SCEC Project 25295: Building a statewide creep rate model from repeating earthquake sequences and geodetic data

Final Report

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Abstract

The goal of the project was to work towards building a statewide creep rate model using slip rate estimates derived from geodetic data and repeating earthquakes. This work primarily involved the detection, characterization and validation of repeating earthquake families across the San Andreas Fault System, which can ultimately be combined with geodetic data to estimate the creep rate distributions on faults of interest. The combination of repeating earthquake information with geodetic data will improve our constraints on fault creep at all depths compared with either data type alone. In the project to date, we have analyzed over 7 million earthquake waveforms across the state of California, both north and south, and identified over 12,000 repeating earthquake families. Faults in southern California show very few repeating earthquakes, compared to the faults of the San Andreas system in central and northern California, likely reflecting a fundamental difference in fault zone properties and materials between the two regions. Results from this work will provide insight into how creep at depth is distributed across California faults, an important constraint on seismic potential and seismic hazard. The project was led by UC Riverside graduate student Norma Contreras, supervised by PI Gareth Funning.

Introduction and background

Repeating earthquakes (REs), collocated events with nearly identical waveforms, are quasi-periodic events thought to repeatedly rupture the same fault patch (Uchida and Bürgmann 2019). Such sequences of events are often associated with aseismic slip ("creep") and have been detected on various creeping faults in California, most famously in the Parkfield segment of the San Andreas fault (e.g. Nadeau et al., 1995), but also on other northern California faults (e.g. Templeton et al., 2008; Shakibay Senobari and Funning, 2019). Using calibrated, empirical relationships, the magnitudes and recurrences of REs can be used to estimate slip per event, and then slip rate, respectively (e.g. Nadeau and McEvily, 1999).

Information from REs is highly complementary to information from geodetic data, such as InSAR and GNSS velocities. While InSAR, in particular, can provide dense maps of surface deformation that can constrain surface creep rate at a high spatial resolution (e.g. Figure 1), the resolving power of such data degrades alarmingly with depth (i.e. resolution is effectively similar in scale to depth) for vertical strike-slip faults. REs, in contrast, can provide well-resolved point estimates of creep rate at such depths. The combination of the two data types, therefore has the potential to provide a significantly more comprehensive picture of the creep across California than would be possible with either data set alone.

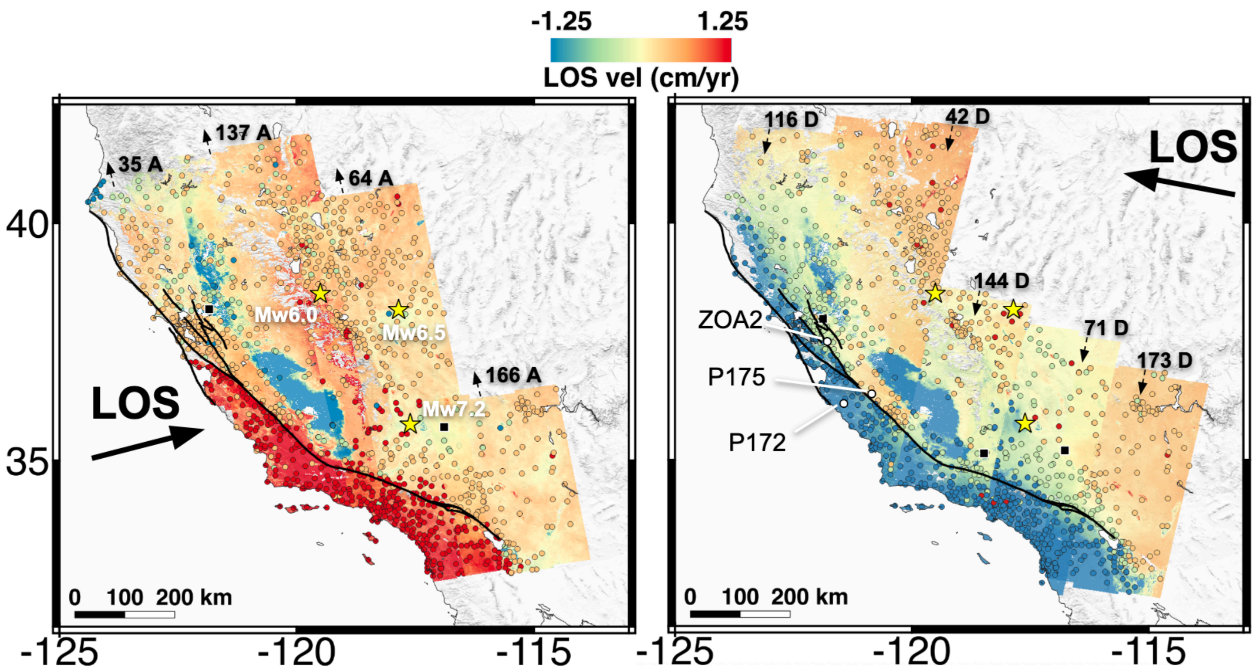

Figure 1: InSAR line-of-sight velocities from four ascending tracks (left) and five descending tracks (right) of the Sentinel-1 mission. Surface creep on the San Andreas fault is one of the most prominent signals that can be seen in the data. From Sangha et al. (2026; submitted to Earth and Space Science).

Building a repeating earthquake catalog

In our previous work, we have developed and refined our method for detecting REs based on pairwise similarity and hierarchical clustering (the "multistation cluster" method, Shakibay Senobari and Funning, 2019). Funning and Shakibay Senobari (2021), produced an automated code based on that method ('FARESearch' – Fully Automated Repeating Earthquake Search; and we use it here to compile RE catalogs for the full inventory of mapped Quaternary faults across California. At its core, the FARESearch method cross-correlates event waveforms against each other, and builds candidate families of REs based on high pairwise similarity of the waveforms between events.

We search for RE sequences along these faults using two different gridding approaches to subset the seismicity involved in similarity comparisons, tailored to the fault orientation and degree of cross-cutting faults in each region. In northern California, where many of the faults run sub-parallel to the San Andreas fault, we apply a simple gridding approach that divides a region into grid cells based on event density. We found that this gridding method is not efficient in the southern California region, where fault systems are cross-cutting. We developed a new gridding algorithm for this region that uses a quadtree approach to divide a region into grids based on event density and grid area; areas with denser seismicity being divided into smaller grid cells. Once we identify candidate REs, we remove “doublets”, or RE sequences with two events. We assume that these are false positives, and discard them from our final catalogs. To estimate the long-term creep rate for a given fault we filter sequences according to their degree of periodicity and continuity following the methodology of Waldhauser & Schaff (2021) to identify quasi-periodic sequences. These sequences should have a semi-periodic recurrence interval and should have events that span the observation period (1984 to 2022). Note that we do not attempt to locate REs within regions with seismic swarms, as we do not expect these to contain long-duration REs. This filtering process removes “burst-type” sequences, i.e. short-duration sequences clustered in time, and leaves RE sequences that represent the long-term creep rate along a fault.

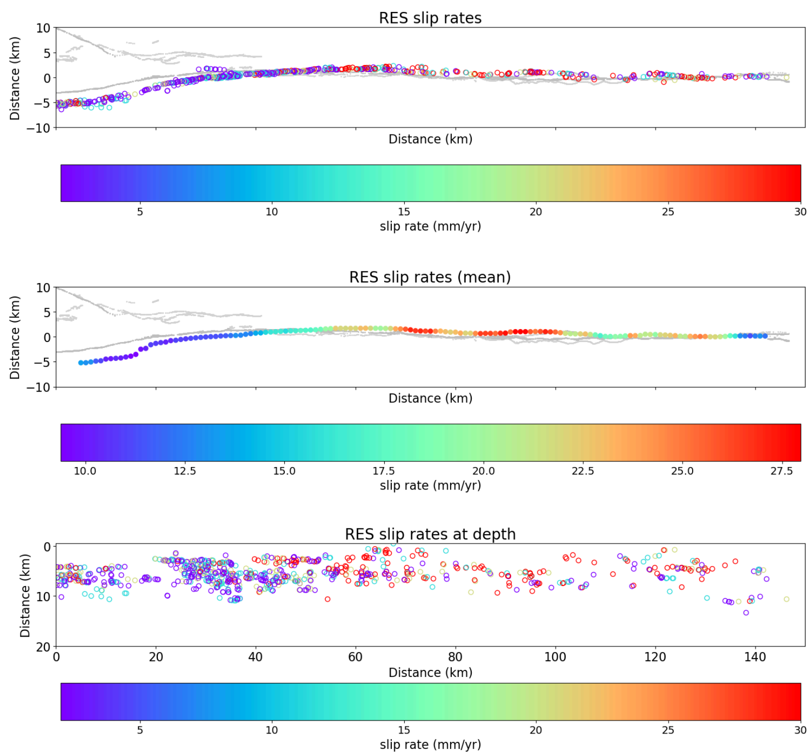

Figure 2: An example of the creep rate estimated using quasi-periodic RE sequences. Shown are quasi-periodic RE sequences for the central San Andreas fault. Sequences are color-coded according to their estimated slip rate (top and bottom panels) which is then averaged along the fault (middle panel). Slip rates overall match known creep rate estimates for this fault.

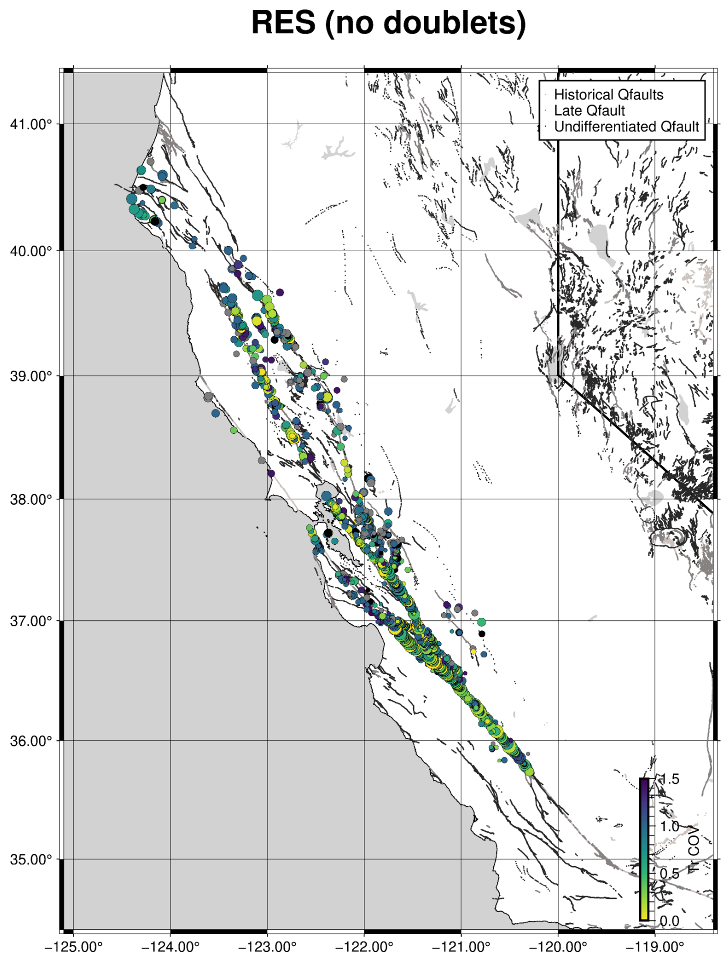

Figure 3: RE sequences identified in regions north of the San Andreas fault's big bend region. Color-scale is the same as in figure 2. Note that asymmetrical station distribution, especially around coastal regions (e.g. around the Mendocino triple junction), may result in false-positives, i.e. events that appear as REs but are not.

The first order pattern of repeating earthquake families across California

We find that long-duration, semi-periodic RE sequences in our catalogs largely align with known creeping faults (e.g. Hayward and Calaveras faults). RE sequences in northern California exhibit more periodic behavior (lower recurrence interval COV values), and are present for longer periods (>10 years). RE sequences in southern California, on the other hand, mostly consist of short-duration (<2 years) "burst-type" sequences (figure 4). As a result, these sequences are clustered in time, indicating that they do not represent long-term creep. In northern California, RE sequences show sensitivity to local large magnitude events, appearing as a change in their recurrence interval. Along the Calaveras fault, for example, RE sequences can be observed accelerating following the 1984 M6.1 Morgan Hill and 2007 M5.5 Alum Rock earthquakes, followed by a gradual decay in the recurrence interval between consecutive REs. This pattern is not as clearly observed in southern California, where few sequences are active for more than 10 years, making it more difficult to observe RE response to nearby seismicity. Note that a group of RE sequences that satisfy the periodicity and continuity requirements can be found to the southwest of the Salton Sea, along the southern end of the San Jacinto fault (figure 3).

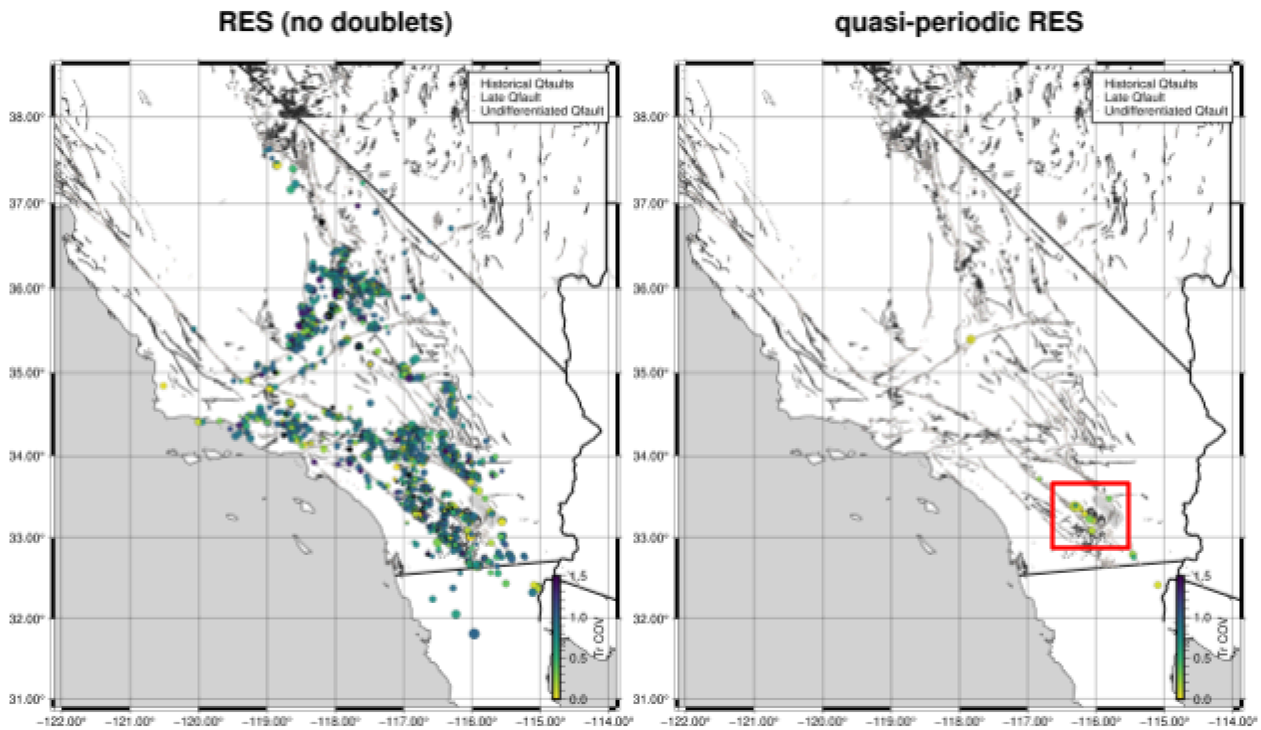

Figure 4: RE sequences identified in the Walker Lane and south of the San Andreas fault's big bend region. (Left) RE sequences identified in the specified regions color-coded according to the coefficient of variation value for the recurrence interval (Tr COV). (Right) Quasi-periodic RES for the same region. The red box denotes a group of quasi-periodic REs on the San Jacinto fault. Note that the color-scale in both maps is capped at a COV value of 1.5 for illustration purposes. Some sequences may have higher COV values. A lower COV value indicates a sequence is periodic, while a higher value indicates it is clustered in time. Event locations are taken from the double-difference catalog of Waldhauser and Schaff (2008).

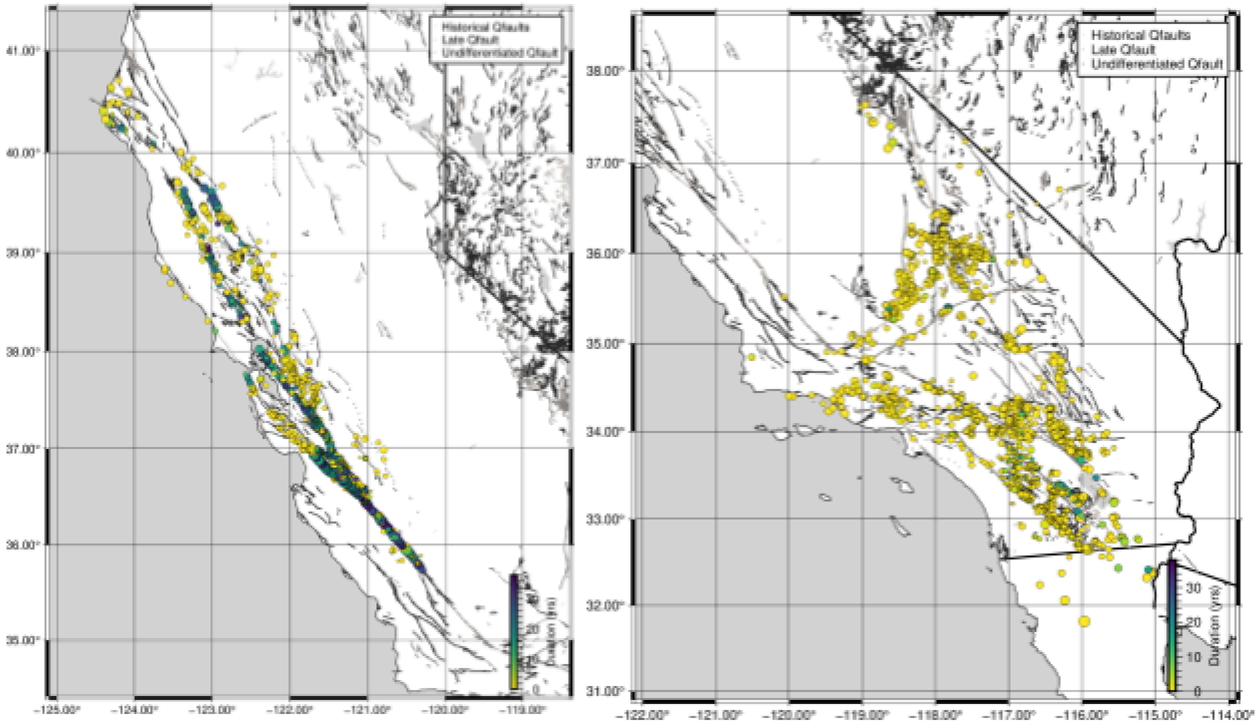

Figure 5: RE sequences for northern California (left) and southern California (right). Sequences are color-coded according to their duration (time elapsed between the first and last event in a sequence).

Conclusions and future work

We searched for RE sequences over California and identified over 102,110 individual REs which can be clustered into 12,011 candidate RE sequences. RE sequences that exhibit semi-periodic behavior and are continuous throughout the observation period are likely representative of creeping behavior along the host faults. As expected, these quasi-periodic sequences are mostly found along well-documented creeping faults, the majority of which reside in northern California. Many of these sequences also show an initial acceleration followed by declaration in the interevent recurrence intervals as a response to local large-magnitude events. RE sequences in southern California are mostly “burst-type” sequences that are not likely to represent creeping behavior. The aperiodic RE sequences found in southern California, however, may reflect a response to transient activity such as geothermal activity or isolated creep events. It is also possible that RE sequences in this region may have recurrence intervals that exceed the length of our observation period, or have recurrence intervals that did not allow us to capture the minimum required 3 events. Overall, our statewide RE catalog largely agrees with the location of known creeping faults.

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