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# Variations in rupture process with recurrence interval in a repeated small earthquake

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**In theory and in laboratory experiments, friction on sliding surfaces such as rock, glass and metal increases with time since the previous episode of slip[1]. This time dependence is a central pillar of the friction laws widely used to model earthquake phenomena[2,3]. On natural faults, other properties, such as rupture velocity[4,5], porosity and fluid pressure[6–11], may also vary with the recurrence interval. Eighteen repetitions of the same small earthquake, separated by intervals ranging from a few days to several years, allow us to test these laboratory predictions *in situ*. The events with the longest time since the previous earthquake tend to have about 15% larger seismic moment than those with the shortest intervals, although this trend is weak. In addition, the rupture durations of the events with the longest recurrence intervals are more than a factor of two shorter than for the events with the shortest intervals. Both decreased duration and increased friction are consistent with progressive fault healing during the time of stationary contact.**

We analyse 18 nearly identical earthquakes that occurred between July 1980 and September 1991 (Table 1). The events were about magnitude 1.5, and were on the Calaveras fault near the southern end of the magnitude-6 1984 Morgan Hill earthquake aftershock zone[12]. They had identical right-lateral strike-slip mechanisms, which is usual for the Calaveras fault, and are isolated by >100 m from the nearest earthquakes of comparable or larger magnitude.

All seismograms were recorded by the short-period vertical-component stations of the Northern California Seismic Network (Fig. 1). The locations of the earthquakes centroids, or geometric centre of moment release, estimated by waveform cross-correlation[13], all lie within 20 m. Each station recorded nearly identical records for all the events. The similarity extends from the initial P arrival throughout the S wave and the coda. Even the nodal arrivals have nearly identical waveforms. Typical cross-correlation coefficients for recordings of multiple events at a common station are in the range of 0.95 to 1.0. The high degree of similarity allows sensitive measurement of differences between the events.

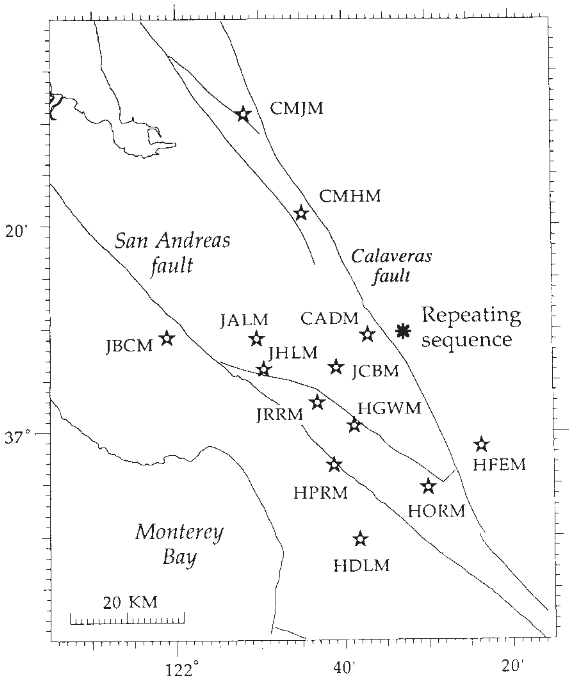

FIG. 1 Map showing the location of the 18 repeating earthquakes and the 13 Northern California Seismic Network (NCSN) stations used in this study. The depth of the earthquakes is 6 km.

We infer that the fault is most probably creeping aseismically in the region immediately surrounding the zone, as is the case for other creeping faults in central California[14]. As the fault creeps in the annular zone surrounding the frictionally locked patch, it repeatedly concentrates shear stress on the same patch, which eventually fails in an earthquake.

The first of the 18 events occurred nearly 4 years before the 24 April 1984 Morgan Hill earthquake[12]. The next 9 occurred in the first 7 months of the Morgan Hill earthquake aftershock sequence at steadily increasing intervals that ranged from 2.5 to 79 days. The rapid lengthening of the intervals follows the empir-

TABLE 1 Earthquake parameters

| Event date | Time (UT) | Relative moment | Duration (s) | Interval (d) |
|---|---|---|---|---|
| 26 Jul. 1980 | 20:04 | 0.92 | 0.037 | ? |
| 26 Apr. 1984 | 14:28 | 0.95 | 0.027 | 2 or 1,370 |
| 29 Apr. 1984 | 04:09 | 0.87 | 0.052 | 3 |
| 3 May 1984 | 22:56 | 1.00 | 0.043 | 5 |
| 12 May 1984 | 08:37 | 1.07 | 0.033 | 9 |
| 27 May 1984 | 18:44 | 0.94 | 0.056 | 15 |
| 13 Jun. 1984 | 21:53 | 0.89 | 0.043 | 17 |
| 15 Jul. 1984 | 05:22 | 0.90 | 0.038 | 32 |
| 3 Sep. 1984 | 08:34 | 1.04 | 0.036 | 50 |
| 22 Nov. 1984 | 21:03 | 1.10 | 0.030 | 79 |
| 21 Oct. 1985 | 13:52 | 0.92 | 0.032 | 334 |
| 15 Jun. 1986 | 18:30 | 1.10 | 0.021 | 237 |
| 19 Jan. 1987 | 08:28 | 1.22 | 0.030 | 217 |
| 9 Feb. 1987 | 22:08 | 0.96 | 0.030 | 21 |
| 21 May 1987 | 04:41 | 0.60 | 0.037 | 99 |
| 4 Jul. 1988 | 13:53 | 1.22 | 0.024 | 410 |
| 7 Jan. 1990 | 17:15 | 1.10 | 0.023 | 552 |
| 21 Sep. 1991 | 10:37 | 1.04 | 0.018 | 648 |

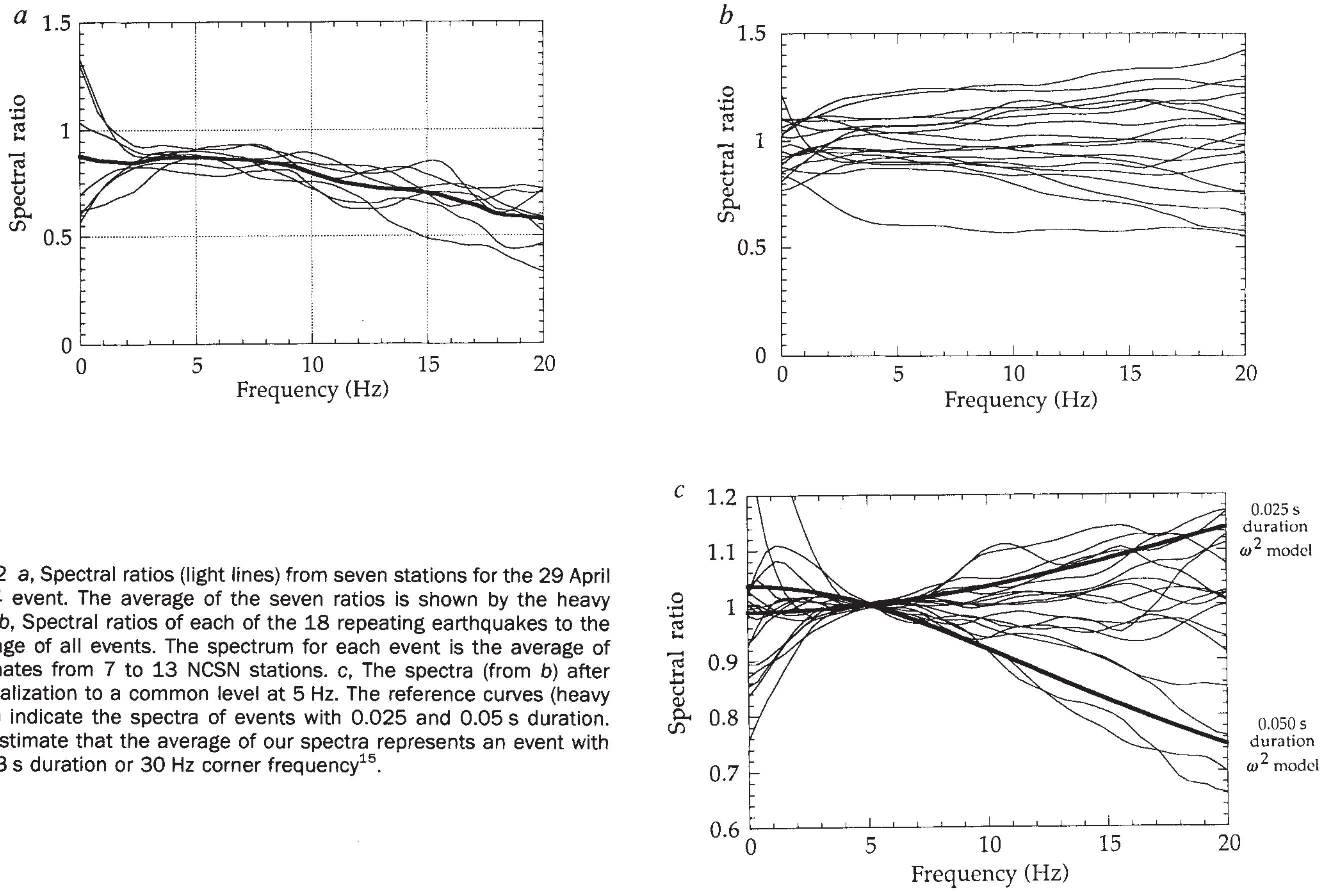

FIG. 2 *a*, Spectral ratios (light lines) from seven stations for the 29 April 1984 event. The average of the seven ratios is shown by the heavy line. *b*, Spectral ratios of each of the 18 repeating earthquakes to the average of all events. The spectrum for each event is the average of estimates from 7 to 13 NCSN stations. *c*, The spectra (from *b*) after normalization to a common level at 5 Hz. The reference curves (heavy lines) indicate the spectra of events with 0.025 and 0.05 s duration. We estimate that the average of our spectra represents an event with 0.033 s duration or 30 Hz corner frequency[15].

ical decay in earthquake rate in aftershock sequences, which is inversely proportional to time elapsed from the main shock. The remaining events occurred at irregular intervals during the next 7 years.

We measure the differences between the events by calculating the ratios of spectra of individual recordings to averaged spectra for each station. This is accomplished by assembling the records of all events from a given station, aligning the first peak, and extracting a 2.56-s window. The mean and trend are removed, the ends of the window are tapered and the amplitude spectra are calculated. The station average is calculated by linearly averaging all records for each station. Finally, the spectral ratios are calculated for every station for each event. Only the most stable stations are used, and only the most noise-free traces included. About half of the available seismograms are retained. Figure 2*a* illustrates this process for an event with less than average high-frequency radiation.

Figure 2*b* shows the spectral ratio of each event to the average for all 18 events. The differences for lower frequencies, 3–7 Hz, are due to differences in seismic moment between events. The relative moments are measured from the spectral ratio amplitude at 5 Hz (Table 1). The coefficient of variation, which is the ratio of the standard of deviation to the mean, is 0.15.

We have confirmed the significance of the differences apparent in Fig. 2*b* and *c* by a similar analysis of another sequence with 13 repeating earthquakes a few kilometres away that occurred from 1984 to 1993. This second sequence of earthquakes shows much less variation in spectral slope, showing that the seismic propagation to the stations is unchanged over time, and the response of the recording system is stable. In addition, examination of the spectra of this second sequence, whose events have very short durations, and several nearby earthquakes of magnitude 0.5 to 1.0, allows us to estimate the absolute durations of the 18-event sequence, which average ~0.033 s.

The corner frequency, which is the reciprocal of the duration of faulting, is usually measured from spectra that extend well above the corner frequency. Although the corner frequencies of these earthquakes (20–50 Hz) are higher than the pass-band of our data (3–20 Hz), the high correlation between the seismograms permits accurate measurement of the subtle differences in spectral level at frequencies below the corner frequency, thus allowing us to estimate source duration. As illustrated in Fig. 2*c*, we estimate duration by comparing the observed ratio of spectral amplitudes at 5 and 15 Hz with the results for a range of $\omega^2$ source models[15] with different durations.

The durations range from 0.018 to 0.056 s, or by about a factor of three. A similar calculation with the less popular $\omega^3$ source model[15] yields a factor of about two variation in duration. Estimated from the durations and a unilateral rupture velocity of 2.5 km $s^{-1}$, the rupture length is 50–100 m, much larger than the centroid location of uncertainty of ±10 m. Combining the rupture length with the magnitude of the events[16] suggests ~1 cm of slip in each event. These quantities are in the range of those estimated for other earthquakes of a similar magnitude[17].

Both moment and duration correlate with the time interval since the previous earthquake, as shown in Fig. 3. These results provide a glimpse of the variability during repeated rupture of the same fault patch. As moment is proportional to the product of stress drop and rupture radius cubed[18], the slight increase in moment that accompanies the several order of magnitude increase in time since the last earthquake probably represents an increase of either ~15% in stress drop or ~5% in patch radius. Because the larger events have shorter durations, an increase in stress drop is more probable.

The most likely reason for an increase in stress drop with recurrence time is that the frictional strength of the fault surface increases with stationary contact time. From the available laboratory data[2,19,20], healing with time of stationary contact produces

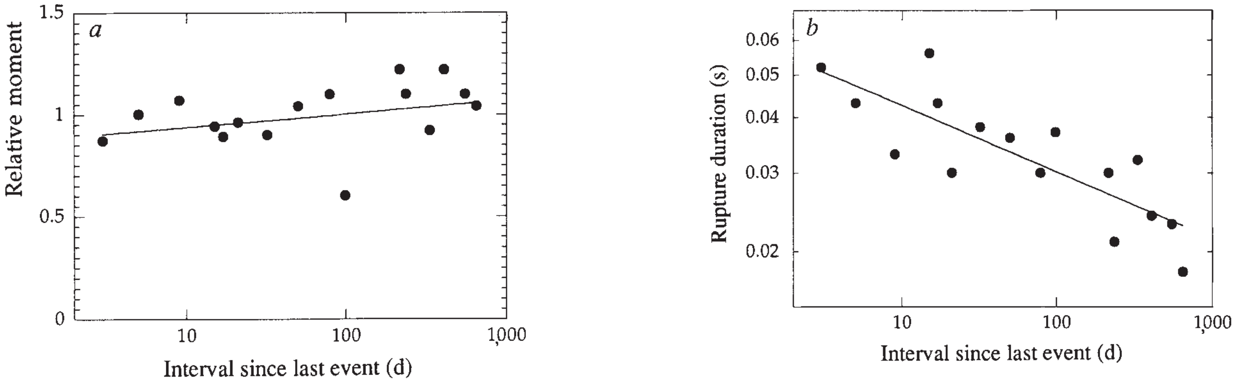

FIG. 3 *a*, Relative moments and *b*, durations of 16 events plotted against the interval since the previous repetition in the sequence. Because we cannot ascertain whether the Morgan Hill main shock broke the Calaveras fault at the location of the 16 April 1984 event, and we do not know the date of the event before that of 26 July 1980, these events are not included. The moments are derived from the spectral levels shown in Fig. 2*b* measured at 5 Hz. The durations of the events are obtained by matching the observed spectral levels and calculated spectral levels at 15 Hz, assuming an $\omega^2$ source model[15], as illustrated in Fig. 2*c*. The solid lines indicate best-fit power-law curves to the data. The anomalously low moment in *b* is the event of 21 May 1987. We do not know why this event is anomalous. Perhaps an undetected smaller event released part of the moment before or after the anomalous event.

about a 3–8% increase in friction for a decade change in recurrence time, in good agreement with the trend shown in Fig. 3*a*. So the earthquake data seem to suggest that the predictions from room-temperature, brittle experiments can be extrapolated to crustal faults. The variations in rupture duration noted below, and the observation that longer recurrence times correlate with smaller moments in the nearby 13-event sequence, however, cause this interpretation to be tentative.

It has been suggested that stress drop for earthquakes increases by a factor of 10 as the interval between subsequent events on the same fault segment increases from tens to thousands of years[21–24]. Such long-term fault healing may be associated with slower processes, such as remineralization, which could be an effect of fluid flow in crustal fault zones[25,26]. This rate of increase is a factor of 50 larger than our observations, and too large to be explained by the magnitude of state-dependent friction determined in short-term laboratory experiments on brittle systems.

The large decrease in rupture duration with increasing time between events is more surprising than the change in moment. It implies that either the rupture velocity or the duration of sliding at each point on the fault must be varying, if the same patch is breaking in each event, as is indicated by the virtually identical waveforms and almost constant moments. It is possible, but less likely, that the shorter-duration events could rupture a patch radius smaller by a factor of about two with an order of magnitude higher stress drop than the longer-duration events. This is not our preferred explanation because it requires a decrease in fault area that would have to offset the increase in stress drop almost exactly to preserve the nearly constant moments.

Laboratory experiments show that the presence of fault gouge[4] and roughening of the fault surface[5] reduce rupture velocity and increase the critical slip distance for seismic faulting[27], which plays a key role in determining the rupture nucleation dimension and thus the average rupture velocity over a small fault area. Such healing processes may account for the variation in rupture duration.

Alternatively, earthquake source models that incorporate fluid diffusion and fault compaction have been proposed[6–11]. Such models, which do not preclude state-dependent frictional effects, have been invoked to explain the low apparent fault strength and lack of fault-zone heat flow anomalies. These models predict dramatic variation in fault-zone properties during the earthquake cycle, which have also not been previously observed *in situ*. The observed signs of changes in moment and rupture duration with changes in recurrence interval are consistent with most models of fault zone healing, although the magnitude of the duration variation is larger than expected.

Qualitatively, therefore, the observation of decreasing duration for increased time since the last event is in agreement with those laboratory experiments and models that suggest physical changes in the fault zone during the earthquake cycle. Such variations in the rupture process may play an important role in rupture initiation, the aftershock process and the earthquake cycle in general. ☐

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