Aseismic Slip and Fault Interaction from Repeating Earthquakes in the Loma Prieta Aftershock Zone

R. C. Turner,[1,2] R. M. Nadeau,[1] R. Bürgmann,[1,2]

R. C. Turner, R. M. Nadeau, and R. Bürgmann, Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA. (rturner@seismo.berkeley.edu)

[1]Berkeley Seismological Laboratory, University of California, Berkeley, California, USA.

[2]Department of Earth and Planetary Science, University of California, Berkeley, California, USA.

Along creeping sections of the San Andreas and other faults, small asperities in the fault zone load and fail in characteristic repeating earthquake sequences which can be used as subsurface creepmeters. Here, we use these virtual creepmeters to examine and compare slip rates on both the northwestern end of the creeping section of the San Andreas Fault near San Juan Bautista and on the nearby sub-parallel Sargent Fault. While creep on the San Andreas increases dramatically due to static stress changes in response to the 1989 Loma Prieta earthquake, the Sargent shows very little immediate response, consistent with Loma Prieta finite slip models that put this section of the fault in a region of less than three bar Coulomb stress increase. After about ten years, the San Andreas creep rate falls back closer to the interseismic rate and variations in creep become coherent in time with the Sargent, indicating a mutual driving force in the system.

1. Introduction

Along creeping sections of the San Andreas and other faults, small asperities in the fault zone load and fail in characteristic repeating earthquake sequences, driven by aseismic creep on the surrounding fault plane. These asperities represent less than 1% of the fault surface and do not contribute significantly to interplate coupling. By discovering these sequences in the seismicity catalog and using the scaling relationship between moment magnitude and fault slip developed by *Nadeau and Johnson* [1998], we can translate these events into a measurement of subsurface creep. This allows for an examination of creep rates, even where (and when) traditional geodetic instrumentation is not deployed — deep within the seismogenic zone, on lesser studied faults, and over periods of time that go beyond available deformation data. Here, we use these virtual creepmeters to examine slip rates on both the northwestern end of the creeping section of the San Andreas Fault (SAF) near San Juan Bautista and on the creeping section of the nearby Sargent Fault (SF) (Figure 1).

We find the expected transient to high repeater activity on the SAF associated with afterslip resulting from the 1989 Loma Prieta M6.9 earthquake (LP) [*Schaff et al.*, 1998; *Nadeau and McEvilly*, 2004]. However, we see little evidence for immediate rate changes on the SF, 5 km away to the northeast and sub-parallel to the SAF(Figure 2). As the high slip rate on the SAF decays over about nine years however, we see a gradual ramp up of activity on the SF and the start of a temporal correlation of slip rate variations on the two faults in which they begin periodically rising and falling together. These observations imply that the faults share a common driving or weakening mechanism.

2. Methods

We consider earthquakes from March 1984 through April 2011 in two rectangular swathes aligned along the strike of the SAF (Figure 1), extending to the northwest the existing catalog of repeating earthquake sequences identified by *Nadeau and McEvilly* [2004] beyond the creeping section of the central SAF. The areas were chosen to include neighboring sub-parallel faults in the search for repeating earthquake activity, particularly the Sargent Fault (SF) which is known to have documented aseismic dextral creep [*Prescott and Burford*, 1976].

Repeating earthquake sequences were identified following *Nadeau and McEvilly* [2004, supplementary material], relying on cross-correlation and spectral coherence methods to characterize waveform similarity between pairs of earthquakes using seismic data from the Northern California Seismic Network (NCSN). Events used in the repeating event search were limited to magnitudes between 1.0 and 3.4 because of limited signal-to-noise ratios and clipping, respectively. Repeating event pairs sharing a common event were then linked to form repeating earthquake sequences.

The properties of these characteristically repeating earthquake sequences has allowed the development of an empirical relationship between magnitude and fault slip [*Nadeau and Johnson*, 1998; *Nadeau and McEvilly*, 2004].

$$d_i = 10^{\alpha} M_0^{\beta} \tag{1}$$

where d_i is in cm and M_0 is in dyne-cm. Values for α and β, used in this study were $\alpha = -2.35 \pm 0.2$ and $\beta = 0.17 \pm 0.001$ [*Nadeau and Johnson*, 1998] where M_0 has been inferred from NCSN preferred magnitudes (M_p) and the empirical relationship $log(M_0) = 1.6M_p + 15.8$ [Wyss et al., 2004].

In this study (Figure 2c), the slip has been averaged over a rolling 0.8 year bin moving in 30 day increments with the average plotted at the time of the end of the bin.

3. Repeating Earthquakes Near San Juan Bautista

The most obvious feature of the repeater catalog, particularly in map view (Figure 1, Figure 2a), is that (with three exceptions that will be discussed further) repeating earthquake sequences don't occur North of 37°N, including the majority of the LP aftershock zone. As this is where the SAF enters the locked zone associated with the southeast termination of the 1906 and LP ruptures, we do not expect repeating earthquakes.

From surface measurements, the SF was previously known to have a creep rate of about 3 mm/yr on its southern strike-slip segment [*Prescott and Burford*, 1976] and it has also been shown to have abundant localized microseismicity along the fault that resembles that of other creeping faults in California [*Waldhauser and Schaff*, 2008]. The presence of repeating earthquakes shows that the SF is indeed creeping at depth along a limited section of the fault.

There are three repeating sequences far to the northwest of all the others in the catalog. Examining the catalog in time (Figure 2b), we see that these three sequences 'turn on' immediately after LP and all of them 'turn off' within a year or two after only one or two repeats. Though having significantly longer recurrence times, these events appear similar to the 'burst-type' repeaters described by *Templeton et al.* [2008] in that these transiently repeating earthquake sequences are probably not reflective of background creep. Instead, we interpret their implied slip as the relief of static stress changes after LP or as a direct reflection of the transient postseismic afterslip evident in regional GPS data [*Bürgmann et al.*, 1997; *Segall et al.*, 2000]. Their locations suggest that they may actually be located off of the primary plane of the SAF.

Other characteristics of the repeaters in the area are also worthy of note. Examined in a depth cross-section along strike (Figure 3c), the repeaters on the SAF trend deeper to about 12 km as they approach the locked zone. The SF repeaters, located only along a roughly 15 km section of the fault, stay above about 8 km depth. The apparently distinct dipping planes of the SF, seen when looking at the depth distribution across the fault (Figure 3b) are an illusion of the projection and collapse to a single plane when viewed in a SF parallel projection. Additionally, 5 km south of Gilroy lies a 2 km long stretch of the SF where no repeating earthquakes are found (Figure 1). Instead, the normally narrow band of background seismicity along the SF appears to broaden abruptly at this point, indicating a locked patch on the fault [*Gans et al.*, 2003]. A narrower gap appears to exist on the San Andreas as well, located at a similar position along strike. This possible correlation may be worthy of further study.

4. Post-Loma Prieta Fault Slip on the San Andreas and Sargent Faults

Before the LP earthquake, the slip rates on the SAF and SF are very different from one another. The SF tapers to a very low rate of 1-2 mm per year while the SAF, also hovering in the 1-2 mm range, experiences a transient rate increase to about 7 mm/year, consistent with pulsing behavior to the southeast observed by *Nadeau and McEvilly* [2004] (Figure 2c). After October 1989, the LP rupture clearly has a large influence on the SAF slip rate southeast of about 160 km in our strike-parallel coordinate system, and strong rate increases of both repeaters and non-repeating aftershocks occur. The 0.8 year smoothed SAF slip rate peaked at 20 cm/year before gradually falling back closer to the interseismic rate of about 1cm/yr. Meanwhile, the SF creep rate inferred from the repeaters shows only a modest initial rise that continues to gradually increase for the next nine years. About 10 years after LP, variations in the SAF and SF slip rates begin to correlate, their slip rates rising and falling with similar timing and amplitude. This new pattern continues for the next ten years but is less apparent beginning in 2010.

Despite not seeing a big increase of SF repeaters in response to LP, there is evidence for shallow transient aftershock activity on the SF (Figure 3). On the SF, these aftershocks occur mostly to the northwest of the repeaters. This is contrasted with the aftershock activity on the SAF which can be seen clearly to overlap with the northwestern SAF repeaters (Figure 3a). So, while there was an increase in seismicity on the northwestern SF as reported by *Reasenberg and Simpson* [1997], that increase did not extend into the creeping section of the SF as it did on the SAF. This is consistent with the subdued slip rate response of the southeastern SF inferred from the repeater data.

5. Discussion

For further examination of the stress effects of the LP earthquake on the SF and SAF, a cross-sectional view of the creeping section, underlaid by a Coulomb stress change map, and repeating earthquake locations is shown in Figure 4. The Coulomb stress change map is based on the finite element rupture model of *Wald et al.* [1991] but similar results are obtained from other rupture models as well [Stein, etc ***********].

The Coulomb stress changes associated with LP dramatically accelerated slip on the SAF, consistent with measurements of increased surface creep [*Behr et al.*, 1997]] and our SAF repeating earthquake inferred slip (Figure 2c). That we do not see an immediate dramatic increase in slip rate on the SF but rather the beginning of a slow increase in activity is consistent with finite rupture models of the LP earthquake that add only a small increase in Coulomb stress to the SF such as that of *Wald, et al.* [1991] (Figure 4). The gradual increase in activity may reflect a contribution from postseismic release at depth.

The general slip rate variation is consistent with the periodic pulsing observed by *Nadeau and McEvilly* [2004] though here we see a similar phenomena effecting two faults simultaneously, indicating that there must be some mutual driving or weakening mechanism in the system. Some possibilities include regional changes in pore fluid pressures which could mutually weaken the faults or gradual migration of slip from below the seismogenic zone toward the surface.

6. Conclusion

The effects of the 1989 Loma Prieta earthquake were both immediate, as in the case of short lived transiently repeating earthquakes, and enduring, as in the case of the gradual increase of activity on the Sargent Fault, likely due to post-seismic relaxation. A qualitative interpretation of the correlated pulsing on the San Andreas and Sargent Faults after about 1999 points to deep-seated loading or weakening transients in the subsurface.

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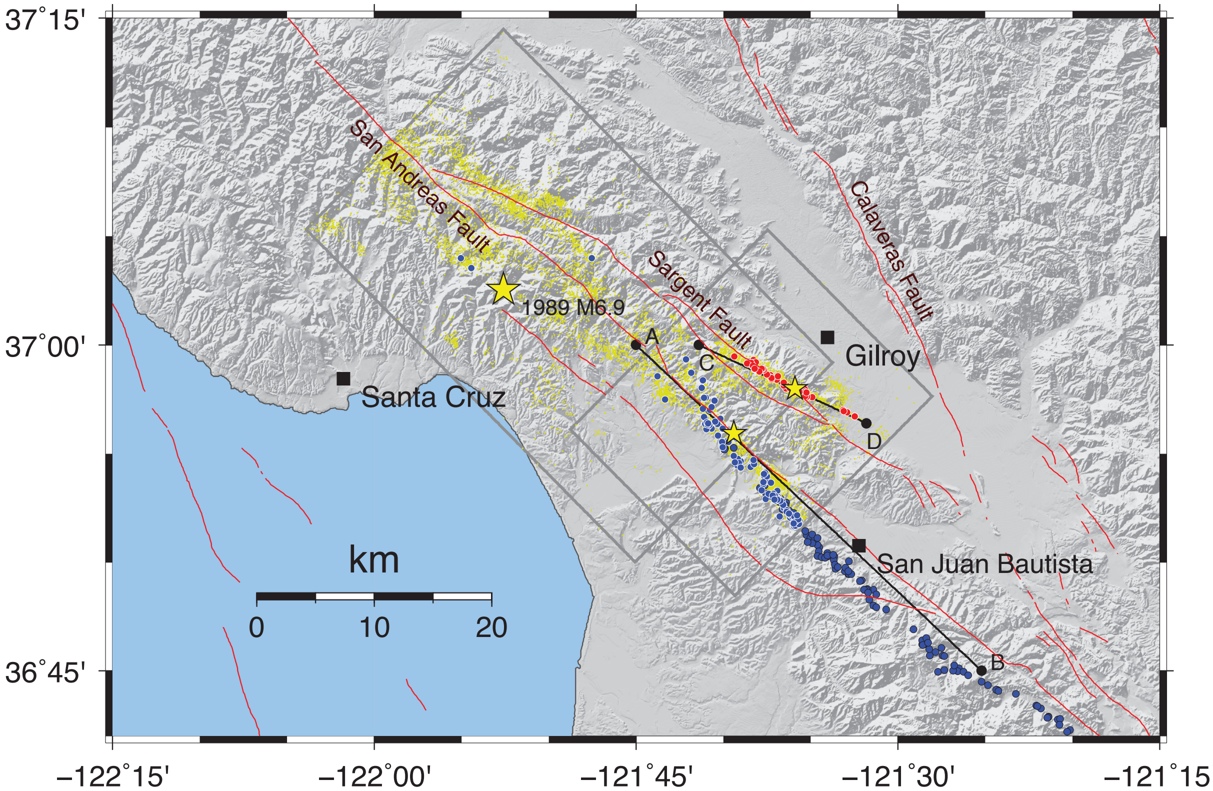

Figure 1. The map shows the overlapping areas in which seismicity has been analyzed boxed in gray with background seismicity shown as yellow points; active faults shown in red include the San Andreas, Sargent, Southern Calaveras-Paicines and Quien Sabe Faults. The dark-ringed blue dots show the previously known repeaters while the newly identified repeaters of this study are light-ringed. The stars mark the epicenters of the 1989 M6.9 Loma Prieta earthquake, the 1990 M5.4 Chittenden earthquake and the 2002 M4.9 on the Sargent Fault. The lines AB and CD show the surface traces of the cross-sections shown in Figure 4.

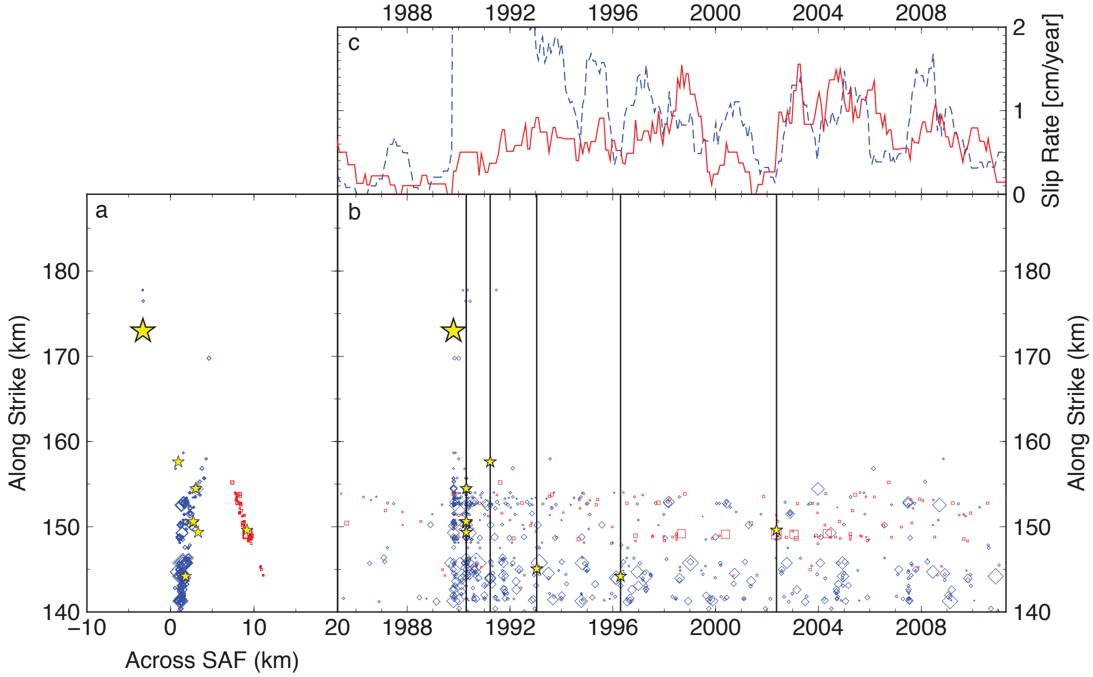

Figure 2. a) Repeaters in map view where the y-axis is the distance along strike from the Parkfield epicenter and the x-axis is the distance from the general strike of the SAF. b) Repeaters in time, along strike. c) Slip rates in cm/yr, calculated from repeating earthquake sequences. Slip rates on the SAF immediately after LP are well off this scale, maxing out at 20 cm/yr in our smoothed projection. In all panels, blue events are on the SAF, red on the SF, with repeaters scaled relative to each other by slip area. The smaller stars, not scaled to the repeaters, show M¿4.5 earthquakes beginning in 1990. Events coincident with significant slip transients are noted. The larger star marks the epicenter of the 1989 Loma Prieta earthquake.

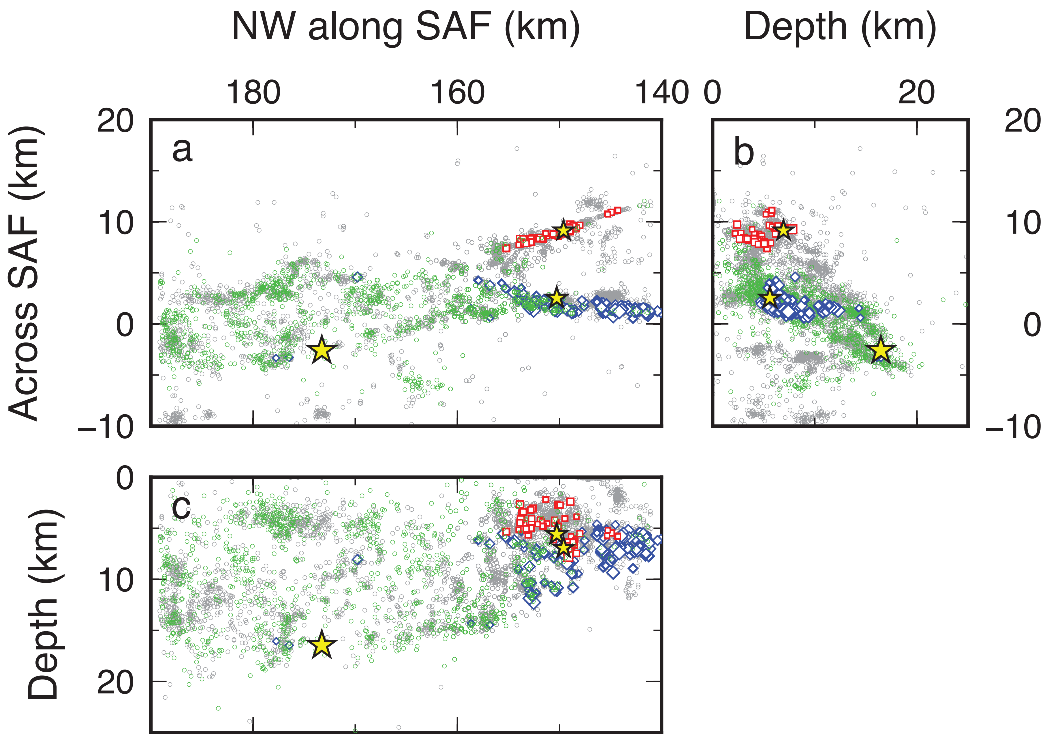

Figure 3. Clockwise from top-left, repeaters are shown here in map view (a), in depth across the faults (b), and in depth along the faults (c). In all panels, blue repeaters are on the SAF, red on the SF. The grey circles show background seismicity and the green circles show all events within a week of the LP earthquake. The LP earthquake, the April 1990 M5.4 Chittenden aftershock, and the 2002 M4.9 earthquake on the Sargent Fault are shown as yellow stars.

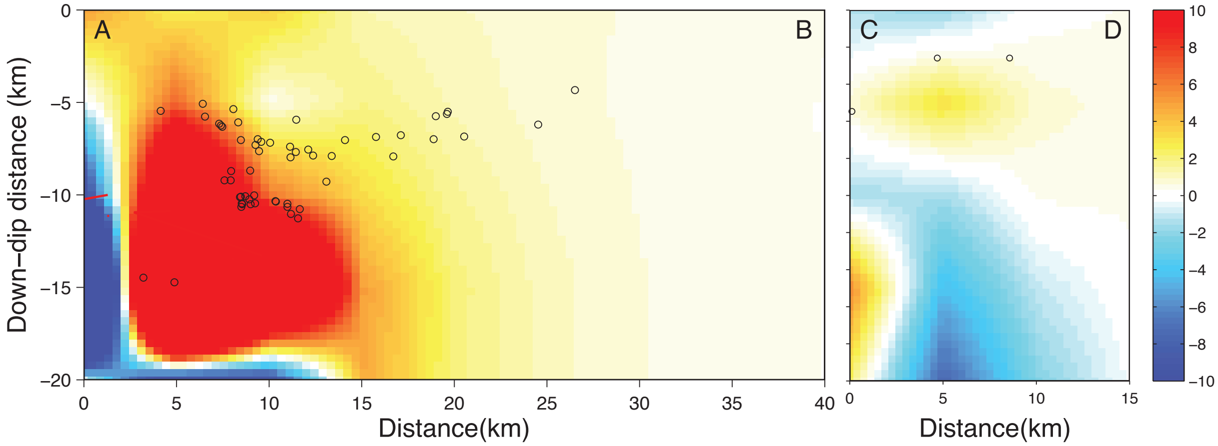

Figure 4. This cross-section shows repeating earthquakes for the week following the 1989 LP earthquake overlaid on the Coulomb stress change to the SAF (left) and the SF (right) from the 1989 LP earthquake based on the finite slip model of Wald, et al., 1991.