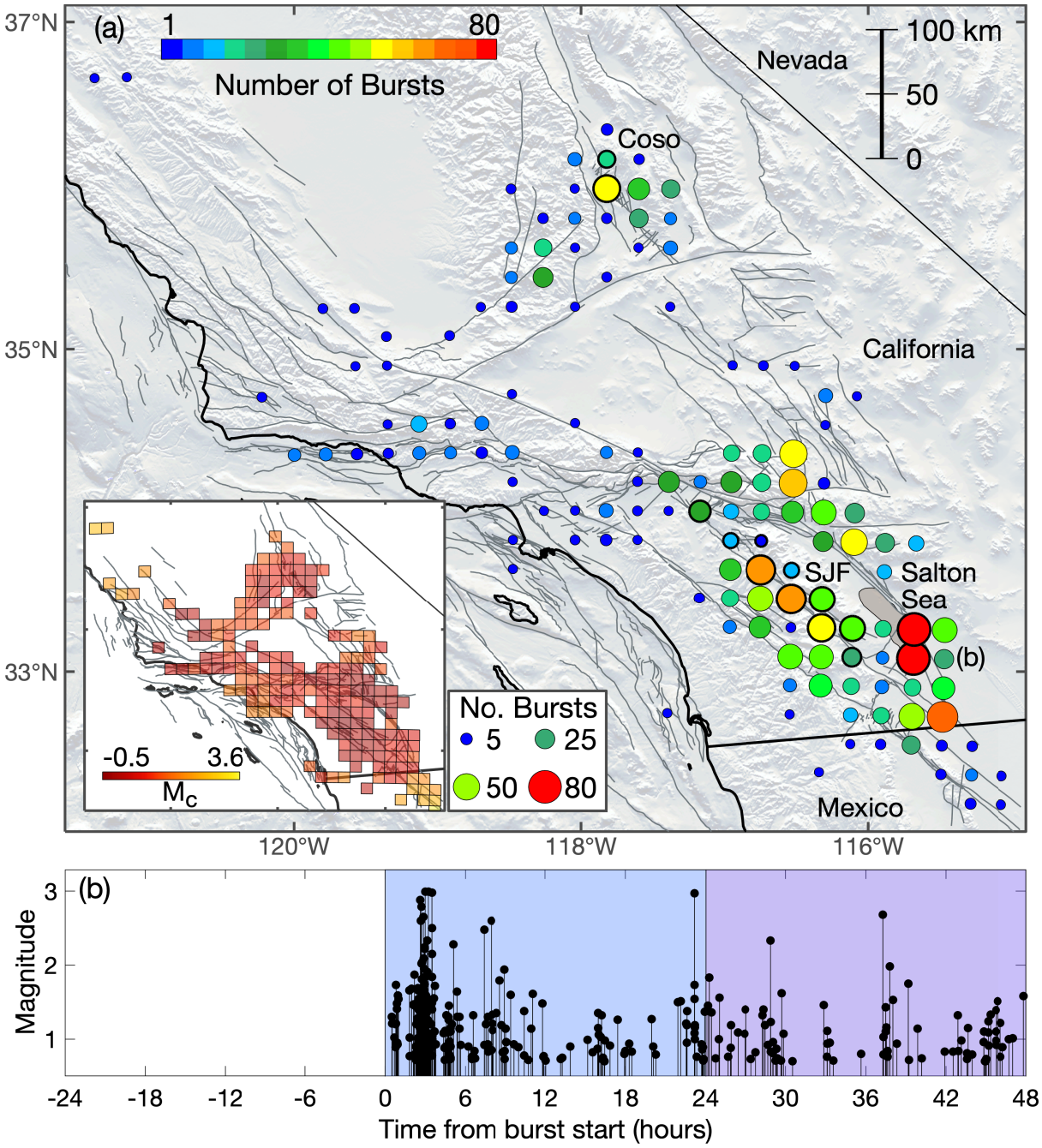

Figure 1: Study area and locations of the identified seismicity bursts. Figure modified from DeSalvio et al. (2026). (a) Number of seismicity bursts identified by the β-statistic in each grid. In (a) markers are both sized and colored by the number of identified bursts. Grids with a thicker outline indicate locations of the Coso geothermal field, Salton Sea geothermal field, and San Jacinto Fault (SJF). Inset shows the magnitude of completeness (M_c) and spatial extent of each grid. (b) Magnitude time series for a seismicity burst identified within the grid adjacent to the (b) label in panel (a), near Brawley, CA, on June 2, 2008. The burst lasts one day (shaded in blue); the seismicity rate change in the subsequent 24-hour period (shaded in purple) is not statistically significant. Seismicity bursts like this are abundant and widespread throughout southern California.

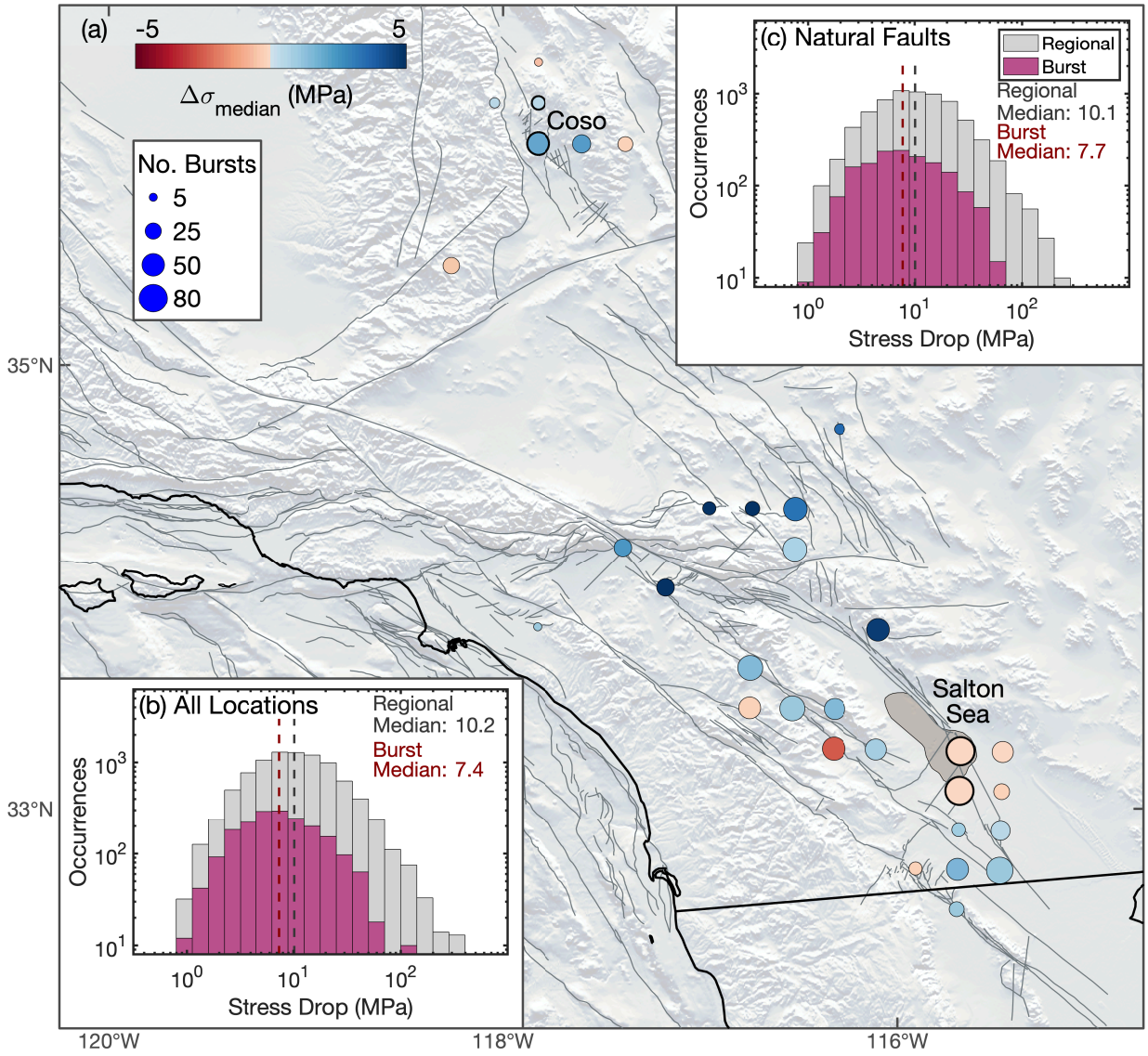

Figure 2: Stress drop distributions. Figure modified from DeSalvio et al. (2026). (a) Map of the differences in the median stress drop values of the burst and regional seismicity at each qualified grid. $\Delta\sigma_{median} = \sigma^{r}_{median} - \sigma^{b}_{median}$, where σ^{r}_{median} and σ^{b}_{median} are the median stress drops of regional and burst seismicity, respectively. (b) Stress drop distributions of the burst and regional earthquakes and (c) those only at natural faults omitting the grid markers in (a) denoted with a thicker outline. Marker size represents the number of identified bursts in each grid. On average, burst seismicity has lower stress drops than the regional seismicity.

Publication and Student Support

This project has led to a peer-reviewed publication in the *Journal of Geophysical Research: Solid Earth*:

> DeSalvio, N. D., W. Fan, A. J. Barbour, and J. L. Hardebeck (2025), Compact Seismicity Bursts Have Different Characteristics from Regional Seismicity, *Journal of Geophysical Research: Solid Earth*, doi:10.1029/2025JB032917.

This project supported Ph.D. student Nicolas D. DeSalvio at the Scripps Institution of Oceanography, UC San Diego. The study constitutes a core component of his doctoral thesis, in which he developed and applied the statistical burst identification method, conducted the comprehensive analyses of burst characteristics, and led the interpretation of the results. The project provided DeSalvio with extensive training in statistical seismology, earthquake source physics, and the analysis of large-scale seismological datasets.

Conclusions

This project has achieved its goal of systematically investigating seismicity bursts and the associated fault zone evolution in southern California. Through the development and application of a new data-driven statistical approach, we identified abundant and widespread highly clustered seismicity bursts throughout the region. These bursts are compact, with the majority contained within a 5 km radius and lasting only a few hours.

The comparison of seismicity burst characteristics with regional seismicity reveals systematic differences in b-values, stress drops, spatiotemporal clustering patterns, and stress ratios. These distinct characteristics indicate that seismicity bursts are controlled by transient fault-zone processes rather than the long-term tectonic conditions that govern regional seismicity. The driving mechanisms include pore fluid pressure changes, aseismic transients, and rate-dependent cascading processes, which can act separately and in tandem to nucleate earthquakes and develop sequences within complex fault networks. These transient processes can temporarily alter local fault-zone friction and stress conditions, generating the identified bursts.

The identified seismicity bursts provide valuable candidates for case studies to further investigate local fault zone processes, offering new opportunities to understand earthquake sequences at kilometer-scale spatial resolution and hour-scale temporal resolution. The methodology developed in this project is readily applicable to other regions with high-quality earthquake catalogs, such as northern California and Japan. Future work can leverage these burst identifications in conjunction with high-resolution imaging techniques to resolve the dynamics of transient fault-zone processes.

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