# Identifying undetected early aftershocks and non-volcanic tremors associated with the 12 August 1998 Mw 5.1 San Juan Bautista earthquake and slow slip event

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Aftershocks are triggered by abrupt changes of stress induced by a larger earthquake. Detailed images of spatiotemporal changes in aftershock activity help delineate the mainshock rupture area. However, large numbers of early aftershocks are not detected because they are masked by large-amplitudes and long-duration of seismic coda waves from the mainshock and other aftershocks. Peng and Zhao [2009] have demonstrated that ~10,000 aftershocks following the 2004 M 6.0 Parkfield earthquake were undetected by the standard earthquake-detection algorithm of the Northern California Seismic Network (NCSN).

We focus on the detection of uncatalogued aftershocks following the 12 August 1998 Mw 5.1 San Juan Bautista (SJB) earthquake. This event was the largest historic earthquake in the SJB area and was associated with a large slow slip event [Uhrhammer et al., 1999]. Additionally, Nadeau and McEvilly [2004] and Templeton et al [2008] found accelerations in repeating microearthquake frequency accompanying the 1998 slow slip event.

Following Peng and Zhao [2009], we have been identifying undetected early aftershocks with a cross-correlation based approach. We use waveforms from 248 SJB earthquakes detected by the NCSN during a 10-day period spanning the 1998 SJB earthquake (9 August through 18 August, 1998) as templates to identify additional, previously undetected earthquakes. Using continuous data recorded by the closest two seismic stations to the 1998 SJB event (BK.SAO and NC.BVY; less than 4 km from the mainshock), our preliminary analysis has detected ~900 individual earthquakes, with the averaged cross-correlation threshold of 0.7 (Figure 1). We have identified four times more aftershocks than listed in the NCSN catalog (Figure 2). We also searched for small foreshocks immediately preceding the mainshock [e.g., Dodge el al., 1996; Bouchon et al., 2011], but no events were detected during the 2 minutes preceding the mainshock.

The locations of the newly detected events will be estimated by a waveform cross-correlation based double-difference relocation. We currently assign the locations of the detected events to that of the template events providing the highest cross-correlation values (Figures 2a and 2b). With the detected early aftershocks, we find that a highly productive burst of aftershocks started 17 hours after the mainshock (Figure 2c). In this aftershock episode, ~100 events occurred within a 3-hour period. These aftershocks occurred in the northwest part of the rupture area (Figure 2c). This aftershock episode may be the result of the redistribution of stress induced by the 1998 SJB earthquake. Strain and creepmeter data of the associated slow slip event do not resolve an acceleration of slip associated with this accelerated aftershock activity.

Both triggered and ambient tremors are found in the SJB region. Gomberg et al. [2007] and Peng et al. [2009] recently identified several triggered tremor events induced by the passage of teleseismic surface waves near SJB and Bitterwater, California. Our preliminary work found a number of instances of ambient tremor (i.e., tremor not triggered by the passage of surface waves) emanating from the SJB area, including the time of the 1998 slow slip event (Figure 3).

As with the Parkfield tremor, differences (i.e., moveout) in the arrival times of tremor energy over widely distributed stations are small, indicating the tremors are occurring at great depth. In addition to the examples shown in Figure 3, several other ambient tremor events were identified during our preliminary search. We suspect, therefore, that as in the Parkfield-Cholame region [Nadeau and Guilhem, 2009; Shelly, 2009], ambient tremor in the SJB region is an ongoing process that is sensitive to small stress changes and that its activity through space and time will reflect stress and deformation changes in the lower crust [e.g., Rubinstein et al., 2009; Thomas et al., 2009], possibly induced by slow slip events, the occurrence of moderate earthquakes or larger-scale tectonically driven processes.

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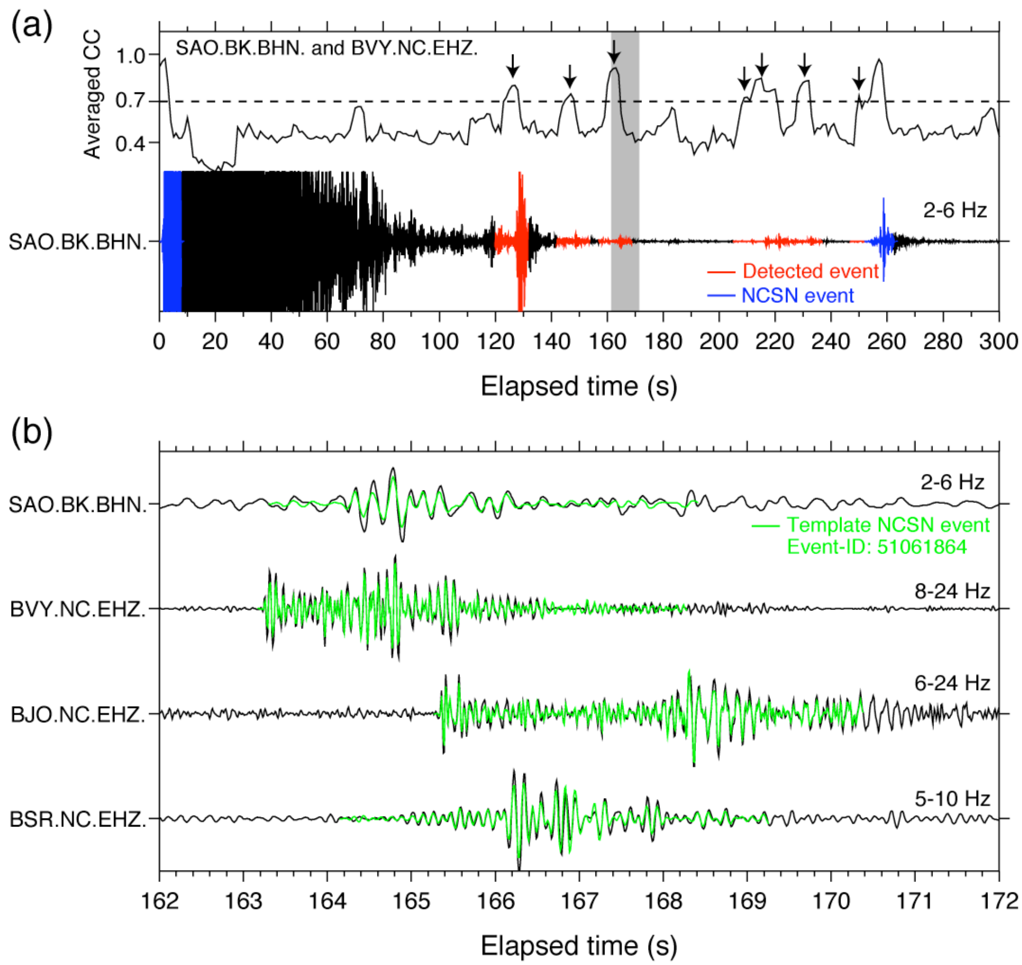


**Figure 1.** Identified early aftershocks following the 1998 Mw 5.1 SJB earthquake. (a) Top panel shows averaged cross-correlation functions based on SAO.BK.BHN and BVY.NC.EHZ data. Highest cross-correlation values were plotted at individual time steps from cross-correlation functions for the 248 template events. Black arrows indicate identified events using the threshold with averaged cross-correlation value of 0.7 (dashed line). Bottom panel shows observed seismograms (black) recorded at BK.SAO in the N-S component with a 2-6 Hz bandpass filter. Waveforms shown in red and blue are the newly detected events and the NCSN events (the first 10-s data). (b) Detected early aftershock at ~160 s after the mainshock shown in grey area in Figure 1a using the template event nc51061864 (M 0.85) occurring ~4 days after the mainshock. Waveforms shown in black and green are the continuous waveforms and the template waveforms.

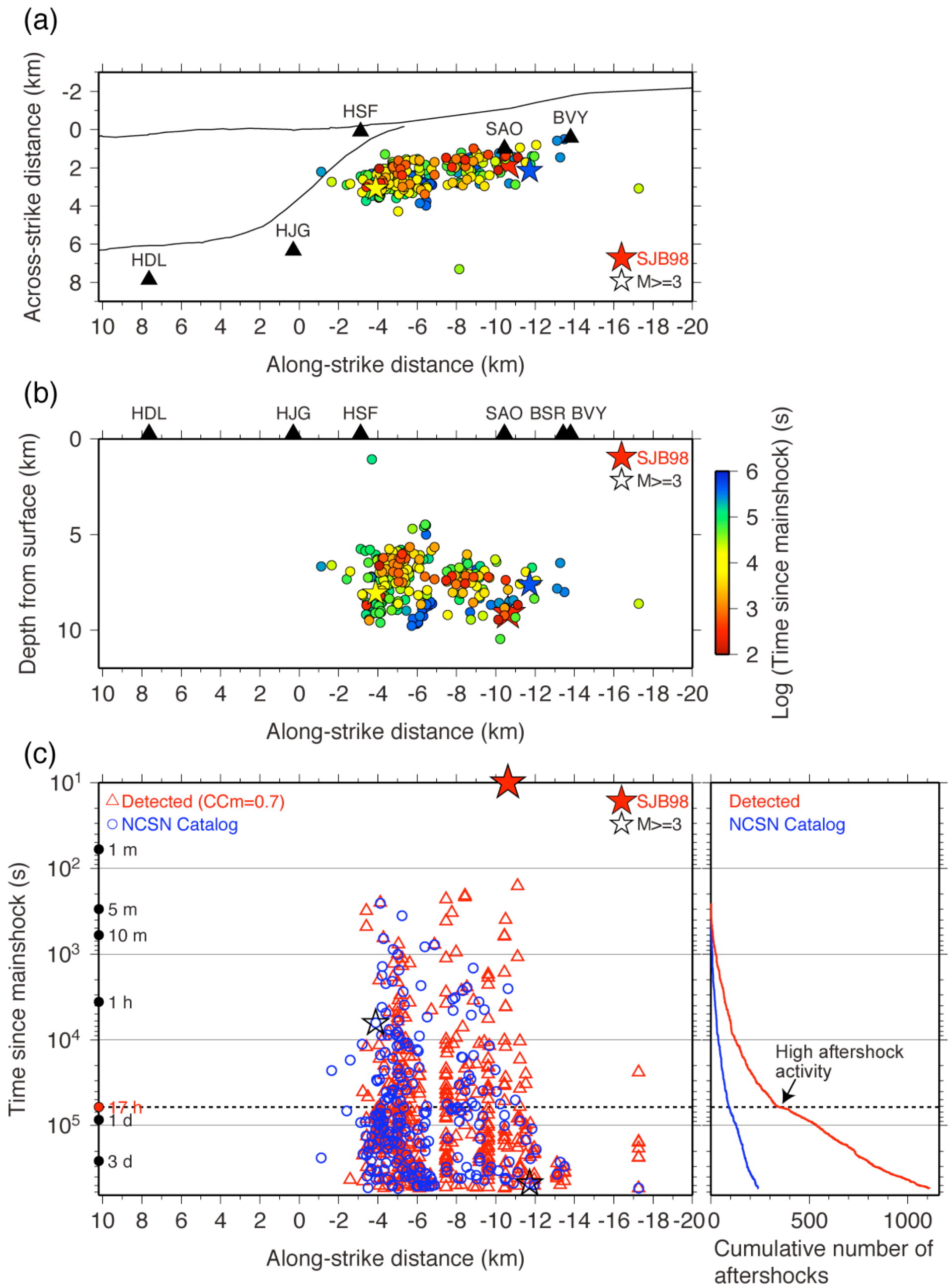


**Figure 2.** Aftershock seismicity following the 1998 SJB earthquake. (a) Map and (b) cross-section views of the newly detected and NCSN events along the San Andreas fault in the SJB area color-coded by the logarithmic time after the mainshock (red star). Triangles are seismic stations. (c) Left panel shows the occurrence times of aftershocks since the 1998 SJB mainshock as a function of the along-strike distances. The blue circles are the events listed in the NCSN catalog and the red triangles are newly detected events by the cross-correlation analysis. Right panel shows the cumulative numbers of aftershocks by the NCSN catalog (blue) and this study (red).

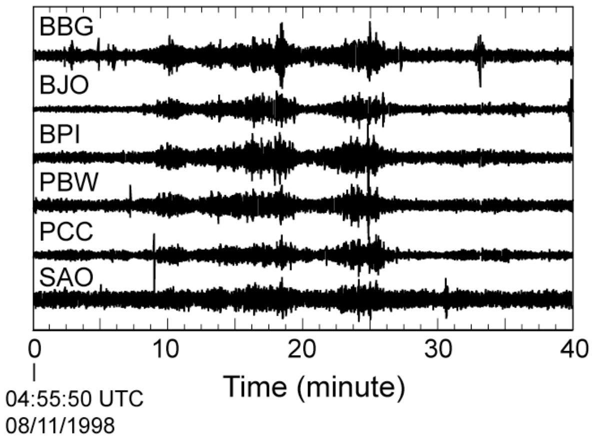


**Figure 3.** Ambient non-volcanic tremor (i.e., not triggered by teleseismic surface waves) associated with the 1998 slow slip event and the 1998 Mw 5.1 SJB earthquake. This tremor occurred in the ~30 hours preceding the 1998 SJB mainshock. Seismic data is bandpass filtered between 1.5 and 8 Hz.