1995

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GEOPHYSICAL RESEARCH LETTERS, VOL. 22, NO. 22, PAGES 3095-3098, NOVEMBER 15, 1995

Fault healing inferred from time dependent variations in source properties of repeating earthquakes

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Abstract. We analyze two sets of repeating earthquakes on the Calaveras fault to estimate in-situ rates of fault strengthening (healing). Earthquake recurrence intervals t_r range from 3 to 803 days. Variations in relative moment and duration are combined to study changes in stress drop, rupture dimension, rupture velocity, and particle velocity as a function of t_r. Healing rates and source variations are compared with predictions of laboratory-derived friction laws. Two interpretations of event duration τ are used: one in which τ is given by the ratio of slip to particle velocity and one in which it scales as rupture dimension divided by rupture velocity. Our data indicate that faults strengthen during the interseismic period. We infer that source dimension decreases with t_r due to aseismic creep within the region surrounding the repeating events. Stress drop increases 1-3MPa per decade increase in t_r, which represents an increase of a factor of 2-3 relative to events with t_r between 10 and 100 days. This rate of fault healing is consistent with extrapolations of laboratory measurements of healing rates if fault strength is high, on order of 60MPa, and stress drop is roughly 10% of this value.

Introduction

Laboratory experiments show that friction of simulated faults increases with time of stationary contact and with decreasing slip rate [*Dieterich*, 1972; *Beeler et al.*, 1994]. These data indicate that faults will strengthen (heal) during the interseismic period. In laboratory experiments, friction increases by 0.03 to 0.08 (5-10% of the absolute value) per decade increase in hold time [*Scholz*, 1990; *Beeler et al.*, 1994; *Karner et al.*, 1995]. However, field-based estimates of fault healing imply that stress drop increases by a factor of 2-5 per decade increase in earthquake recurrence interval [*Kanamori and Allen*, 1986; *Scholz et al.*, 1986]. This discrepancy could be due to higher healing rates on natural faults or differences between the way healing rate is measured: laboratory experiments measure changes in "static" frictional strength, whereas seismic estimates derive from stress drop, which is proportional to the difference between static and dynamic friction. Also, existing field estimates have been made by comparing faults from different tectonic regions and with different total offsets and recent slip rates. Thus, these estimates could be contaminated by other effects.

Earthquakes that repeatedly rupture the same fault patch offer the opportunity to improve our understanding of healing rates of natural faults and to assess the efficacy of laboratory-derived friction laws in nature. In this paper we use repeating earthquakes to examine the effect of recurrence interval on source properties and to estimate in-situ the rate of fault healing. We compare source variations and the seismic healing rate with predictions of laboratory-derived friction laws.

Paper number 95GL03076
0094-8534/95/95GL-03076$03.00

Repeating Earthquakes

Recent developments in the recognition and analysis of repeating earthquakes allow for high resolution estimates of subtle differences between events [*Poupinet et al.*, 1984; *Vidale et al.*, 1994; *Ellsworth*, 1995; *Nadeau et al.*, 1995; *Beroza et al.*, 1995]. We use two sets of M≈1.5 earthquakes recorded by the Northern California Seismic Network (NCSN) during the period 1980-1994 [*Ellsworth*, 1995]. Seismic properties of the events, analysis techniques, and implications for earthquake forecasting have been described in detail [*Vidale et al.*, 1994; *Ellsworth*, 1995]. Here, we summarize only a few pertinent aspects of the events.

The sequences occur on the Calaveras fault just beyond the southern limit of the 1984 M6.2 Morgan Hill rupture (Figure 1). The NCSN catalog is complete to about M=1.0 for this locale, making it possible to accurately identify all events belonging to CA1 or CA2 since 1980; hence, the seismic recurrence interval is known. The sequences occur at depths of 6 and 8km, respectively, and are separated by 2km along strike (Figure 1). The northernmost sequence, CA1, consists of 19 events of M 1.4-1.6. The second sequence, CA2, consists of 14 events of similar magnitude. Waveforms for events within each set are nearly identical from the P-wave through the coda [*Ellsworth*, 1995] and cross correlation techniques show that relative centroid locations are within ±10m [*Vidale et al.*, 1994]. Because the relative location uncertainties are smaller than the likely rupture dimension (diameter 50-100m) each set is considered to represent repeated rupture of the same fault patch.

Observations of Moment and Duration

Of the 19 events in the CA1 sequence, one occurred before the 1984 Morgan Hill earthquake. Since we do not know whether the CA1 patch slipped during the Morgan Hill mainshock, we also exclude the first aftershock, leaving 17 events with known recurrence interval (Figure 2). For these events, moment increased 10-15% per decade change in t_r (Figure 2a). Source duration decreased systematically with t_r at a rate of about 35% per decade for both ω^{-2} and ω^{-3} source models (Figure 2b).

The CA2 sequence (Figure 3) contains fewer aftershocks and longer average repeat times than CA1. With the exception of one event, an aftershock that occurred 11 days after the Morgan Hill

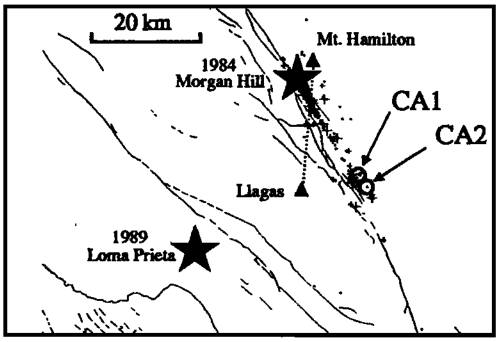

Figure 1. Location of the CA1 and CA2 repeating sequences on the Calaveras fault, California. Seismicity along the Calaveras fault is shown by crosses. Stars denote epicenters of largest recent earthquakes. *Prescott et al.* [1986] made geodetic measurements between Llagas and Mt. Hamilton. (After *Ellsworth,* 1995.)

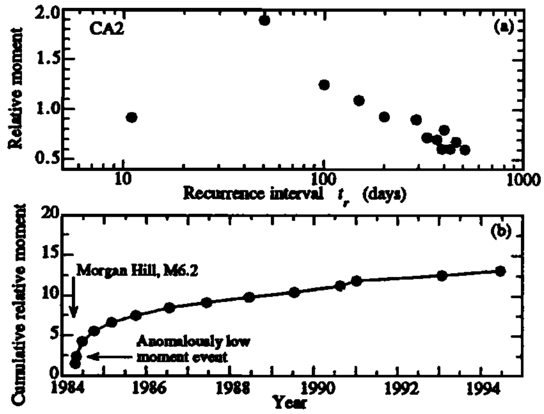

Figure 3. Data for the CA2 sequence of 14 repeating earthquakes. (a) Relative moment vs. recurrence interval. We were unable to determine f_c for the CA2 sequence, which appears to have shorter duration than CA1. Moment decreased systematically with recurrence interval for interevent times greater than 50 days. (b) cumulative moment release vs. event date showing decay of the aftershock rate to a roughly constant moment release rate.

event, the CA2 sequence shows decreasing moment with recurrence interval (Figure 3a).

Analysis of Source Parameter Variations

We consider possible variations in source parameters in the context of a circular earthquake rupture of radius r. In this case, moment is $M_o = \pi r^2 G u$, where G is shear modulus and u is average slip, and average stress drop is $\Delta\sigma = 7\pi G u/16r$, which yields $M_o = 16\Delta\sigma r^3/7$, leading to:

$$\frac{dM_o}{dt_r} = \frac{16}{7}\left[r^3\frac{d\Delta\sigma}{dt_r} + 3\Delta\sigma r^2\frac{dr}{dt_r}\right], \qquad (1)$$

where $d(\Delta\sigma)/dt_r$ and dr/dt_r are the seismic healing rate and dependence of rupture dimension on interevent time, respectively. Added constraint is provided by estimates of characteristic event duration τ (Figure 2b). Two interpretations of τ may be made.

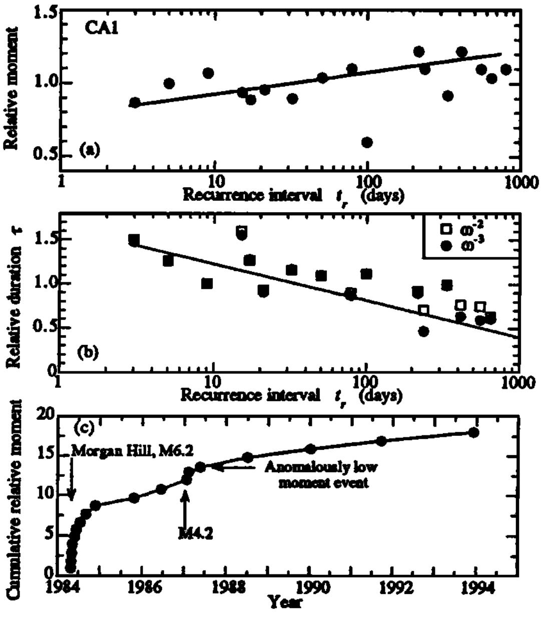

Figure 2. Data for the CA1 sequence of 18 events on the Calaveras fault. Relative moment was determined by comparing spectral levels at 5Hz and corner frequency f_c was estimated by normalizing the spectra at 5Hz and comparing the observed spectral slope with normalized theoretical spectra within the available frequency range (<20Hz) [*Vidale et al.*, 1994]. (a) Line shows 15% increase in moment per decade increase in recurrence interval. (b) Duration is proportional to f_c^{-1}. τ =1.0 corresponds to event duration of 0.033s. Line shows 35% decrease in relative duration per decade increase in t_r. Duration decreases systematically with t_r and is insensitive to differences between source models. We do not have duration data for the December 1993 event. (c) Cumulative moment release vs. event date. The combination of aftershocks of 1984 Morgan Hill earthquake and background seismicity results in the unusually large range of recurrence intervals [*Ellsworth,* 1995]. A nearby M4.2 event in early 1987 triggered three events, one with anomalously low moment.

First, we take τ as the time required for rupture to expand over the entire fault area: $\tau = r/V_r$, where V_r is average rupture velocity. In this case, variations in τ with interevent time are due to variations in source dimension or average rupture velocity

$$\frac{d\tau}{dt_r} = V_r^{-1}\frac{dr}{dt_r} - \frac{r}{V_r^2}\frac{dV_r}{dt_r}. \qquad (2)$$

By combining (1) and (2) we can show the range of possible solutions for the repeating earthquake data in terms of changes in stress drop, rupture radius, and rupture velocity. Figure 4a shows the locus of possible solutions for a given value of dM_o/dt_r, taking $\Delta\tau/\Delta t_r$=-35%/decade (from Figure 2b). Although the data do not allow a unique solution, two common assumptions may be considered: constant rupture dimension and constant rupture velocity.

Because of our interpretation of τ, leading to equation (2), if the source radius is independent of t_r (upper horizontal, dashed line in Figure 4a), rupture velocity must increase by 35% per decade increase in t_r, which would imply a 15%/decade increase in stress drop (Figure 4a). Alternatively, if rupture velocity is constant, r decreases 13m/decade and stress drop increases 120% per decade change in t_r. The CA2 sequence shows roughly a 75% decrease in moment per decade. We do not have duration data for CA2. Assuming the same change in duration as for CA1, the CA2 events indicate a 35%/decade increase in stress drop and a 13m/decade decrease in rupture radius.

Equation (2) and Figure 4a are based on τ being the time required for rupture to expand over the entire fault area. An alternative view is that τ is the ratio of slip to particle velocity V_p on the fault: $\tau = u/V_p$. In this case, τ would correspond to the local

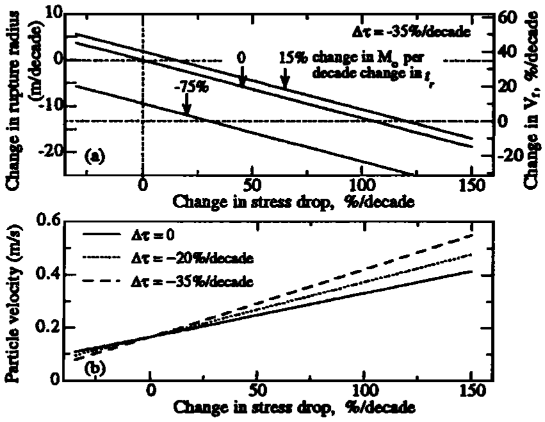

Figure 4. Changes in earthquake source parameters for two models relating changes in moment and duration. In (a) event duration is $\tau = r/V_r$, and in (b) $\tau = u/V_p$. Changes are per decade change in recurrence interval and are relative to an event with t_r=100 days, for which M_o=5.5x10^{11}Nm, τ=0.025s, r=37.5m, $\Delta\sigma$=4.6MPa and average slip and rupture velocity are 0.4cm and 1.5km/s, respectively. (a) Locus of possible solutions for observed moment and duration variations. The plot is made for $\Delta\tau/\Delta t_r$=-35%/decade. CA1 sequence shows $\Delta M_o/\Delta t_r$=15%, thus for constant rupture velocity (lower, horizontal dashed line) stress drop increases 120%/decade and source radius decreases 13m/decade. The CA2 sequence indicates ≈75% M_o reduction per decade and the line is drawn assuming the same change in duration and average event size as CA1. (b) Relationship between absolute particle velocity and change in stress drop for constant rupture size and $\tau = u/V_p$. The change in stress drop is directly proportional to the change in M_o, thus for 35%/decade decrease in τ and 15%/decade increase in stress drop, V_p increases 0.03m/s per decade increase in t_r.

rise time on the fault, which is comparable to average rupture duration for some fault models. Combining this with the relation between M_o and average slip, yields: $V_p = M_o / \tau G \pi r^2$. Differentiating this with respect to interevent time and combining it with (1) gives a relation between dV_p/dt_r and $d(\Delta\sigma)/dt_r$ as a function of $d\tau/dt_r$, which is plotted vs. V_p in Figure 4b. As expected, particle velocity scales directly with stress drop. For a given increase in stress drop, particle velocity increases as the change in duration decreases (Figure 4b). The line of constant duration has slope of 0.04 (m s^{-1})/MPa, which, consistent with our rupture velocity, is about a factor of two lower than experimental measurements and the theoretical relation for a self-similar rupture with uniform stress drop: $V_p \approx \Delta\sigma V_r / G$ [*Scholz*, 1990, p. 173].

For the CA1 sequence, we can estimate absolute changes in stress drop and particle velocity (Figure 5). For constant V_r, stress drop increases 2-3MPa per decade increase in t_r (Figure 5a). On the other hand, V_r may increase with t_r if rupture resistance S decreases with t_r, which is expected if average σ_o on the fault plane increases with t_r ($S = (\sigma_y - \sigma_o)/(\sigma_o - \sigma_d)$, where σ_o, σ_y, σ_d are the local values of initial stress, yield strength, and dynamic frictional strength, respectively). However, even a 20%/decade increase in V_r does not change significantly the estimate of fault healing rate, which is in the range 1-3MPa/decade (Figure 5a).

To get a further sense of the uncertainty in this estimate, we use the second interpretation of τ to evaluate changes in the average particle velocity of the CA1 events (Figure 5b). The data show about a 0.05m/s increase in V_p/decade, which using the above relation between asymptotic V_p and dynamic stress drop indicates 1MPa/decade increase in stress drop. Thus the two approaches yield similar estimates of seismic healing rate.

Discussion

Frictional strengthening in laboratory experiments is generally attributed to increased contact area or enhanced adhesion at asperity contacts [*Scholz*, 1990]. Applied to natural faults, the lab data predict: 1) that fault strength will increase with increasing seismic recurrence interval and 2) that the size of individual ruptures will be constant or increase slightly with t_r, presuming that ruptures correspond to individual frictional contacts.

Strictly, point 1 relates only to yield strength σ_y and not necessarily to seismically-estimated healing rate since laboratory measurements are made of the increase in peak friction with waiting time, whereas seismic healing rate is based on changes in stress drop $\Delta\sigma = \sigma_y - \sigma_d$. The values may be compared if healing causes increased yield strength σ_y but no change in dynamic frictional strength σ_d. Then for failure under uniform initial stress σ_o ($\sigma_o \approx \sigma_y$) the lab data predict that stress drop increases by the amount of frictional healing: 0.03 times effective normal stress. Taking 18MPa/km as an average effective lithostatic gradient, our repeating earthquake sequences have effective normal stress σ_n = 100MPa, and thus the laboratory healing rates predict that stress drop will increase about 3MPa per decade increase in t_r.

Since frictional healing rate scales with strength [Scholz and Engelder, 1976], faults that are significantly weaker or that slide under significantly lower normal stress should exhibit lower healing rates; for σ_n = 10MPa, the predicted healing rate would be ≤ 0.3MPa/decade.

The laboratory prediction agrees with our in-situ estimate of seismic healing if rupture velocity is approximately independent of recurrence interval (Figure 5a). However, that requires a systematic decrease in rupture size with recurrence interval, which is counter to point 2 above. For the CA1 sequence, this difficulty can be avoided if one takes the view that duration is local slip duration at a point on the fault. In this case, the healing rate is about 1MPa/decade (Figure 5b) and no change in rupture size is required. However, the CA2 data cannot be explained in this way. Decreasing moment with recurrence interval requires either that

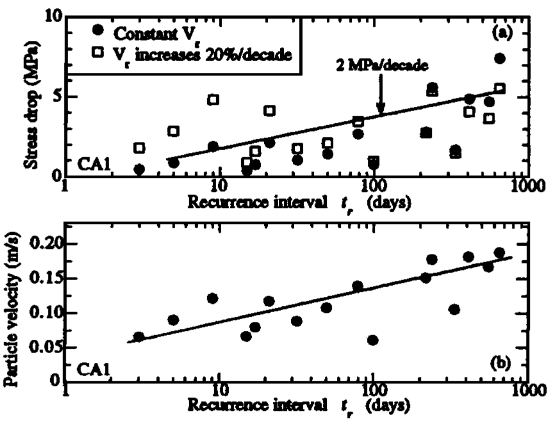

Figure 5. Stress drop (a) and particle velocity (b) for the CA1 sequence. Each plot uses data of Figure 2a and the ω^{-2} data of Figure 2b scaled to absolute values. (a) Stress drop assuming duration $\tau = r/V_r$. The data show a 2-3MPa/decade change in stress drop. Our techniques resolve relative changes much better than absolute values and thus the possible indication that stress drop goes to zero at finite t_r is not significant. (b) Particle velocity for the CA1 events assuming constant rupture size and that duration is $\tau = u/V_p$. Line shows 0.05m/s increase in V_p per decade, which corresponds to a 1MPa/decade increase in stress drop. Slip increases from about 0.3 to 0.5cm over the range or t_r.

stress drop or source radius decrease with recurrence interval. Although either of these are possible under special conditions, a negative change in stress drop is less likely because it implies decreasing peak friction with hold time, which is equivalent to velocity-strengthening frictional behavior. In this case, the fault patch would not be expected to fail seismically.

On the other hand, geodetic measurements on the line shown in Figure 1 [*Prescott et al.*, 1986] show steady slip at a rate that mimics the recurrence rate of the repeating events [*Ellsworth*, 1995]. This, coupled with the lack of seismicity in regions surrounding the repeating events suggests that these regions slip aseismically. Thus, the CA1 and CA2 fault patches may represent frictional contacts that are continually loaded by aseismic creep in the surrounding regions. In this case, longer intervals between events would be expected to result in greater aseismic slip around the rupture patches and thus greater slip at the edges of the patch prior to nucleation. In the context of rate/state friction laws, the edges of the patch would represent regions of slight velocity weakening to velocity neutral frictional behavior, producing conditionally unstable behavior.

Although we focus on time-dependent frictional strengthening as a mechanism to explain the observed source variations, we cannot rule out other effects such as fluid pressure variations or other changes in the state of stress [e.g., *Sleep and Blanpied*, 1994; *Palmer et al.*, 1995]. For example, compaction and fluid pressure variations following the 1984 Morgan Hill earthquake could modify stress drop and source duration. However, it is difficult to envision how this would lead to systematic source variations with recurrence interval. Moreover, the frictional healing mechanisms we discuss are expected to operate even if other processes are active.

Conclusions

Data from the CA1 sequence show that stress drop increases 1-3MPa/decade increase in t_r. These data show that characteristic event duration decreases with waiting time, which is consistent with increasing particle velocity and/or increasing rupture velocity and decreasing source radius with t_r. Although interpretation of CA2 is less certain, these data favor the interpretation that source radius decreases slightly with increasing t_r, presumably due to aseismic creep on the perimeter of the rupture patch.

Our laboratory-based interpretation of healing rate differs from previous estimates [e.g., *Scholz et al.*, 1986], which focus on the rate of change of the absolute friction value and the expected fractional change in stress drop with recurrence interval assuming total stress drop. For a stress drop of a few MPa, our laboratory-based predictions and seismic estimates indicate that faults heal at rates sufficient to produce a factor of 2-6 increase in stress drop per decade increase in recurrence interval. These healing rates are consistent with previous work based on differences in scaling properties of intraplate and interplate earthquakes. However, the seismic healing rates are consistent with laboratory measurements only if fault strength is high, on order of 60MPa. If faults are significantly weaker, with effective normal stresses and shear strengths of order 10MPa, predicted healing rates are a factor of 5-10 lower than our seismic estimates. Further laboratory work is necessary to determine healing rates at elevated temperature and fluid pressure for comparison with in-situ, seismic estimates.

Acknowledgments. We thank N. Deichmann, E. Humphreys, M. Blanpied, J. Boatwright, C. Scholz and two anonymous reviewers for critical comments, suggestions, and discussion. CM was supported by USGS award 1434-94-G-2417, NSF grant EAR-9316082, and a Kerr-McGee career development chair at MIT.

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(Received May 8, 1995; Revised July 3, 1995;
Accepted August 29, 1995.)