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Aseismic slip and fault interaction from repeating earthquakes in the Loma Prieta aftershock zone

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[1] 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 deep slip rates on both the northwestern end of the creeping section of the San Andreas Fault near San Juan Bautista and on the nearby subparallel Sargent Fault. While creep on the San Andreas increased dramatically due to static stress changes in response to the 1989 Loma Prieta earthquake, the Sargent showed very little immediate response, consistent with Loma Prieta finite slip models that put this section of the fault in a region of less than 3 bar Coulomb stress increase. After about 10 years, the San Andreas creep rate fell back close to the interseismic rate, and variations in creep became coherent in time with the Sargent, indicating a mutual driving force in the system.**Citation:** Turner, R. C., R. M. Nadeau, and R. Bürgmann (2013), Aseismic slip and fault interaction from repeating earthquakes in the Loma Prieta aftershock zone, *Geophys. Res. Lett.*, *40*, doi:10.1002/grl.50212.

1. Introduction

[2] 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 identifying 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 event recurrences 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 less well-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).

All Supporting Information may be found in the online version of this article.

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[3] We find the expected transient to high repeater activity on the SAF associated with afterslip resulting from the 1989 Loma Prieta *M*6.9 earthquake (LP) [*Schaff et al.*, 1998; *Nadeau and McEvilly*, 2004]. However, we see little evidence for immediate rate changes on the SF, 5–10 km away to the northeast and subparallel to the SAF (Figure 2). As the high slip rate on the SAF decays over about 9 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

[4] We consider earthquakes from March 1984 through April 2011 in two rectangular swathes aligned along the strike of the SAF (Figure 1). This data set extends to the northwest the existing catalog of repeating earthquake sequences identified by *Nadeau and McEvilly* [2004] beyond the creeping section of the central SAF and into the LP aftershock zone—a task more readily accomplished now with greater available computing power. The areas were chosen to include neighboring subparallel faults in the search for repeating earthquake activity, particularly the Sargent Fault (SF) which is known to have geodetically documented aseismic dextral creep [*Prescott and Burford*, 1976].

[5] The methods used for sequence identification are described in the supplementary material of *Nadeau and McEvilly* [2004], with the details specific to this study (stations per event pair, distances of stations used, specific channels and frequencies used in cross-correlation) included in the Supporting Information to this paper. The method relies 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. Sequences whose average event magnitudes were less than 1.5 were also not used in order to minimize issues with catalog completeness.

[6] The properties of these characteristically repeating earthquake sequences have allowed the development of an empirical relationship between earthquake moment and fault slip [*Nadeau and Johnson*, 1998; *Nadeau and McEvilly*, 2004], which has proven to be remarkably robust in various tectonic settings [*Chen et al.*, 2007].

$$d_i = 10^{\alpha} M_0^{\beta} \quad (1)$$

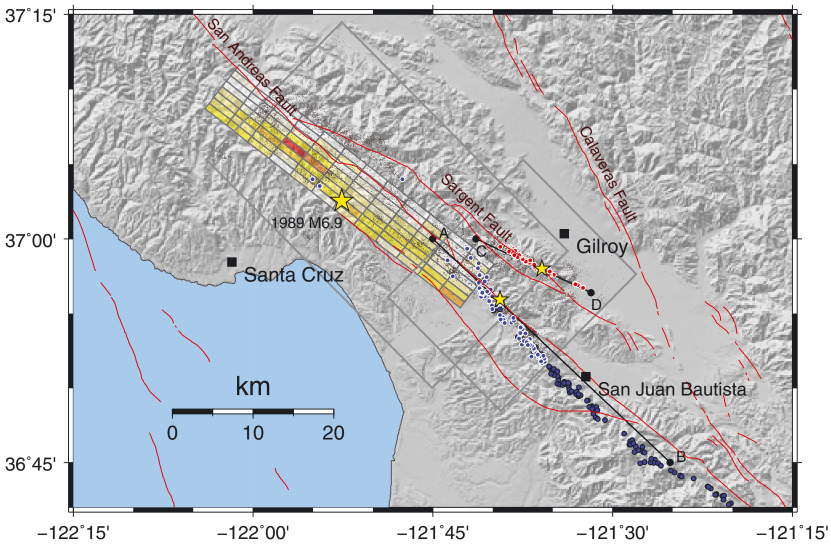

Figure 1. The map shows the overlapping areas in which seismicity has been analyzed boxed in gray with background seismicity shown as black points; dark-ringed blue dots show the previously known repeaters, while the newly identified repeaters of this study are light-ringed. Active faults are shown in red. The stars mark the epicenters of the 1989 *M*6.9 Loma Prieta earthquake, the 1990 *M*5.4 Chittenden earthquake, and the 2002 *M*4.9 on the Sargent Fault. The color-coded rectangular grid represents the surface projection of the slip model of *Wald et al.* [1991] with red indicating a peak slip of 5.13 m. The lines AB and CD show the surface traces of the cross-sections shown in Figure 4.

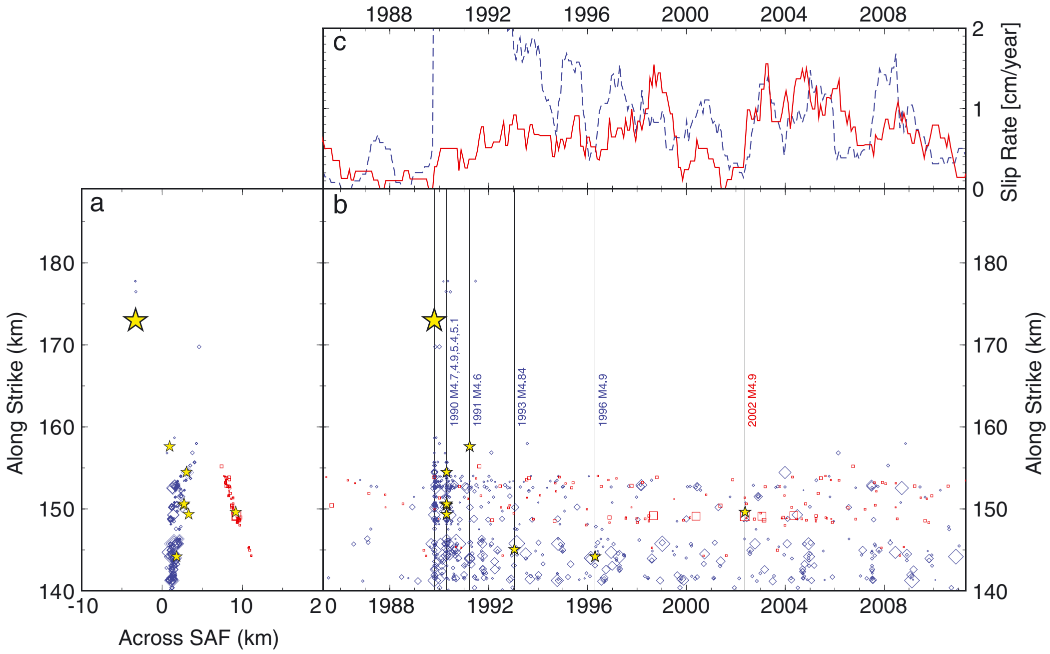

Figure 2. (a) Repeaters in map view where the *y* axis is the distance along strike from 35.955°N, 120.495°W near Parkfield, CA, and the *x* axis is the distance from the general strike of the SAF. (b) Repeaters in time, along strike. (c) Slip rates in centimeters per year (cm/yr), calculated from repeating 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. The smaller stars, size 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.

where d_i is slip in centimeters and M_0 is seismic moment in dyne-centimeters, inferred from NCSN preferred magnitudes (M_p) using the empirical relationship $\log(M_0) = 1.6M_p + 15.8$ [*Wyss et al.*, 2004]. Values for α and β used in this study are $\alpha = -2.35 \pm 0.2$ and $\beta = 0.17 \pm 0.001$ based on calibration with geodetic data at Parkfield [*Nadeau and Johnson*, 1998] and verified in numerous locations and environments. The seemingly high

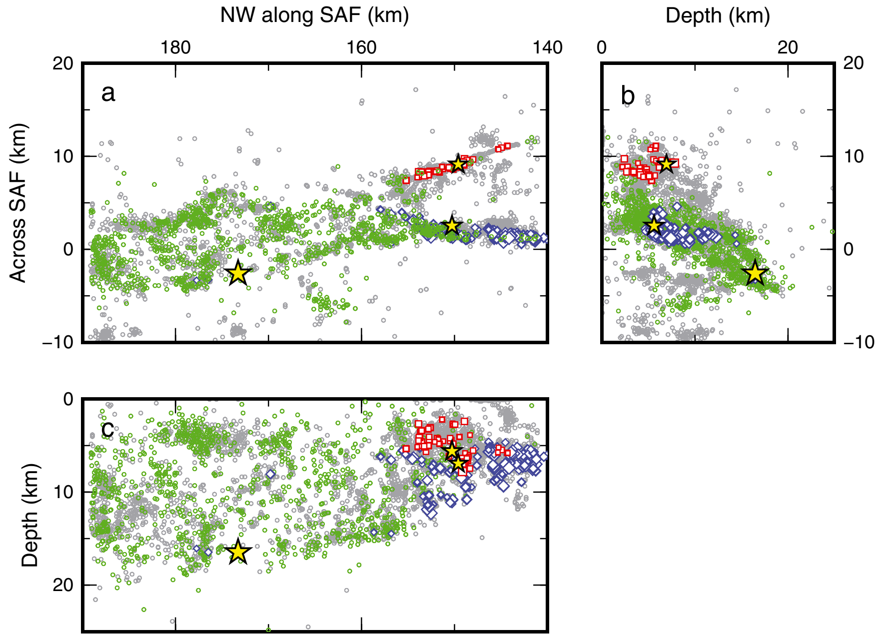

Figure 3. Clockwise from top left, repeaters are shown here (a) in map view, (b) in depth across the faults, and (c) in depth along the faults. In all panels, blue repeaters are on the SAF, red on the SF. The gray circles show background seismicity, and the green circles show all events within a week of the LP earthquake. The LP earthquake, the April 1990 *M*5.4 Chittenden aftershock, and the 2002 *M*4.9 earthquake on the Sargent Fault are shown as yellow stars. The coordinate system is as described in Figure 2. Note that in Figure 3a, aftershocks are plotted on top of the repeaters to emphasize their extension into the creeping SAF. In Figures 3b and 3c, the repeaters are plotted on top of the aftershocks to emphasize the trend to greater depths in the northwest.

slip per event and implied stress drops associated with this empirical relation are understood as a product of heterogeneity [*Dreger et al.*, 2007] and/or the magnitude-dependent contribution of aseismic creep to the repeating earthquake slip budget [*Beeler et al.*, 2001; *Chen and Lapusta*, 2009]. To obtain a time series of slip rate from a population of repeating sequences, the average slip rate is computed within a rolling 0.8 year window moving in 30 day increments, with the average slip rate plotted at the time of the end of the averaging window (Figure 2c).

3. Repeating Earthquakes Near San Juan Bautista

[7] The most obvious feature of the repeater catalog, particularly in map view (Figures 1 and 2a), is that (with three exceptions that will be discussed further) repeating earthquake sequences do not 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 necessarily expect repeating earthquakes.

[8] 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.

[9] 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, having only one or two repeats. Although 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 ongoing 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 [*Segall et al.*, 2000]. Their locations are deep (8.3, 16.0 and 16.8 km) and suggest that they appear to be off the primary plane of the SAF and rather on the fault that ruptured in the LP earthquake and in the west dipping thrust faults to the northeast.

[10] The distribution of repeating earthquake sequences illuminates the geometry and extent of creeping portions of the SAF and SF. 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 (see Supporting Information). 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,

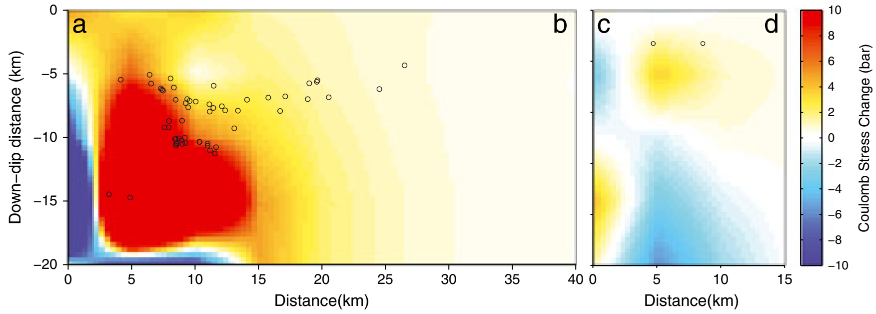

Figure 4. This cross-section shows repeating earthquakes for the week following the 1989 LP earthquake overlaid on the Coulomb stress change (in bars) to the SAF (left) and the SF (right) from the 1989 LP earthquake based on the finite slip model of *Wald et al.* [1991]. A surface trace of the cross-sections can be seen in Figure 1. Points A and B correspond to approximately 162 km and 121 km in our strike-parallel coordinate system referred to in Figure 2.

located at a similar position along strike, suggesting a feature across or between the two faults. Indeed, while it is difficult to resolve a feature of such small scale, *Lin and Thurber* [2012] observe a low velocity structure in this area.

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

[11] Before the LP earthquake, the SF tapers to a very low rate of 1–2 mm per year, while the SAF, initially 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 nonrepeating aftershocks occur. The 0.8 year smoothed SAF slip rate peaked at 200 mm/year before gradually falling back closer to about 10 mm/yr by year 2000—still well above the pre-seismic rate of about 2.5 mm/yr. Meanwhile, the SF creep rate inferred from the repeaters shows only a modest initial rise that continues to gradually increase for the next 9 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 10 years but is less apparent beginning in 2010.

[12] 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 a strong 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

[13] 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 [*Toda et al.*, 2011]. The Coulomb stress change map is based on the rupture model of *Wald et al.* [1991] and takes the coefficient of friction on the SAF and SF to be μ=0.2. Other rupture models were tested including those of *Beroza* [1991], *Steidl et al.* [1991], and *Emolo and Zollo* [2005], the results of which can be seen in the Supporting Information to this paper.

[14] The coseismic Coulomb stress changes of up to 70 bar associated with LP strongly encouraged 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 on the SF and enduring acceleration on the SAF may reflect a contribution from postseismic viscoelastic relaxation at depth as described by *Pollitz et al.* [1998].

[15] The general slip rate variation is consistent with the periodic pulsing observed by *Nadeau and McEvilly* [2004], although here we see a similar phenomenon affecting two subparallel faults simultaneously, indicating that there is 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 time-dependent shear below the seismogenic zones of both faults. Further correlations between the faults are shown in Figure 2b, where several of the $M > 4.5$ events after 1990 on the SAF and SF are seen clearly to correspond in time with dramatic slip rate increases on one or both faults.

6. Conclusion

[16] 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 10 year-long creep acceleration on the SAF and the gradual increase of activity on the SF, likely due to postseismic 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. This also represents a

continuation to the north of the pulsing behavior along the length of the creeping section of the SAF observed by *Nadeau and McEvilly* [2004].

[17] With the exception of two repeating earthquake pairs that we associate with short-term postseismic afterslip rather than background slip, no repeating earthquakes are found among the abundant aftershocks of the LP rupture zone (Figure 3). On the SF, the repeaters also stop rather abruptly as one moves to the northwest, but there remains, again, abundant seismicity.

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