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Triggering of repeating earthquakes in central California

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Key Points:
- We found weak correlation of perturbations and shortened recurrences
- The weak correlation exists for perturbations > ~20 KPa
- The weak correlation exists for both nearby and remote perturbations

Supporting Information:
- Readme
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6

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Abstract Dynamic stresses carried by transient seismic waves have been found capable of triggering earthquakes instantly in various tectonic settings. Delayed triggering may be even more common, but the mechanisms are not well understood. Catalogs of repeating earthquakes, earthquakes that recur repeatedly at the same location, provide ideal data sets to test the effects of transient dynamic perturbations on the timing of earthquake occurrence. Here we employ a catalog of 165 families containing ~2500 total repeating earthquakes to test whether dynamic perturbations from local, regional, and teleseismic earthquakes change recurrence intervals. The distance to the earthquake generating the perturbing waves is a proxy for the relative potential contributions of static and dynamic deformations, because static deformations decay more rapidly with distance. Clear changes followed the nearby 2004 M_w6 Parkfield earthquake, so we study only repeaters prior to its origin time. We apply a Monte Carlo approach to compare the observed number of shortened recurrence intervals following dynamic perturbations with the distribution of this number estimated for randomized perturbation times. We examine the comparison for a series of dynamic stress peak amplitude and distance thresholds. The results suggest a weak correlation between dynamic perturbations in excess of ~20 kPa and shortened recurrence intervals, for both nearby and remote perturbations.

1. Introduction

Dynamic triggering of the earthquakes and nonvolcanic tremors has been widely observed in various tectonic settings [*Hill and Prejean*, 2007; *Peng and Gomberg*, 2010, and references therein]. In many cases, the triggering relationship is established by the occurrence of the local earthquakes or tremor during the passage of large-amplitude surface waves of distant earthquakes [*Velasco et al*., 2008; *Peng et al*., 2009; *Wu et al*., 2011], which can be explained by frictional failure on critically stressed faults via the Coulomb failure criteria [*Hill*, 2008, 2010]. However, in many cases, the elevated seismicity rates are identified after the passage of surface waves, and the mechanisms for such delayed triggering are still unclear [*Hill and Prejean*, 2007]. Possible mechanisms include fault zone frictional contact changes [*Parsons*, 2005], pore fluid redistribution [*Brodsky and Prejean*, 2005], aftershocks of instantly triggered events [*Brodsky*, 2006], multiple surface waves circling the Earth [*Peng et al*., 2011], and nonlinearly induced elastic changes in the fault gouge induced by seismic waves that destabilize the material [*Johnson and Jia*, 2005].

Repeating earthquakes have been identified near Parkfield, CA [*Nadeau et al*., 1995; *Lengline and Marsan*, 2009; *Rubinstein et al*., 2012a; *Chen et al*., 2013; *Turner et al*., 2013], in numerous other regions [e.g., *Peng and Ben-Zion*, 2005; *Schaff and Richards*, 2011; *Yamashita et al*., 2012; *Yu and Wen*, 2012; *Yu*, 2013] and in the laboratory [*Savage and Marone*, 2008; *Rubinstein et al*., 2012b; *Johnson et al*., 2013]. A repeating earthquake family is a group of events with similar waveforms, epicenters, and magnitudes, resulting from repeated ruptures of the same patch of fault or nearly the same patch [*Nadeau and Johnson*, 1998]. Repeating earthquakes provide a useful case to understand the earthquake cycle and interactions, given the nature of fixed source and quasiperiodic recurrences [*Lengline and Marsan*, 2009]. Previous studies have found that the 1984 $M_w6.2$ Morgan Hill, 1989 $M_w6.9$ Loma Prieta, and 2004 M_w6 Parkfield earthquakes significantly reduced the recurrence times of nearby repeating earthquakes [*Schaff et al*., 1998; *Peng and Ben-Zion*, 2005; *Lengline and Marsan*, 2009; *Chen et al*., 2010b]. *Chen et al*. [2010a] found that nearby moderate (*M*4–5) earthquakes could also shorten the recurrence times of repeating earthquakes in Parkfield. Laboratory studies also show the same phenomenon under certain stress conditions [*Johnson et al*., 2012].

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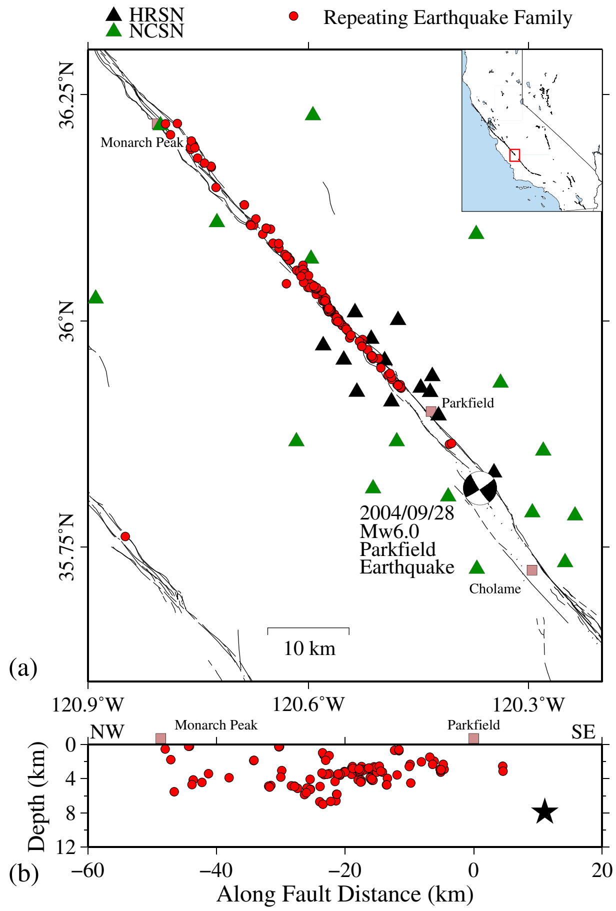

Figure 1. (a) Map of the study region of central California. The solid red circles show the locations of the 165 repeating earthquake families used in this study. The epicenter of the 2004 M_w6.0 Parkfield earthquake is indicated by the moment tensor solution. The black and green triangles show the locations of the High-Resolution Seismic Network and Northern California Seismic Network stations, respectively. The black lines indicate active faults, and the brown squares mark towns. The inset is a map of California with the red box showing the region plotted in the main map. (b) Cross-section view along the SAF with the 2004 Parkfield earthquake hypocenter (black star) and the hypocenters of the 165 repeating earthquake families (red circles). The other symbols are the same as in Figure 1a.

Recently, Chen *et al.* [2013] investigated the triggering effect of nearby seismicity on repeating earthquakes and found that nearby earthquakes had negligible effect on the regularity of the recurrence of repeating earthquakes when their cumulative static stress changes were considered, but individual high-stress changes shortened intervals. They found no repeating earthquakes triggered during the passage of seismic waves from nearby seismicity, but they also suggested that delayed dynamic triggering could not be ruled out [*Chen et al.*, 2013]. We hypothesized that the irregularity in repeating earthquake recurrence intervals may also reflect dynamic perturbations from more remote earthquakes, but the subtlety of their impact requires additional statistical analyses.

Here we examine a repeating earthquake catalog of 165 repeater families with ~2500 repeating earthquakes to investigate the delayed triggering effects of dynamic perturbations of passing seismic waves on repeating earthquake recurrence. We use a Monte Carlo method to test whether dynamic perturbations shorten the recurrence intervals of repeating earthquakes. We present evidence of a possible, but weak correlation between the dynamic perturbations and the shortened recurrence times. We then discuss several possible explanations for the observations.

2. Data and Analysis Procedure

2.1. Repeating Earthquake and Perturbing Earthquake Catalogs

We employ the repeating earthquake catalog developed by *Lengline and Marsan* [2009], who identified repeating earthquake "families" based on three criteria: (1) identical rupture sizes, (2) identical recorded waveforms, and (3) overlapping sources. The data set contains 334 families with 2414 repeating earthquakes from 1984 to 2006. The repeating earthquake sources generally locate along the San Andreas Fault (SAF; Figure 1). The magnitudes of the repeating earthquakes range from ~1 to 3, and the depths are generally shallower than ~7 km. Additional details about the data set are given by *Lengline and Marsan* [2009].

We considered potential perturbations to the recurrence intervals of Parkfield repeating earthquakes associated with global earthquakes in the Advance National Seismic System (ANSS) catalog from 1984 to 2006. The magnitudes of the perturbing earthquakes range from 4 to 9, and the depths are generally shallower than ~200 km. The ANSS catalog was obtained from the Northern California Earthquake Data Center website (http://www.ncedc.org/anss/catalog-search.html).

2.2. Analysis Procedure

We selected repeating earthquakes before the 2004 Parkfield earthquake to exclude the large influence of the local M_w6 earthquake [*Lengline and Marsan*, 2009; *Chen et al.*, 2010b] and required at least 4 repeating

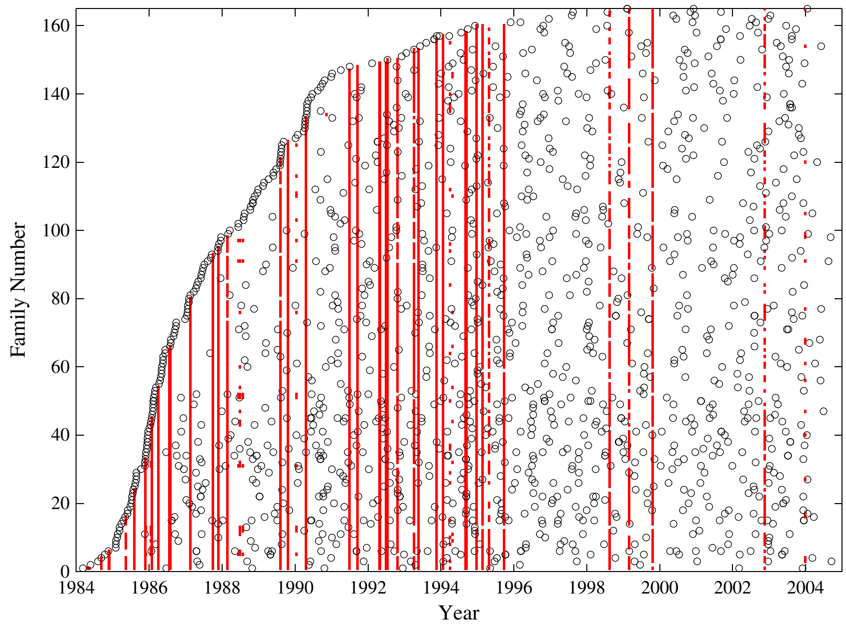

Figure 2. The timing of all the repeating earthquakes and dynamic perturbations. Each row (*y* value) corresponds to a repeating earthquake family, with recurrence times shown as black circles. The vertical red lines show the timing of dynamic stress perturbations larger than 20 kPa. Some of the vertical red lines are fragmented because the earthquake only caused dynamic stress perturbations larger than 20 kPa for some families.

earthquakes in each family to estimate the variability in recurrence intervals. This resulted in 165 families with 1364 repeating earthquakes (Figure 2).

We estimated the dynamic stresses imposed by global $M > 4$ earthquakes on each repeating earthquake family based on the perturbing earthquake's magnitude and distance from the family's location, following *van der Elst and Brodsky* [2010]. For near-field perturbing earthquakes (within 800 km), we use the empirical ground motion regression equation

$$\log_{10} PGV = -2.29 + 0.85M - 1.29\log_{10} R \tag{1}$$

where *PGV* is the peak ground velocity in cm/s, *M* is the moment magnitude of the perturbing earthquake, and *R* is the hypocentral distance in kilometer, to estimate the ground velocity [*Campbell and Bozorgnia*, 2007]. For far-field perturbing earthquakes (beyond 800 km), as the ground motion is dominated by the long-period surface waves, we use the surface wave magnitude relation

$$\log_{10} A_{20} = M_S - 1.66\log_{10} D - 2 \tag{2}$$

where A_{20} is the ground displacement of surface waves at 20 s period, M_S is the surface wave magnitude, and *D* is the epicentral distance in degree [*Lay and Wallace*, 1995]. Then the ground displacement is converted to ground velocity using the approximation

$$PGV \approx 2\pi A_{20}/T \tag{3}$$

where $T = 20$ s [*Aki and Richards*, 2002]. We convert the *PGV* of both near- and far-field perturbing earthquakes to dynamic stress using the equation

$$DS = PGV \times G/V \tag{4}$$

where *DS* is dynamic stress, *G* is the shear modulus, which is assigned as a nominal value of 30 GPa, and *V* is the phase velocity assumed to be 3.5 km s^{-1} [*Hill et al.*, 1993]. We kept only the perturbations with dynamic stress greater than 1 kPa, which is slightly lower than the smallest dynamic stress capable of triggering earthquakes and tremor [*Peng et al.*, 2009], resulting in ~10^5 perturbations. A total of 5212 perturbations with dynamic stress larger than 20 kPa exist in the catalog, from 65 perturbing earthquakes (Figure 2 and Figure S1 in the supporting information).

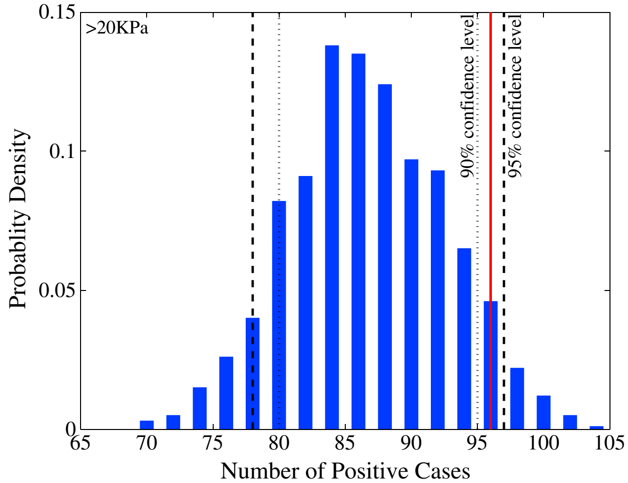

Figure 3. Monte Carlo results for a dynamic stress perturbation threshold of 20 kPa. The blue bars show probability distribution function of the 1000 counts of perturbations that occur within shortened recurrence intervals, derived using perturbations with their times randomized. The vertical black dashed and dotted lines show the 5%–95% and 10%–90% levels, respectively. The vertical red line marks the observed count.

Next we use a Monte Carlo method to test whether the perturbations affect the recurrence times of the repeating earthquakes. We first separated the repeating earthquakes in each family into two groups: (1) perturbed, when there are one or more perturbations between the repeating earthquake and the preceding repeating earthquake and (2) unperturbed, when there is no perturbation between repeating earthquakes. We then obtain the recurrence times for all the repeating earthquakes (except the first one in each family), and we estimate a reference recurrence time for each family using the mean recurrence interval of all the unperturbed repeating earthquakes in the family. We require at least two unperturbed events to estimate the variance in the reference interval. We compare the recurrence intervals of the perturbed repeating earthquakes with the reference interval for that family and count the number (N_0) of perturbed repeating earthquakes with recurrence times shorter than the reference value (positive cases, see Figure S2 in the supporting information).

To compare N_0 with the count of shortened intervals expected by chance, we derived a distribution of shortened intervals containing dynamic perturbations (positive cases) by randomizing the perturbation times. We randomized the timing of all the perturbed intervals using a standard uniform distribution randomization scheme and repeated the above procedure to obtain the number of positive cases generated by these random perturbations. We generate a distribution of values by repeating this process a thousand times, using newly randomized perturbation times for each estimate of N_i, $i = 1–1000$. We also repeat the test using only perturbations that exceed specified stress or distance values, within certain stress ranges, and with only families with relatively lower coefficient of variance (COV) of recurrence time. Distance in these tests serves as a proxy for the relative contributions of static and dynamic stress changes, noting that dynamic stresses decrease with distance much more slowly than static stress changes.

3. Results

Figure 3 shows the Monte Carlo test result using all the 165 repeating earthquake families and all perturbations larger than 20 kPa. Figure 3 shows that the number of shortened perturbed intervals from the 1000 trials using randomized perturbations ranges from ~70 to ~104, with the 90% and 95% confidence levels at 95 and 97, respectively (i.e., 90% of the 1000 randomizations yield N values less than 95). For the real perturbations, $N_0 = 96$ out of 142 perturbed events, which lies between the 90% and 95% confidence levels (Figure 3). Our results suggest that the observed patterns of perturbation and repeater times could be weakly correlated. We also tested using a gamma distribution randomization scheme, and the results do not show substantial differences (Figure S3 in the supporting information).

The test result using different dynamic stress thresholds with no distance restriction is shown in Figure 4a. The observed values of perturbed shortened intervals correspond to confidence levels derived from randomized distributions that increase from ~70% to ~90% when the dynamic stress thresholds increase from 1 kPa to ~20 kPa. As noted above, for thresholds $>$ ~20 kPa, the observed values are in the 90–95% range, indicating that the weak correlation starts at the threshold of ~20 kPa and persists for higher thresholds. Figure 4b shows the results using different minimum distance thresholds for a stress threshold of 20 kPa. The observed case are generally in the ~90–100% range of the randomized distributions, even when we only select perturbations beyond 200 km, where static stress changes are likely insignificant (Figure 4b).

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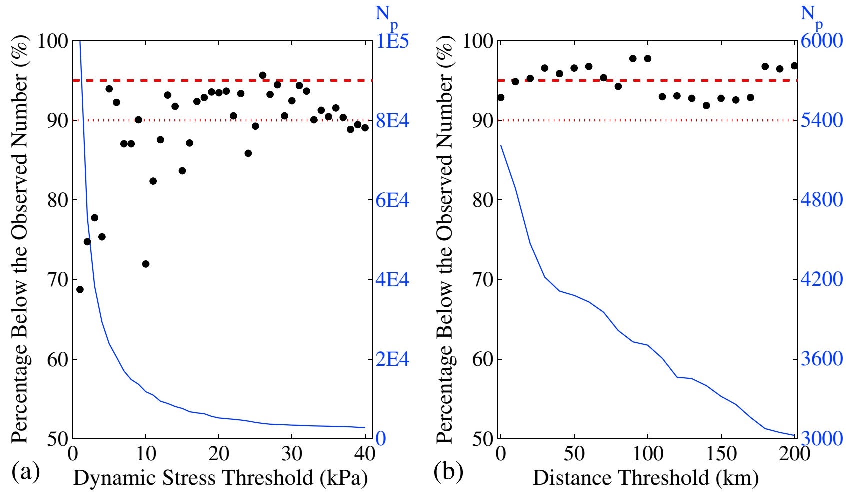

Figure 4. (a) Monte Carlo test results using different dynamic stress thresholds. Black circles show the fraction of the distribution of counts derived with randomized perturbation times below the observed count. The blue curve shows the number of perturbations (N_P) for each dynamic stress threshold. The horizontal red dashed and dotted lines mark the 95% and 90% levels, respectively. (b) Similar plot as in Figure 4a using different distance thresholds.

We repeated the test by selecting perturbations within certain dynamic stress ranges to exclude the influence of large perturbations, and the results show only slightly lower percentages than using lower thresholds of dynamic stresses (Figure S4 in the supporting information), suggesting that the results shown in Figure 4a are not dominated by the influence of large perturbations. The test results by selecting only families with relatively lower COV of recurrence time suggest no strong dependence of the results on COV threshold, except when we use a very low COV threshold (0.2) with 20 families, which have only limited samples of perturbed repeaters for the Monte Carlo test (Figure S5 in the supporting information).

4. Discussion

Our results suggest that dynamic perturbations may shorten recurrence intervals, based on the comparisons between observed numbers of shortened intervals containing perturbations and distributions derived from randomized perturbation times. We find that the observed numbers generally lie in the ~90–95% range of the randomized distributions (Figure 4), indicative of a possible correlation that has weak statistical significance [*Zar*, 1984].

Previous studies have not investigated the effects of remote perturbations on the recurrence of repeating earthquakes. *Chen et al*. [2010a] showed that the recurrence intervals of the repeating earthquakes were most likely to be shortened by nearby *M*4–5 earthquakes within a distance of ~5 km and attribute these observations to the static stresses induced by the *M*4–5 events. *Chen et al*. [2013] extended the investigation to *M*1–4 events and found that only static stress perturbations $>$ ~30 kPa shortened recurrence intervals. *Chen et al*. [2013] suggested that both static stress and aseismic afterslip play important roles in triggering and that triggering by dynamic stress is not likely significant but cannot be ruled out.

In this study we found a weak correlation between the dynamic perturbations and shortened recurrence intervals. The minimum dynamic stresses showing weak correlation with shortened recurrence time are ~20 kPa (Figure 4a), similar to the static stress triggering threshold inferred by *Chen et al*. [2013]. However, the actual triggering threshold for the Parkfield repeaters could be lower than 20 kPa due to observational limitations. When potential perturbations from all distances are included (Figures 3 and 4a), the weak correlation could be due to a combination of dynamic and positive static stresses, as we cannot distinguish between these for nearby events. On the other hand, the observation that the weak correlation does not change appreciably as the distance to the source of the perturbing waves increases (Figure 4b) indicates that the dynamic stresses may be important. If important at larger distances, we infer that they must be important at all distances, as only the characteristics of the waves at the affected faults matter (i.e., the faults have no knowledge of how far the waves traveled to the fault).

A “clock-advance” model has been used to explain triggered earthquakes and tremor [e.g., see *Gomberg*, 2010, and references therein], in which triggered events are simply inevitable failures that happen early due to the loading from passing seismic waves. While most often the model has been applied to a population of sources that each fail in turn at some steady ambient rate, the repetitiveness and regularity of repeating earthquakes are perhaps even more consistent with the assumptions of inevitability and steady ambient rate [*Chao et al*., 2013]. If preceding dynamic stress perturbations clock advanced some of the Parkfield repeating earthquakes, the delay between the perturbation and repeater failure implies that the perturbation either weakened the fault or altered conditions around it [*Dieterich*, 1994; *Johnson and Jia*, 2005; *Brenguier et al*., 2008] rather than simple Coulomb failure being responsible [*Hill*, 2008, 2010]. We did not observe clear instantly triggered repeating earthquakes (Figure 2), which are consistent with the lack of instant triggering of regular earthquakes in the Parkfield region [*Peng et al*., 2009]. However, we cannot rule out the possibility that the lack of instantly triggered earthquakes could be due to the incompleteness of the catalog. The shortest delay time between a perturbation and the following repeating earthquake is ~7.5 min, and the delay times less than ~1 day are very rare (Figure S6 in the supporting information). We surmise that gouge material destabilization induced by seismic waves may be responsible for the observed triggering delays as has been observed in laboratory [*Gomberg and Johnson*, 2005; *Johnson et al*., 2008], discrete element model studies [*Ferdowsi et al*., 2013], and brittle-ductile frictional modeling studies [*Trugman et al*., 2013]. Fluid effects may help modulate this behavior, but central California is not a geothermal region, so mechanisms involving pore fluid redistribution and pore pressure changes may not be as important as in geothermal regions [*Taira et al*., 2009].

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