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Postseismic response of repeating aftershocks

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Abstract. The recurrence intervals of repeating earthquakes on the San Andreas Fault in the Loma Prieta aftershock zone follow the characteristic $1/t$ decay of Omori's law. A model in which these earthquakes occur on isolated patches of the fault that fail in stick-slip with creep around them can explain this observation. In this model the recurrence interval is inversely proportional to the loading rate due to creep. Logarithmic velocity strengthening friction predicts $1/t$ decay in creep rate following the mainshock. The time dependence of recurrence is inconsistent with a simple viscous constitutive relationship, which predicts an exponential decay of loading rate. Thus, our observations imply postseismic slip at seismogenic depth under a power law rheology. The time dependence of postseismic deformation measured geodetically may be diagnostic of whether postseismic deformation is caused by creep or possible viscoelastic deformation at greater depths.

Introduction

Omori's law of aftershock decay holds that the frequency of aftershocks decays as the reciprocal of time following the mainshock [*Scholz*, 1990]. Elastic stress changes, such as those exerted on a fault by a large earthquake, act instantaneously and by themselves can not explain the time dependence of aftershocks; however, there are several possible physical mechanisms that can give rise to the observed time-dependence.

Failure triggered by pore fluid diffusion provides an explanation of aftershock decay [*Nur and Booker*, 1972]. After the mainshock, pore pressure varies spatially and decays as $e^{-1/t}$ with time [*Booker*, 1974], but accounting for all the contributions along the length of the fault leads to $1/t$ behavior for the overall decay of aftershock frequency.

Rate- and state-variable friction has also been shown to give rise to the observed decay rate of aftershocks [*Dieterich*, 1994]. In this model stress changes are assumed to lead to time-dependent nucleation of a population of earthquakes on adjacent parts of the fault. A similar dynamic model of rapidly accelerating crack growth also reproduces Omori's law [*Shaw*, 1993].

In this paper we consider the recurrence intervals of repeating micro-earthquakes on the San Andreas Fault in the aftershock zone of the 1989 Loma Prieta earthquake (Figure 1). We find that the repeat times of individual repeating earthquake sequences follow Omori's law. We hypothesize that the repeating earthquakes occur on relatively isolated patches on a fault that is otherwise creeping. This suggests that the recurrence interval is inversely proportional to the loading rate due to creep and that the observed $1/t$ behavior reflects the creep response of the San Andreas fault to the stress step from the Loma Prieta mainshock. Logarithmic velocity strengthening friction predicts the observed $1/t$ response. This represents a new mechanism whereby aftershocks follow Omori's law.

Repeating Earthquakes

We use the same criterion as in a previous study of temporal variation in coda-Q [*Beroza et al.*, 1995] to identify six sets of repeating earthquakes. Events within a multiplet have relative location precision of ± 7 m and are generally separated by less than 20 m. The average magnitude of the earthquakes is 1.5, correponding to a source radius of about 30 m for a 3 MPa stress drop and so represents approximate repeated rupture of the same fault patch. The multiplets contain from 10 to 19 events and are separated from each other by up to 3 km. The depths of these sequences range from 8 to 9 km. Figure 2 shows the similarity of seismograms from one multiplet recorded at Calnet station HCA.

Time-Dependent Recurrence

The aftershocks in each multiplet occur most frequently right after the mainshock. Figure 3 shows inverse recurrence interval for the six multiplets as a function of time on log-linear and log-log plots. Exponential time decay should appear as a straight line on the log-linear graph (upper panel) where the slope is the coefficient of t in the exponent. Power law decay should appear as a straight line on a log-log graph (lower panel) where the slope is equal to the power, p, of t^p.

In each case the recurrence interval of the repeating aftershock sequences follows a power law rather than exponential decay. The repeating aftershock sequences also match the t^p decay in frequency for the whole collection of Loma Prieta aftershocks for which $p = -1.01$, i.e. Omori's law. Values of the exponent, p, for individual repeating aftershock sequences are: -0.78, -0.89, -0.90, -0.96, -0.98, and -1.04, with average standard errors of ± 0.05.

Velocity-Dependent Friction and Creep

We believe that the repeating earthquakes occur on relatively isolated patches of the fault that is otherwise creeping aseismically. It is difficult to understand how the fault could otherwise repeatedly set up conditions for the recur-

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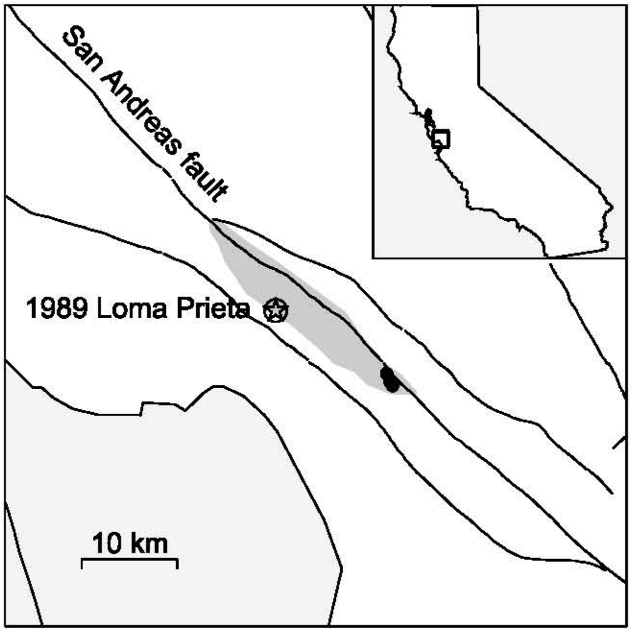

Figure 1. Six multiplets (dots) on the San Andreas fault in the aftershock zone (shaded) of the 1989 Loma Prieta earthquake.

rence of the same micro-earthquake. This suggests that the frequency of recurrence is proportional to the loading rate due to creep and that the observed $1/t$ behavior reflects the creep response of the San Andreas fault to the stress step from the Loma Prieta mainshock. A simple viscous fault zone rheology, in which resistance to slip is linearly proportional to velocity, is inconsistent with our observations because it predicts that fault slip will decay exponentially under external stress.

Pore fluid diffusion can explain Omori's law for all the events within the volume surrounding the fault [*Booker*, 1974]; however, change in pore pressure, and therefore stress, is a complicated function of space and time and so does not offer a simple explanation of our observations for repeating aftershock sequences at a fixed location.

A logarithmic velocity strengthening friction law [*Dieterich*, 1978], on the other hand, predicts the observed $1/t$ decay in loading rate for creep as follows. Assume that stress drop, $\Delta\tau$, for each event is constant. This implies that shear stress rate, $\dot{\tau}$, is inversely proportional to recurrence interval, T_r,

$$\dot{\tau} = \frac{\Delta\tau}{T_r} \sim \frac{1}{T_r}. \quad (1)$$

Consider a stably sliding zone subjected to the static stress increase of the mainshock. As creep continues this region will be destressed proportional to the amount of total slip. Therefore stress rate decay is proportional to the sliding velocity, V,

$$\dot{\tau} \sim -kV, \quad (2)$$

where k is a coupling constant dependent on the geometry of the stuck patch and the creeping region. For quasistatic sliding, the frictional resistance Φ will equal the shear stress, and so,

$$\dot{\tau} = \dot{\Phi}. \quad (3)$$

For a creeping fault, we adopt a velocity strengthening steady-state friction [*Rice and Gu*, 1983].

$$\mu_{ss} = \mu_0 + (a-b)\ln\left(\frac{V}{V_0}\right), \quad (4)$$

$$\Phi = \mu_{ss}\sigma_n, \quad (5)$$

The frictional coefficient, μ_0, corresponds to a reference velocity, V_0, and σ_n is the normal stress. Assuming constant normal stress,

$$\dot{\Phi} = \sigma_n \frac{d\mu_{ss}}{dt} = \sigma_n \frac{d\mu_{ss}}{dV}\frac{dV}{dt}. \quad (6)$$

Differentiating equation (4) with respect to velocity yields,

$$\frac{d\mu_{ss}}{dV} \sim \frac{1}{V}. \quad (7)$$

Relating equations (2), (3), (6), and (7) obtains:

$$\frac{dV}{dt} \sim -V^2, \quad (8)$$

which yields,

$$V \sim 1/t. \quad (9)$$

While creep progresses and the sliding regions are destressed according to (2), stuck patches that fail in repeating earthquakes are loaded proportionally but with opposite sign. So

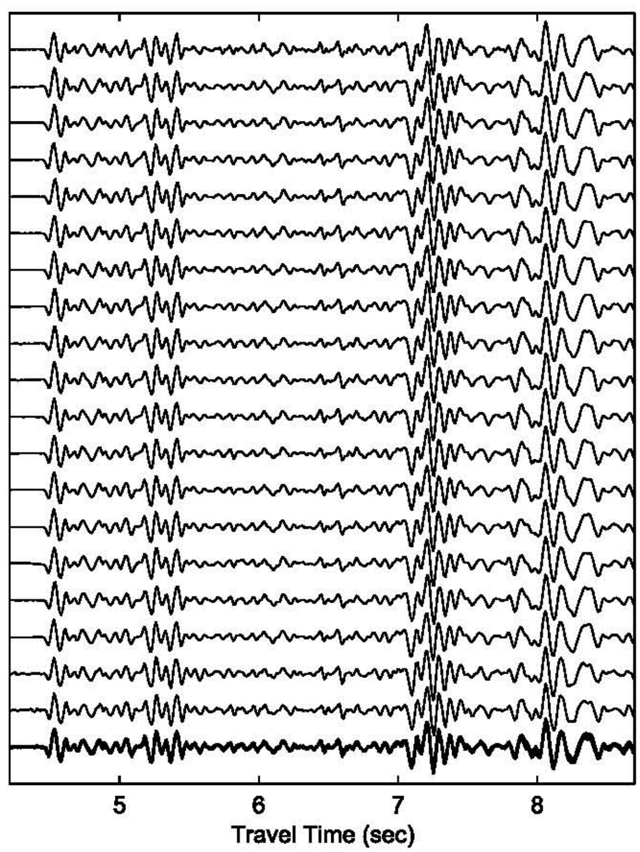

Figure 2. Unfiltered seismograms of 19 events within one of the six multiplets. Bottom trace shows all events superposed.

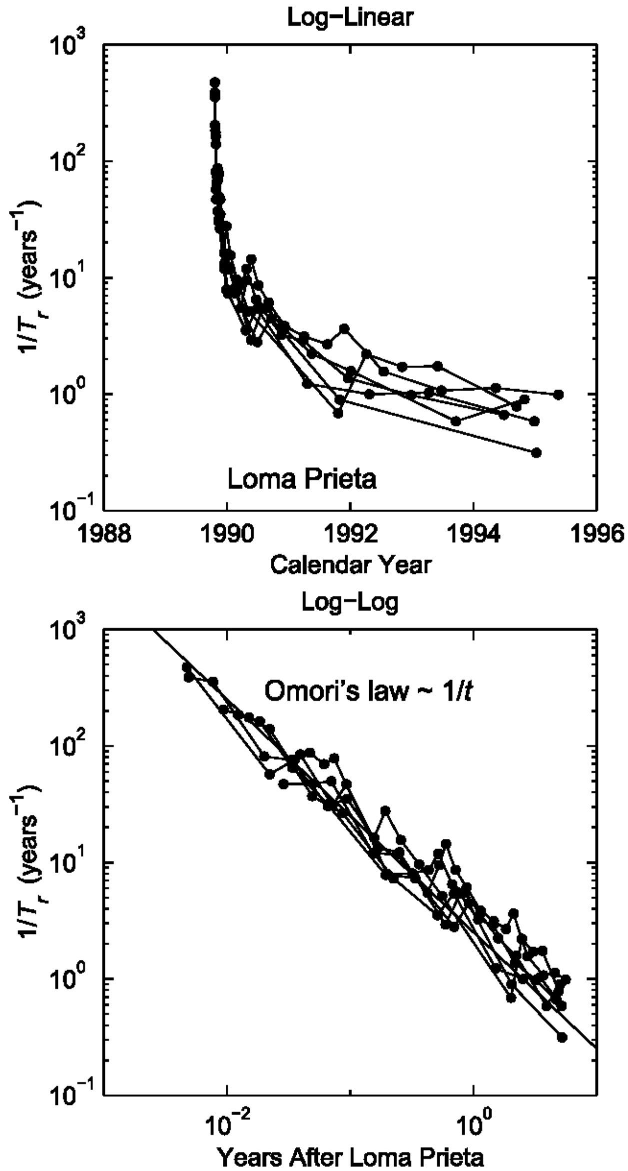

Figure 3. Inverse recurrence interval as a function of time on log-linear and log-log plots, displaying power law time decay for each of the six multiplet s.

from (1) and (9), the predicted stress rate measured by the recurrence interval of the earthquakes will vary as,

$$\dot{\tau} \sim kV \sim 1/t, \quad (10)$$

consistent with our observations.

Experiments record similar $1/t$ relaxation during slide-hold tests and show that rate effects dominate state effects at low slip velocities, comparable to stable fault creep [*Reinen et al.*, 1994]. In a separate study of repeating earthquakes on the Calaveras fault, the variation of seismic moment with recurrence interval was interpreted as showing state dependence [*Vidale et al.*, 1994] manifested as greater fault healing for longer contact time. Unlike our study, their observation applies to the stuck part of the fault rather than the part that is creeping. Earthquakes necessarily occur in zones of velocity weakening, whereas velocity strengthening gives rise to stable creep.

We have also identified sets of repeating aftershocks of the 1984 Morgan Hill, California earthquake, which occurred on the Calaveras fault. These sequences show power law behavior as well, but with greater variability in the value of p (from -0.6 to -1.0). This greater variability may be due to the large postseismic transient (greater than the coseismic change) observed geodetically following this event [*Prescott et al.*, 1986]. That is, the creep response of this fault may involve more than the response to a stress step imposed by the mainshock. Alternatively, it may reflect the fact that the distribution of repeating aftershocks studied on the Calaveras fault are separated by much greater distances than the events studied on the San Andreas fault and that different parts of the fault exhibit different rheologies (i.e. plastic behavior for $p \neq 1$).

It is interesting to note that detailed creepmeter measurements of afterslip following earthquakes reveal it is the accumulation of smaller creep events [*Smith and Wyss*, 1968; *Bilham*, 1989]. The events show similar Omori's law decay in frequency as our aftershocks, slipping roughly equal amounts, and so may be considered aseismic analogs of our repeating earthquakes. Individual creep events are universally observed to slip according to a power law [*Wesson*, 1988]. Geodetic and creep measurements of postseismic transients for the 1966 Parkfield [*Smith and Wyss*, 1968], 1968 Borrego Mountain [*Burford*, 1972], 1976 Guatemala [*Bucknam et al.*, 1978], 1979 Imperial Valley [*Harsh*, 1982], 1987 Superstition Hills [*Bilham*, 1989], and 1992 Landers earthquakes [*Shen et al.*, 1994] all show power law decay. To our knowledge, there does not yet exist an example of a postseismic transient that exhibits exponential decay.

Conclusions

We find that recurrence intervals of individual repeating earthquake sequences in the aftershock zone of the 1989 Loma Prieta earthquake follow Omori's law. This behavior is predicted by the creep response to a stress step for a logarithmic velocity strengthening friction law. Thus, there are two mechanisms whereby Dieterich-Ruina friction can lead to Omori's law. The first mechanism is that earthquake nucleation occurs by self-driven accelerated runaway to failure, which is controlled by friction on the fault patch itself [*Dieterich*, 1994]. The second mechanism, proposed in this paper, is that Omori's law can arise from repeated rupture on the same fault patch when rate-dependent friction controls the loading velocity of the creep on the surrounding fault. Both mechanisms may be expected to operate in aftershock sequences.

This $1/t$ behavior arising from logarithmic velocity strengthening has been pointed out previously for laboratory [*Reinen et al.*, 1994] and surface-based measurements [*Marone et al.*, 1991]. What is new in our work is we have used the time dependence of repeating aftershocks to probe these properties at depth. Our method provides a local measure of the rheology at depth; here at 8 to 9 km on this portion of the San Andreas, although the exact spatial location is not constrained. The occurrence of these repeating events indicates significant postseismic creep and suggests the existence of velocity strengthening and velocity weaking zones interspersed at seismogenic depths. Earthquake rupture may therefore be arrested or retarded as it propagates into velocity strengthening zones.

It is often difficult to distinguish postseismic slip at seismogenic depths from viscous postseismic slip in the deeper, ductile regime [*Nur and Mavko*, 1974] with available geodetic measurements. A non-linear "hot-friction" model using the same constitutive law as (4) proposes that transients may be explained by creep below a locked seismogenic zone [*Linker and Rice*, 1997]. Our results suggest that the time-dependence of postseismic deformation may help to discriminate between aseismic creep – either at seismogenic depths or deeper – and viscous deformation.

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