Summary

To construct the Modified Mercalli Intensity (MMI) ShakeMap for the 1868 Hayward earthquake, we started with two sets of damage descriptions and felt reports. The first set of 100 sites was compiled by A.A. Bullock in the Lawson (1908) report on the 1906 San Francisco earthquake. The second set of 45 sites was compiled by Toppozada et al. (1981) from an extensive search of newspaper archives. We supplemented these two sets of reports with new observations from 30 sites using surveys of cemetery damage, reports of damage to historic adobe structures, pioneer narratives, and reports from newspapers that Toppozada et al. (1981) did not retrieve. The Lawson (1908) and Toppozada et al. (1981) compilations and our contributions are assembled in the Site List.

The Modified Mercalli Intensities for these localities were evaluated using the Stover and Coffman (1993) version of the MMI scale, as implemented by Boatwright and Bundock (2005) in their analysis of the 1906 San Francisco earthquake. Because the cemeteries damaged by the 1868 earthquake were damaged again forty years later by the 1906 earthquake, we had to devise a new methodology for analyzing cemetery damage. The correspondence between building damage and intensity was also adjusted to accommodate the relative fragility of the American pioneer masonry and Mexican adobe buildings.

For a few sites, specifically San Francisco and in the East Bay, the descriptions of damage and shaking are reasonably complete. For more distant sites in Monterey, Santa Cruz, and Sonoma Counties, however, the descriptions can be extremely brief. At further distances, the descriptions are simply lists of localities where the earthquake was "felt". In generating the new MMI intensity maps, all 170 sites were identified and located. However, some intensities were not used because the reported effects were implausibly strong. For instance, Lawson (1908) reported that a stone house built by John Wolfskill near Winters (at *r* ~ 140 km from the fault) was strongly damaged by the earthquake. This effect implies an MMI 7-8 intensity level, where the next most distant MMI 7-8 occurred in Pacheco, *r* ~ 50 km from the fault.

Even with these additional sites (~35 new or significantly revised intensities, about 20% of the total), the spatial density of the 1868 intensities does not approach the density obtained by Boatwright and Bundock (2005) for the 1906 earthquake. There were simply

far fewer people and newspapers in California in 1868 than there were in 1906, and the newspaper reports were less reliable. The detailed (small scale) ShakeMaps included in this report for San Francisco, Oakland, Hayward, and San Jose demonstrate the lack of population. The street grids indicate the “built-up” areas, and the intensity sites are plotted as yellow diamonds. The railroad linking San Francisco, Oakland, and San Jose are also shown with dashed green lines: the transcontinental railroad was completed only six months after the 1868 earthquake.

In contrast to the isoseismal maps drawn by Stover and Coffman (1993) and Toppozada et al. (1981), ShakeMap interpolates values from a model attenuation curve that has been adjusted to fit the real data rather than contouring the intensity data. The relative scarcity of intensity sites makes the method of interpolation critical. In particular, ShakeMap fills out the unequally spaced intensity estimates by interposing false sites in areas without data. Interpolation of intensity data accounts for soil classes at each interpolated site. The attenuation relations used to generate the intensity estimates at these sites are a mixture of the PGA and PGV attenuation relations from Boore et al. (1997) where the overall amplitudes (the source terms) are adjusted to fit the isoseismal data. To fit the 1906 and 1868 intensities at distances beyond the source-receiver distances for which Boore et al. (1997) derive their regression curves, we add an anelastic attenuation term, $exp[-0.004\, r_{JB}]$ where r_{JB} is the Joyner-Boore distance to the fault rupture in kilometers. This modification of the Boore et al. (1997) attenuation relation is shown in Figure 1.

The intensities estimated at distances of $40 \leq r_{JB} \leq 100$ km from the fault appear to systematically exceed the intensity predicted from the attenuation curves. This difference, which was also seen in the 1906 intensity data, could be derived from a breakdown of the relation between intensity and peak ground motion or from a propagation anomaly. That is, the MMI 5 - 7 intensities at these distances could either be associated with ground motions lower than those predicted by the Wald et al. (1999) $I_{MM}(PGA, PGV)$ relations, or the ground motions at these distances were greater than predicted by the Boore et al. (1997) attenuation relation. We note that $40 \leq r_{JB} \leq 100$ km is also the distance range at which S-waves are critically reflected from the Moho. Somerville et al. (1991) attribute the damage in San Francisco and Oakland from the 1989 Loma Prieta earthquake to this phenomena, nicknamed the “Moho bounce.”

Overall, the intensities are generally symmetric around the fault, but vary with both distance and azimuth. To the north, Pacheco (MMI 7-8), Martinez (MMI-7), and Bolinas (MMI 7-8) were strongly shaken, while Benicia (MMI 6-7), Vallejo (MMI 6), and San Rafael (MMI 6-7) escaped with little damage. Further north, the shaking at Petaluma (MMI 7) and Santa Rosa (MMI 6-7) was probably amplified by the basins in which these towns are situated. To the south, Mountain View (MMI 8) was more strongly shaken than San Jose (MMI 7-8) and Santa Clara (MMI 7), while Gilroy (MMI 6-7) suffered more damage than Santa Cruz (MMI 6) and San Juan Bautista (MMI 6).

Figure 1 suggests a graphical approach to constraining the epicenter for the 1868 earthquake. If we cut the fault into northwestern and southeastern halves at Hayward and plot the intensities for sites that lie within 60º of the strike of these two fault segments, we can compare the intensities and strength of the radiation in the two directions. Figure 2 shows the geometry of these cutouts, and Figure 3 compares the intensities in the two directions. They are almost exactly matched both in the near-field, $r_{JB} \leq 20$ km, and at regional distances, $40 \leq r_{JB} \leq 100$ km. This symmetry implies that the rupture was mostly bilateral.

On closer inspection of Figure 3, however, we see a group of relatively low intensities located from $20 \leq r_{JB} \leq 30$ km to the northwest of Hayward. These low intensities suggest that the rupture may have been slightly stronger to the southeast. If the stress release was uniform, then these low intensities could correspond with an epicenter located just northwest of Hayward, between Hayward and San Leandro. The narrative of Captain Petersen of San Lorenzo, who “heard a great rumble off across the fields toward San Leandro. He lookt quickly in that direction, and over a mile away could see the great wave rapidly approaching.” This account approximately corroborates this epicentral location.

What is perhaps most striking about the intensity distribution is the relatively weak shaking at the ends of the fault: Oakland (MMI 7) and Berkeley (MMI 7-8) to the northwest and Niles (MMI 7-8) and Warm Springs (MMI 7-8) to the southeast. The intensities are weaker than predicted by bilateral rupture models with directivity. One explanation for these weak intensities is that there was little stress release at the ends of the 1868 rupture. This hypothesis corresponds reasonably well with the large rate of creep at the southeastern end of the Hayward fault, but there is no matching creep rate anomaly on the fault to the north of Mills College (Lienkaemper et al., 2001).

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