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Nonlinear strong ground motion in the M_L 5.4 Chittenden earthquake: Evidence that preexisting damage increases susceptibility to further damage

Justin L. Rubinstein and Gregory C. Beroza

Department of Geophysics, Stanford University, Stanford, California, USA

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[1] We use 55 repeating earthquake sequences located near the 1989 M_w 6.9 Loma Prieta earthquake to identify time dependent velocity changes in the shallow crust. In addition to large delays caused by the Loma Prieta mainshock, the M_L 5.4 Chittenden earthquake, an aftershock of Loma Prieta, caused direct *S* wave delays of up to 6ms and *S* coda delays exceeding 15ms. We attribute the delays to cracks formed or opened during the strong shaking of the Chittenden earthquake, the same mechanism believed responsible for the delays observed following Loma Prieta. The magnitude of the delays caused by Chittenden strongly correlate with those caused by Loma Prieta. This suggests that rocks recently damaged by nonlinear strong ground motion are particularly susceptible to further damage until they are completely healed. Therefore, we expect that the onset of nonlinearity will occur at substantially lower ground motion for large aftershocks than would otherwise be anticipated. *INDEX TERMS:* 5104 Physical Properties of Rocks: Fracture and flow; 3220 Mathematical Geophysics: Nonlinear dynamics; 7212 Seismology: Earthquake ground motions and engineering. **Citation:** Rubinstein, J. L., and G. C. Beroza (2004), Nonlinear strong ground motion in the M_L 5.4 Chittenden earthquake: Evidence that preexisting damage increases susceptibility to further damage, *Geophys. Res. Lett.*, *31*, L23614, doi:10.1029/2004GL021357.

1. Introduction

[2] Previous studies have observed significant velocity reductions coincident with large ($M > 6$) earthquakes, including the Loma Prieta earthquake [*Rubinstein and Beroza*, 2004], the Morgan Hill earthquake [*Schaff and Beroza*, 2004], the Hector Mine earthquake [*Li et al.*, 2003], the Landers earthquake [*Li et al.*, 1998], and the Izmit and Duzce earthquakes [*Peng and Ben-Zion*, 2004]. For observations away from the fault (>1 km), the velocity reductions are believed to be caused by strong shaking damaging rocks (nonlinear strong ground motion) [*Rubinstein and Beroza*, 2004; *Schaff and Beroza*, 2004; *Vidale and Li*, 2003]. This mechanism requires particularly strong shaking (large earthquakes) to produce significant velocity changes. There is some evidence that medium magnitude earthquakes can also cause velocity reductions, albeit small ones; *Rubin* [2002] documented *S* delays of 2ms and *P* delays of 1ms at a station 10 km away from a M4.7 earthquake.

[3] In this study, we examine velocity reductions caused by another medium magnitude earthquake, the M_L 5.4 Chittenden earthquake, the largest aftershock of the M_w 6.9 Loma Prieta Earthquake. The delays associated with it are much larger than those observed by *Rubin* [2002] in both magnitude (*S* delays > 5ms) and spatial extent (*S* delays > 2ms at distances exceeding 40 km), despite the fact that the earthquakes are similar in size. To explain this difference, we propose a model whereby the preexisting damage from the Loma Prieta earthquake made these sites more vulnerable to further damage by the Chittenden earthquake.

2. Data and Methods

[4] The data and techniques used in this paper are the same as those used in *Rubinstein and Beroza* [2004], where a complete description of the data and methodology can be found. Below is a summary of our data and methods.

[5] We study 55 repeating earthquake sequences (multiplets) on the San Andreas Fault just south of the rupture zone of the 1989 Loma Prieta earthquake to identify time varying seismic velocity changes (Figure 1). Cross-correlation measurements reveal that events within multiplets are all located within meters of each other. These events were recorded by the Northern California Seismic Network (NCSN) and archived at the Northern California Earthquake Data Center (NCEDC). The NCSN is a network of high gain, short period seismometers that record at 100 samples per second. The events span from 1984 through the end of 1999. The aftershock sequences of Loma Prieta and Chittenden brought a sudden increase in the rate of repeating events [*Schaff et al.*, 1998], improving the temporal resolution at which we can observe the velocity changes.

[6] The Chittenden earthquake sequence occurred April 18–19, 1990, approximately six months after the Loma Prieta earthquake (October 17, 1989) and was a period of increased seismic activity during which thirteen $M > 3$ earthquakes occurred in a small region just to the southeast of the rupture zone of the Loma Prieta earthquake. This swarm had a series of twelve $M > 3$ earthquakes within 4 hours on April 18 that was comprised of seven $M > 4$ earthquakes and two $M > 5$ earthquakes. The thirteenth $M > 3$ earthquake occurred approximately 24 hours after the first $M > 3$ earthquake. The largest earthquake in this sequence was M_L 5.4, which we refer to as the Chittenden earthquake.

[7] We use a moving window cross correlation technique to identify temporal changes in wavespeed manifest as late/early arriving phases in a repeating earthquake sequence (Figures 2a and 2b). We only examine vertical components and clipped data are removed. The correlation uses

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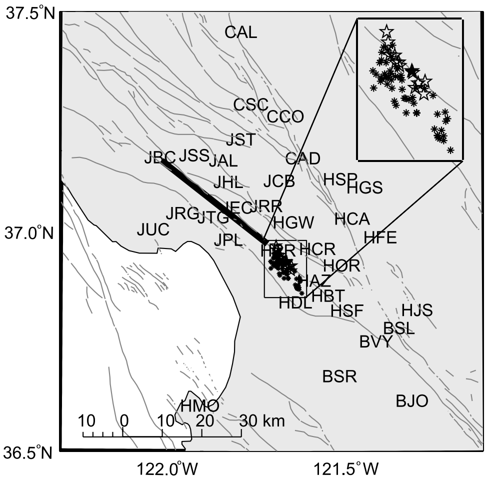

Figure 1. Map of the study region showing: NCSN stations used in this study, vertical projection of the upper limit of the Loma Prieta rupture as thick solid line (planar model from *Marshall et al.* [1991]), epicenters of 55 multiplets as asterisks, events of the Chittenden earthquake sequence as unfilled stars, the M_L 5.4 Chittenden earthquake as a filled star, and mapped faults as thin, grey lines.

128 sample windows that are weighted by a Hanning function and are shifted at 5 sample increments. Prior to the cross-correlation, all the traces for each multiplet at each station are aligned to the manually picked *P* arrival of the reference event for that multiplet-station pair. As a result, the delay that we compute is the difference between the *S* (or other phase) minus *P* times of the reference and data events.

[8] Although delays are largest in the *S* coda (Figures 2c, 2d, and 2e), we examine the delays of the direct *S* wave because it is more consistent from multiplet to multiplet than the early *S* coda. The delays we measure can be treated as differences between two points on a time varying station correction function (of *S* delays), hereafter referred to as the *S* delay function. We estimate the function at each station using the *S* delays computed from the cross-correlation measurements as the data (Figure 3). This function is discretized irregularly in time, with more samples following both the Loma Prieta and Chittenden earthquakes. The reasoning for this is twofold: there is more data (higher seismicity rate for the repeating earthquakes) immediately following these two earthquakes and the change in the *S* delay function is largest in these time spans as well. Using the *S* delay function, we compute the delays caused by the Chittenden and Loma Prieta earthquakes for each station. The coseismic delay is the difference between the value of the *S* delay function of the days before and after the earthquake.

3. Results

3.1. Observations

[9] Immediately following the Chittenden earthquakes, we observe a sudden increase in delays varying in strength

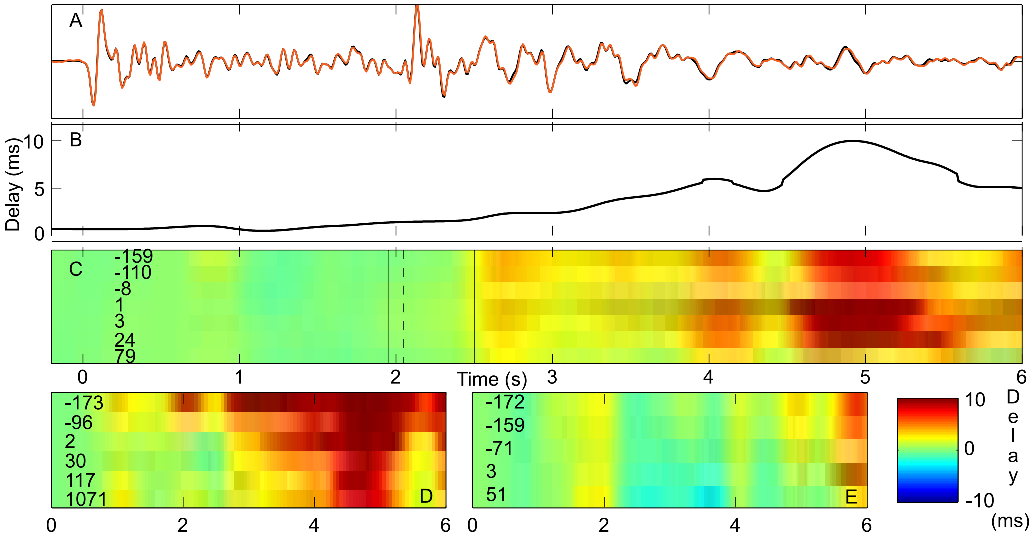

Figure 2. (a) Seismograms from events 3 (black) and 4 (red) in repeating earthquake sequence 27, recorded by HGW. Event 4 was one day after the Chittenden earthquake. Event 3 was 8 days before the Chittenden earthquake. The seismograms are aligned on the *P* arrival and plotted on the same time axis, where time is seconds after the *P* arrival. Note the separation between the two traces with time into the trace. (b) Relative delay between event numbers 3 and 4 for multiplet 27 at HGW. The largest delays are in the *S* coda. (c) Relative delays for all of repeating sequence 27 recorded at HGW. Each horizontal line represents a seismogram, with calendar time increasing down the y-axis. Shading represents the delay of the seismogram represented by the horizontal stripe relative to the reference seismogram. Warmer shades represent larger delays. The column of numbers at time = 0.2s indicate the number of days after the Chittenden earthquake that the event occurred (negative numbers indicate number of days before it, Loma Prieta was 182 days before Chittenden). Note the first two events are soon after Loma Prieta and have large delays that decrease with time. The fourth event is just after Chittenden and shows a sudden increase in delays, which slowly decreases back towards zero. The dashed vertical line is a theoretical *S* arrival time pick, the solid vertical lines represent the bounds of the *S* wave window used to compute the *S* delay. (d) Multiplet 21 at JRR. (e) Multiplet 53 at HPR.

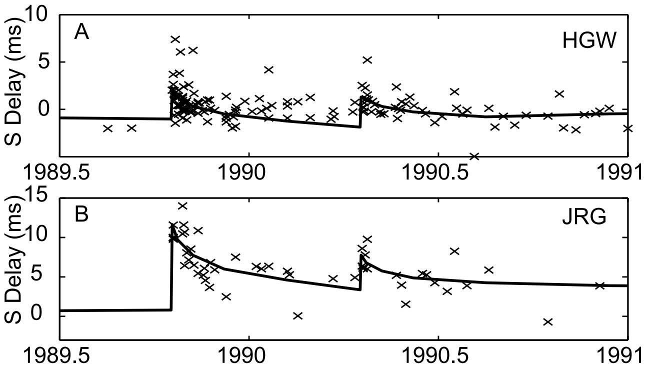

Figure 3. Raw *S*-delay values plotted versus time for all multiplets recorded by (a) HGW and (b) JRG. The *S* delay function for each station is overlain. To fit the delay measurements to the predictions of the *S* delay function, the *S* delay predicted for the reference event of each multiplet is added to delay values. This fits the data to the model because the delay value at the reference event is treated as zero in the delay calculation.

throughout the seismogram at many stations (Figure 2). The delays are largest in the *S* coda, with changes in delays coincident with Chittenden exceeding 15ms (e.g., JEC). The delays for other phases are still significant, including the *S* arrival where delays can exceed 5ms (e.g., JTG). Following the Chittenden earthquake sequence, the delays decrease with calendar time (Figures 2c–2e, 3, and 4). The healing of these delays is log-linear with time, the most rapid healing occurring immediately after the earthquake and healing slowing with increasing time after the earthquake (Figures 3 and 4). Although the behavior of the delays is consistent from station to station (sudden increase following the Chittenden earthquake sequence, delays being largest in the *S* coda, and a log-linear decay of delays following the earthquake sequence), the strength of the delays varies significantly (Figure 5). This behavior parallels the behavior of delays caused by the Loma Prieta earthquake as observed by the same stations for the same repeating earthquake sequences [*Rubinstein and Beroza*, 2004]. The similar time dependent behavior of the delays (both from event to event and within the individual seismograms) leads us to appeal to the same mechanism for both earthquakes, the growth and/or opening of cracks caused by the strong shaking of an earthquake.

3.2. Factors That Influence the Magnitude of Delays

[10] There is a weak dependence of the strength of the delays caused by the Chittenden earthquake on the distance to the Chittenden earthquake (Figure 5a); the stations with the largest delays tend to be closer to the Chittenden earthquake than those with smaller changes in delay. For example, station HPR is the closest station to the Chittenden earthquake. The change in *S* delays caused by the Chittenden earthquake at HPR is one of the largest we observe, exceeding 4ms. The correlation between the magnitude of Chittenden induced delays and distance to the Chittenden earthquake swarm, further supports our argument that nonlinearity in the strong shaking of the Chittenden earthquake caused the velocity reductions, because shaking should be strongest near the earthquake source. Unfortunately, strong motion "ShakeMaps" are unavailable for any of the members of the Chittenden earthquake sequence, so we cannot compare the strong shaking to the strength of observed delays. As a result, we are only left with distance to the earthquake as a measure of strong shaking.

[11] We find that the magnitude of the delays imparted by the Chittenden earthquake depends strongly on the magnitude of the delays caused by the Loma Prieta earthquake (Figure 5b). As the magnitude of the *S* delay caused by the Loma Prieta earthquake increases, the *S* delay caused by Chittenden increases as well. This suggests that rocks damaged by the Loma Prieta earthquake were more susceptible to further damage by strong ground motion in later quakes than those left undamaged by the Loma Prieta earthquake. To generalize, until a rock has completely healed from damage, it is in a weakened state and is more susceptible to further damage than it would be in an undamaged state. A similar phenomenon has been observed by *Vidale and Li* [2003], who observe increased delays in fault zone trapped waves on the not yet completely healed Johnson Valley Fault (damaged not by strong motion, but by the rupture of the 1992 Landers earthquake) caused by the 1999 Hector Mine earthquake, which occurred 7 years later and approximately 20–30 km away.

[12] We believe that the weakened state of the shallow crust after the Loma Prieta earthquake allowed the Chitten-

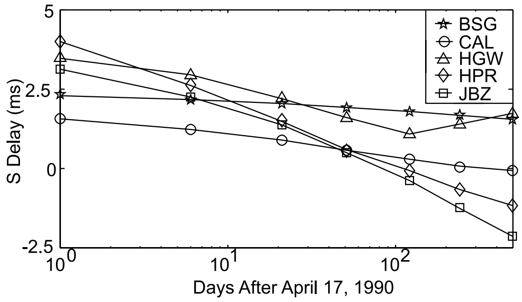

Figure 4. *S* delay function for stations BSG, CAL, HGW, HPR, and JBZ plotted against the logarithm of the number of days after April 17, 1990, the day before the Chittenden Earthquake.

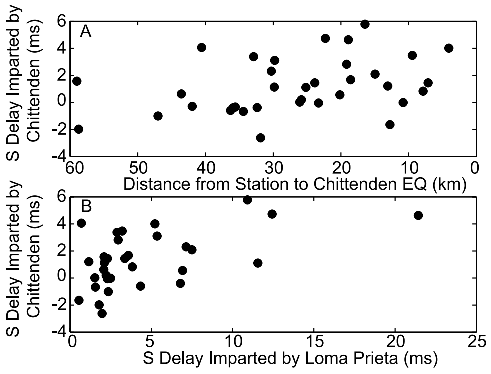

Figure 5. (a) Delay caused by Chittenden plotted versus distance of station to the Chittenden earthquake. (b) *S*-delay caused by Chittenden plotted versus *S*-delay caused by Loma Prieta.

den earthquake, a medium magnitude earthquake, to cause significantly more damage than it would have were it not soon after the Loma Prieta earthquake. To test this claim in detail would require a M5 earthquake that is isolated in time from larger earthquakes that has at least one repeat of a repeating earthquake sequence soon before and after it. We do not have data that meet these criteria.

3.3. Limitations and Outliers

[13] We believe that the velocity reductions we observe were caused by the Chittenden earthquake because it was the largest earthquake in the Chittenden earthquake sequence. We are unable to be certain whether the damage was caused solely by the M_L 5.4 Chittenden earthquake or if the accumulated effects of a number of events in the Chittenden sequence caused the delays. This cannot be tested because we have no repeats that occur in between events in the Chittenden sequence. Previous findings that show that the strength of shaking is the controlling factor in the strength of nonlinearity [*Rubinstein and Beroza*, 2004; *Guyer et al.*, 1998; *Ostrovsky et al.*, 2000] suggest that the majority of the damage was likely caused the M_L 5.4 Chittenden earthquake.

[14] For several stations the model indicates that there are negative delays coincident with the Chittenden earthquake, i.e., that the *S* wave is actually arriving faster immediately following Chittenden than it does prior to Chittenden (Figure 5). This would be in contrast to our findings for Loma Prieta and might suggest another mechanism; however, this effect is very small (<2ms advance) at all but one of these stations. An exhaustive examination of individual delay measurements at these stations does not show a sudden decrease in *S* arrival time for these stations coincident with the Chittenden earthquake. Instead, we find that these stations do not respond to the Chittenden earthquake, in that there is not a detectable increase or decrease in arrival times of any phase (not just the direct *S*) at these stations. The advance in arrival time that the *S* delay function shows is the continuing response to Loma Prieta (which at this point in time would be a healing of the delays caused by Loma Prieta—a decrease in delays). Our analysis allows this because in computing the *S* delay function we do not apply smoothing across the Chittenden earthquake.

[15] There are two stations, BPR and BSR that show a decrease in *S* arrival times coincident with the Chittenden earthquake. Because the stations are both very far away (>30 km) from the Chittenden earthquake, we suspect some process unrelated to the earthquake is affecting the near surface velocity at these stations.

4. Summary

[16] We have used repeating earthquake sequences to identify *S* arrivals that are consistently late immediately following the Chittenden earthquake sequence. This behavior has been previously observed at the same stations for the Loma Prieta earthquake as well. The similarity of the delays caused by the Chittenden earthquake and the delays caused by the Loma Prieta earthquake suggests that they are caused by the same process: the growth and opening of cracks caused by the strong shaking of the earthquake exceeding the strength of the local rocks near the surface (nonlinear strong ground motion). We are unable to differentiate whether the largest earthquake in the Chittenden earthquake sequence, M_L 5.4, is responsible for the observed change in delays or if the cumulative effect of some/all of the medium magnitude events in the sequence (five M4.0–4.9 events and two M5.0–5.4 events) that caused the velocity reductions. Because the shaking was strongest in the largest event, we believe that most, if not all, of the damage was caused by the M_L 5.4 Chittenden earthquake. Either way, the magnitude of and the spatial extent to which we observe the delays caused by Chittenden exceed what we would expect had the Chittenden earthquake sequence not occurred in the aftermath of the larger, Loma Prieta earthquake. We believe that the weakened condition of rocks that Loma Prieta left facilitated and significantly increased the damage that the Chittenden earthquake sequence was able to cause. The correlation between the strength of delays caused by the Loma Prieta earthquake and the delays caused by the Chittenden earthquakes supports this argument. From this, we infer that earth materials recently damaged by nonlinear strong ground motion are more susceptible to subsequent nonlinearity in strong shaking than they are in an undamaged state.

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G. C. Beroza and J. L. Rubinstein, Department of Geophysics, Stanford University, 397 Panama Mall, Stanford, CA 94305–2215, USA. (justin@pangea.stanford.edu)