

An analysis of spatio-temporal variations of seismicity and strain in the Salton Trough

Report for SCEC Award # 18055

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I. Project Overview

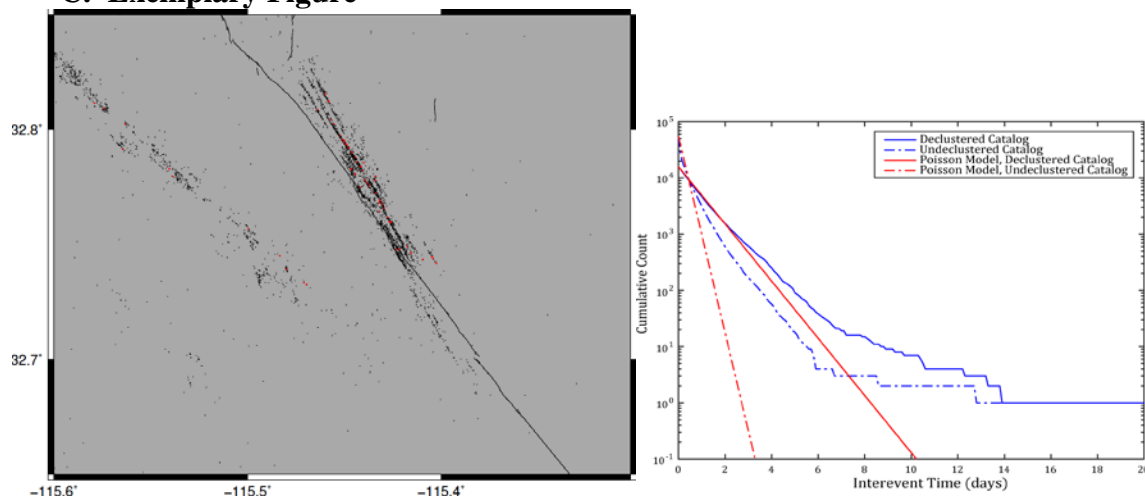
A. Abstract

We analyze the spatiotemporal variations in seismicity and strain in the Salton Trough. We used a template matching catalog spanning ten years. We examined both individual earthquake clusters and long-term variations in seismicity rate. Long term strain rates show a seasonal pattern. However, we have not detected a seasonal pattern with the seismicity. Seismicity streaks are clearly evidenced on portion of Imperial fault but don't follow the same temporal statistics as similar streaks seen on the creeping portion of the San Andreas fault. Interevent time distribution of the background seismicity is apparently not Poissonian due to long period of quiescence not predicted by the model.

B. Intellectual Merit

This research is contributing to advancing the understanding of fault processes and earthquakes at a fundamental level and to potentially improving methods for seismic hazard assessment. A fundamental finding, which needs further investigation, is that the seismicity analyzed as part of this project does not seem to follow the classical Poisson process assumed in seismic hazard studies.

C. Exemplary Figure



Caption. Relocated seismicity from in the Imperial fault region (black dots). Red dots indicate the locations of template events that detected more than 50 earthquakes over the 10 year period. Intervent time distributions don't follow the prediction of the Poisson model, even after removal of aftershocks sequence.

D. SCEC Science Priorities:

Category: B (Integration and Theory)

P1.e, "Evaluate how stress transfer among fault segments depends on time, at which levels it can be approximated by quasi-static and dynamic elastic mechanisms...", **P5.c**, "Assess limitations of long-term earthquake rupture forecasts by combining patterns of earthquake occurrence and strain accumulation...", and **P5.e**, "Exploit anthropogenic (induced) seismicity as experiments in earthquake predictability."

E. Project Publications

None yet related to that particular project.

F. Boarder impact.

The project provided support for a summer undergraduate research intern (Joe Duncan-Duggal)

II. Technical report

The Salton Trough stands out as one of the most seismically active regions of southern California (Figure 1). It serves as a transition between the southern end of the San Andreas fault system and the rifting regime present in the Gulf of California (Sharp, 1982). Over the last century, the region has exhibited diverse earthquake phenomena including several large magnitude earthquakes (1940 Mw 6.9; 1979 Mw 6.4), frequent swarms (Johnson & Hadley, 1976; Chen & Shearer, 2011; Hauksson et al., 2017), some of which were accompanied with slow slip events (Lohman & McGuire, 2007; Wei et al., 2015), and shallow creep (Lindsey & Fialko, 2016; Lyons et al., 2002). The area is characterized by a relatively high heat flow (Doser and Kanamori, 1986) and hydrothermalism, having several major geothermal plants currently in

operation. The Salton Trough is a prime test place to study the factors that control earthquake triggering.

The physical mechanisms by which earthquakes are triggered are still not well understood. Earthquakes can result from static (e.g. Dieterich, 1994) and dynamic stress changes (Felzer & Brodsky, 2006). These stress changes can result from natural factors such as coseismic strain (Stein, 1999), interseismic and postseismic strain (Pollitz & Cattania, 2017), spontaneous aseismic strain transients (e.g. Lohman & McGuire, 2007), fluid pressure variations (Johnson et al., 2017), surface load variations due to hydrology

(Hainzl et al., 2013; Johnson et al., 2017; Luttrell et al., 2007), solid earth tides (e.g. Cochran et al., 2004; Beeler & Lockner, 2003; Ader et al., 2014), and thermoelastic strain (e.g. Ben-Zion & Allam, 2013). Earthquakes can also be induced by man-made activities (Brodsky & Lajoie, 2013; Wei et al., 2015). All these processes have been or can potentially be documented within the Salton Trough. Depending on the local heat flow, strain rate and geology, we

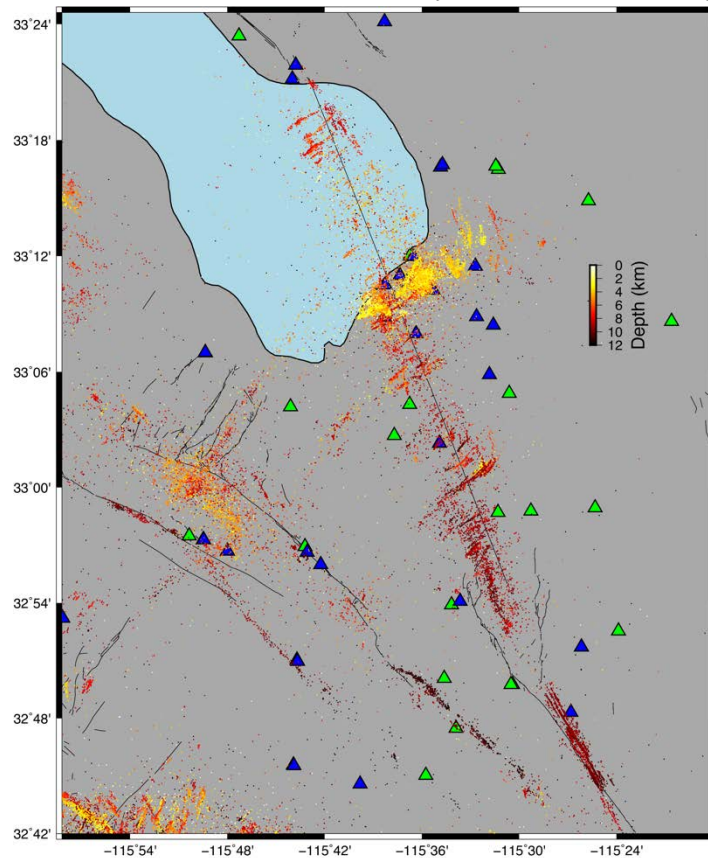


Figure 1. Map of the Salton Trough region. Relocated seismicity (2006-2016) is from the catalog of Hauksson et al. (2012). GPS and seismic stations are shown as green and blue triangles, respectively.

expect to see systematic variations of the characteristics of the seismicity such as sensitivity to forcing factors, the ‘swarminess’ of earthquake clusters, and the ratio of seismic and aseismic strain. While all these physical mechanisms may be capable of generating earthquakes, it is generally difficult to establish correlations because of the limited resolution of standard seismicity catalogs and the difficulty of extracting subtle geodetic signals. In a previous study focused on the Yuha Desert (Ross et al., 2017), we have shown that the joined analysis of seismicity catalogs obtained and geodetic time series provide a powerful means to identify spatio-temporal variations of seismicity and strain. In this particular case, two pulses of seismicity were found: one which migrated as $\log(t)$, characteristic of seismicity driven by afterslip and

another one \sqrt{t} a characteristic of seismicity driven by fluids. Analysis of the geodetic data revealed a coeval signal which must have been 93% aseismic. We expect to make similar findings when analyzing the data from the Salton Trough. Over the period 2008-2016, the regional catalog for the Salton Trough has only about 25,000 events, with a completeness magnitude of about M 1.5. Excluding the 2010 El Mayor-Cucapah sequence, there are only about 3-4 events per day on average. At these rates, significant variations in the background rate are difficult if not impossible to resolve, and for the most active clusters, the finer spatiotemporal details are often invisible. The catalog augmented with the template matching will be instrumental to the research proposed here.

Under this new research project we undertook a more comprehensive analysis of spatiotemporal variations in seismicity and strain in the Salton Trough using a template matching catalog spanning ten years. We examined both individual earthquake clusters and long-term variations in seismicity rate. The analysis aims at a better understanding of the physical processes driving seismicity in the Salton Trough and the potential diagnostic attributes of these processes.

Results

To reveal regional seismicity patterns in high-resolution, we used a template matching algorithm to detect previously unidentified earthquakes across the entire region over a ten year period (2008-2017).

Template matching (matched-filter) algorithms use existing seismograms of well-recorded earthquakes to correlate against continuous data and find weakly recorded (and previously unidentified) earthquakes (Peng & Zhao, 2009; Ross et al., 2017; Shelly et al., 2016). These methods typically identify an order of magnitude more events (e.g. Skoumal et al., 2015) than standard techniques like STA/LTA. The significantly expanded catalogs allow for detailed analyses of earthquake sequences and triggering that are impossible with standard catalogs. For example, in a standard catalog, a cluster of 10 events over a period of several days may have 100-200 events in a template matching catalog and would be now suitable for detailed analyses. As these methods are computationally intensive, they have been commonly applied to the most active earthquake sequences in relatively compact spatial regions to limit the amount of data to be processed.

We used the existing regional catalog of ~25,000 events as templates to build a new catalog with ~302,000 events (12x increase). To perform these calculations, we utilized an array of 180 NVIDIA graphical processing units (GPUs) with the method of Ross et al. (2017). The GPUs enabled efficient calculation of the cross-correlation functions over the sizable waveform dataset.

Further, there are 106 clusters with at least 200 events. These clusters are a mixture of mainshock-aftershock sequences and swarms, with many lasting only a few days or less. A most important aspects of the catalog is that it spans a full decade in time, which will allow for detailed statistical analyses with the potential to resolve weak, but persistent patterns present in the seismicity data.

The Salton Trough has excellent GPS coverage going back to at least 2006 (Fig. 1). However, they are notably dominated by the El Mayor-Cucapah sequence and its postseismic deformation, which continues even to the present day. We used an independent component analysis (ICA) technique (Gualandi et al., 2016) to analyze the time series, as it has proven extremely efficient in separating tectonic and non-tectonic signals, and detecting subtle geodetic signals correlated with earthquake swarms without resorting to parametric models (Gualandi et al., 2017a; Gualandi et al., 2017b; Larochelle et al., 2019).

We applied the ICA technique to the GPS data for all stations to identify the dominant temporal patterns common to all stations. Figure 2 shows the first three independent components from the time of the El Mayor-Cucapah earthquake until the 2012 Brawley Swarm. The first and third independent components contain postseismic deformation associated with El Mayor-Cucapah and its largest aftershock (M 5.7), while the second component contains a more periodic signal which could be related to thermoelastic strain or surface hydrology. These two possibilities are being evaluated. These three components explain most (>90%) of the variance in the GPS data across the network. We use these components and the residual signals (represented by higher order components from the ICA analysis) to analyze correlations with seismicity patterns.

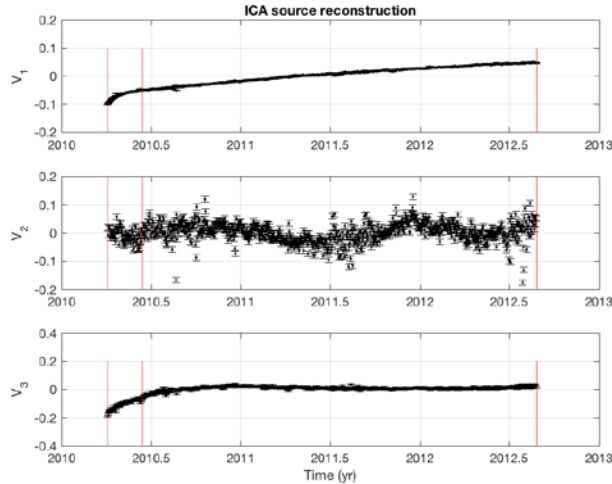


Figure 2. Application of the Independent Component Analysis technique to the GPS data. Each of the three independent components explains a portion of the variance common to all stations and GPS components in the region. The fact that the postseismic deformation shows up in at least two components indicates that the process is not stationary. This postseismic signal clearly has a seismicity signature. The seasonal component (V_2) could be due to surface hydrology or thermoelastic strain. In any case, the related stress variations could modulate seismicity.

We have used a Shuster test to evaluate eventual periodicities in the seismicity catalog and found no evidence for a detectable response to Earth tides and seasonal loading using the standard catalog of Hauksson et al. The analysis on the catalog obtained from template-matching is underway. Also, the analysis might require considering the focal mechanisms as different phases of the seismicity response are expected for different fault orientations (Bettinelli et al, 2007; Johnson et al, 2017).

2. Systematic analysis of earthquake clusters

To investigate the processes and properties that control the evolution of earthquake sequences, we focused on the 106 sequences in the catalog that contain at least 200 events. These sequences differ from typical repeating earthquake sequences (e.g. Nadeau and Johnson 1998) as they do not represent repeated rupture of the same patch; rather they are events of various sizes that are occurring nominally ~100 m from each other. For the region near the Imperial fault, there are more than 50 such families with at least 50 detections each (red dots, Figure 3). The cumulative temporal evolution of each family show a relatively steady rates over time. Other families exhibit more burst-like behavior and are dominated by often a single short-duration cluster. There is further some suggestion that the rates of these sequences are affected by the 2010 El Mayor-Cucapah and 2012 Brawley swarms. The potential relationship to creep at depth remains an important to investigate further as a next step.

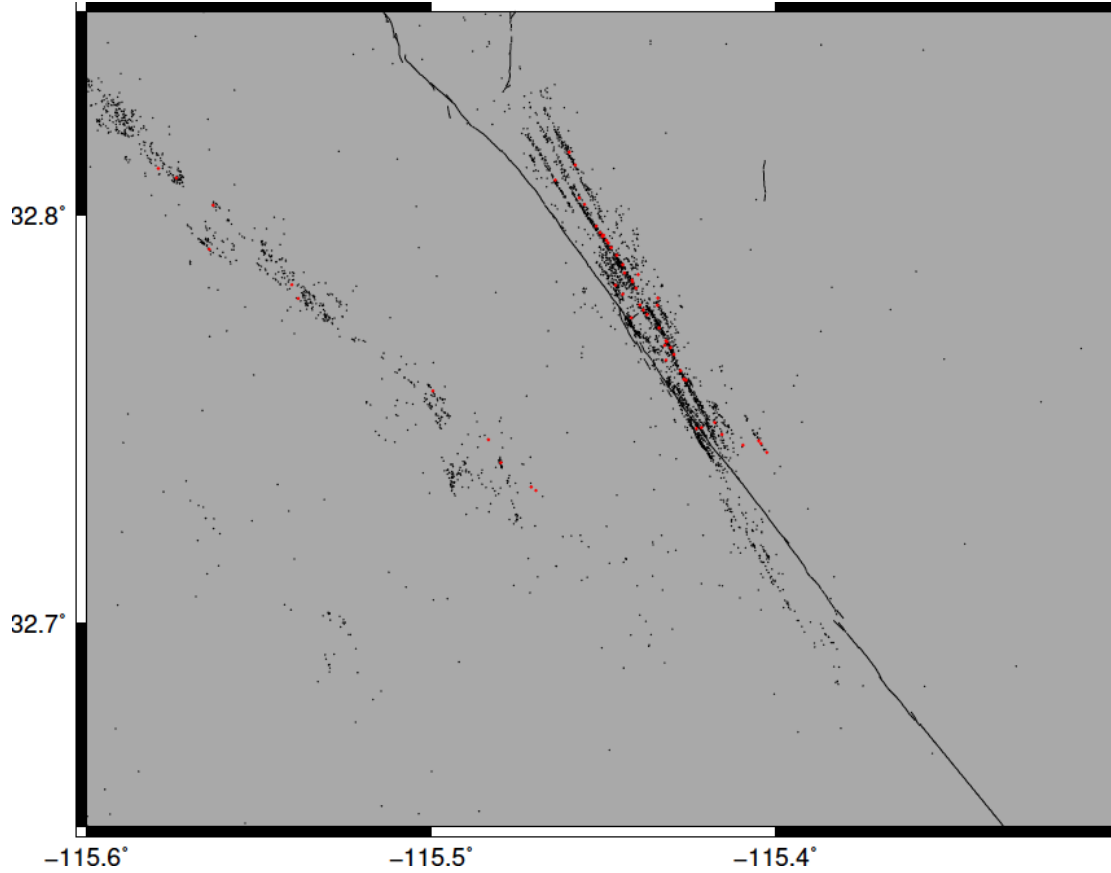


Figure 3. Relocated seismicity from in the Imperial fault region (black dots). Red dots indicate the locations of template events that detected more than 50 earthquakes over the 10 year period.

3. Interevent time statistics

We also analyzed interevent time distributions of the background seismicity to assess whether these events obey the expected Poisson statistics (Gardner and Knopoff, 1974). We used the method of Zialapina and Ben-Zion (2013) to extract the background seismicity (Figure 4) from the catalog of Hauksson et al. (2012). The interevent time distribution of this population of events fits the prediction from the Poisson model at short time interval, but show a very fat tail. We conducted that analysis at different scales (whole of Southern California, Imperial Valley, Brawley swarm area) and found this observation to be robust and systematic. We are investigating it further using the catalog derived from template matching. If robust, this observation will be evaluated in view of the loading rates derived from geodesy as the long quiescence could be expected from decelerated loading during postseismic relaxation. Alternatively it could relate to the earthquake nucleation process or interseismic healing.

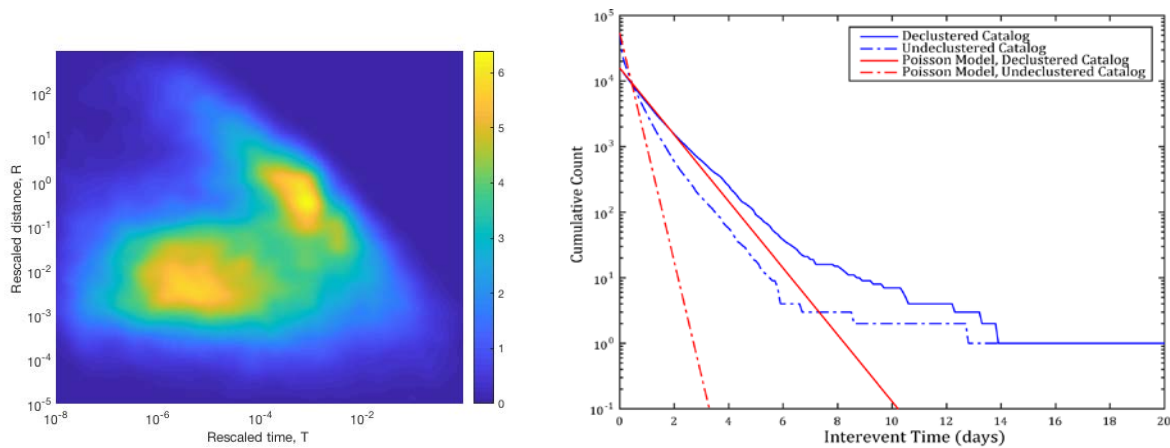


Figure 4. (left) Separation of background seismicity and clustered seismicity using the method of Zaliapin and Ben-Zion (2013), applied to the Catalog of Hauksson et al. (2012) for Southern California. (right). Interevent time distribution of total seismicity ('undeclustered') and background ('declustered') seismicity in Southern California from the catalog of Hauksson et al. (2012). The distribution fits better the prediction of the Poisson model for the declustered catalog. However we note a very fat tail that suggests period of persistent quiescence not predicted by the Poisson model.

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