The Amador Valley Earthquake of July 3, 1861

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Abstract

A moderate M~6 earthquake occurred in the Amador and San Ramon Valleys on July 3, 1861. Adobe and wood-frame houses situated near the Calaveras fault from Pleasanton to San Ramon were damaged, with the strongest damage in Dublin. A newspaper reported an apparent fault scarp, "extending six to eight miles." Two of the damaged adobes and a damaged wood-frame church have survived as historic buildings; we have located all of the other damaged buildings from historical sources. We use the attenuation of peak ground acceleration and peak ground velocity from the 2004 Parkfield earthquake to analyze the set of Modified Mercalli Intensities obtained for the 1861 earthquake. Fixing the rupture on the Calaveras fault allows us to estimate a moment magnitude of M = 6.0±0.3 and a rupture length of 12 km. Unfortunately, the inversion cannot determine the uncertainty of the rupture length. The estimate of fault slip, 44 cm, is similarly uncertain, although in general agreement with recent correlations of fault slip and moment magnitude for strike-slip earthquakes. Manaker et al. (2003) obtain a geodetic slip of 6.7 mm/yr at depth below the San Ramon segment of the Calaveras fault. Comparing the fault slip to this geodetic rate yields a recurrence interval of 66 years, less than half the time elapsed since the Amador Valley earthquake occurred in 1861.

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Introduction

On the afternoon of July 3, 1861, a moderate (**M**~6) earthquake struck the Amador Valley, damaging adobe and wood-frame buildings in Dublin, a wood-frame house in San Ramon, and at least three adobe houses near Pleasanton. All of these damaged structures were situated near the Calaveras fault, which runs along the western edge of the Amador and San Ramon valleys. In addition, a newspaper reported that "In Amador Valley, ... a chasm was made in the ground extending from six to eight miles, of width in some places of from three to four inches." These reports allow us to partially map the earthquake rupture, an unusual circumstance for an earthquake of this size.

Combining the near-fault damage reports with the felt reports compiled by Toppozada et al. (1981) from towns as far away as Sacramento, Stockton, and Santa Cruz, allows us to make a speculative MMI ShakeMap for this pre-seismologic earthquake. We are aided in this effort by the similarity between 1861 Amador Valley earthquake and the September 26, 2004, Parkfield earthquake (**M**6.0). Not only are the magnitude and focal mechanism of the two events similar, but the physical settings of the faults between the coast range and the western foothills of the San Joaquin Valley are similar, so the attenuation of intensity should be similar as well.

The 1861 Amador Valley earthquake is the largest historic event located on the northern Calaveras fault. Kelson et al. (1996) found evidence for as many as five paleo-earthquakes in a set of trenches ~2 km north of the Calaveras reservoir, and proposed that infrequent **M**~7 earthquakes rupture the length of the northern Calaveras. The location of the 1861 earthquake on the San Ramon segment, where we expect the strain to decrease, and the timing of the 1861 earthquake, suggest that this sub-segment may behave independently of the rest of the northern Calaveras fault.

Newspaper and Scientific Accounts

The *Alameda County Gazette* of July 8, 1861, published the original report of earthquake effects in Amador Valley. Unfortunately, this issue of the *Gazette* is missing from the archives (see the California Newspaper Project). The article published in the *San Mateo County Gazette* of July 13, 1861, partially recaps the original report:

> The Alameda Gazette remarks that the shocks of the recent earthquake were quite severe and disastrous in Amador Valley, Alameda County. The furniture of J.W. Dougherty was considered damaged; the roof of his kitchen (a tile one) was thrown off, chimneys thrown down, and several persons thrown violently to the ground, while others were made temporarily blind by the shock. The waters in the creeks in that vicinity were thrown from their beds apon the plain, and near Mr. Dougherty's house a large chasm was formed in the earth. The chimneys of the dwelling house of Joel Harlan, near by, were destroyed, and Mr. Harlan was thrown heavily against a wall, the side of his head and face being considerably bruised thereby.

The *Contra Costa Gazette* of July 20, 1861, republished by Rodgers and Halliday (1992), summarizes the article somewhat differently:

> We notice in the Alameda Gazette, an account of the effects in that county of the recent earthshaking. In Amador Valley, near the line with our own county, a chasm was made in the ground extending from six to eight miles, of width in some places of from three to four inches. The main part of the two-story house of Mr. Dougherty was nearly thrown to the earth; holes from eight to ten inches wide were opened at its top; pieces of adobe were scattered about the floors inside, and upon the ground outside, and large quantities of the tiles on the roof were dislodged and thrown about in different directions.

> Although wooden buildings suffered less, yet in these crockery and mirrors were broken, and dry goods cast promiscuously over the floor. The house of Mr. Fallon was moved several inches from its old site; several adobe houses were severely shattered, and the church had its windows thrown open, the front steps removed from the building, and one of the doors thrown into the street.

Regarding the adobe houses to the south, the *San Francisco Daily Morning Call* states that "In Amador Valley it shook down an adobe house belonging to Senor Alviso, and knocked the tiles from the other houses," while the *Daily Alta California* states that "the adobe houses of Alviso and the two Bernals, were also cracked." Remarkably, two of these three houses, the Francisco Solano Alviso house and the Agustin Bernal house, are still standing and in the California and National Registers of Historic Places, respectively.

In a summary of seismicity from 1800 to 1864 presented to the California Academy of Sciences, Trask (1864) describes three other earthquake effects:

> July 4th, 16h. 11m. A severe shock of earthquake occurred at San Francisco. It consisted of three distinct waves following each other in very rapid succession. Its effects to the east of the city in the San Ramon Valley were more severe. Near the house of Mr. Larabie it opened a large fissure in the earth. In the vicinity of Mr. Porter's it opened a new spring of water, and a small running stream was also caused near Mr. Hunt's. For several days after light shocks were repeated at intervals.

To locate these houses and effects, we used Hoffman's 1873 *Map of the Regions Adjunct to the Bay of San Francisco* and Thompson and West's 1878 *Atlas of Alameda County*. Figure 1a shows a map of the region, while Figures 1b and 1c show insets reproduced from the 19th century maps with the various damage sites indicated in red. While the sites near Dublin and Pleasanton were readily located, the sites in the San Ramon Valley were problematic. We identified Mr. Larabie as Dr. Labaree, in agreement with Rogers and Halliday (1992), but we could only locate Porter at the eastern end of Green Valley, and we could not locate Hunt at all. We note that the effects at these last two sites were associated with new springs and are not indicative of surface faulting, as Rogers and Halliday (1992) imply.

Modified Mercalli Intensities

We re-evaluated the Modified Mercalli Intensities for these localities using Stover and Coffman's (1993) revision of the MMI scale, as implemented by Boatwright and Bundock (2005 and 2008) in their analyses of the 1906 San Francisco earthquake and the 1868 Hayward earthquake. The correlation of strong ground motion with intensity that underpins ShakeMap is based explicitly on Stover and Coffman's (1993) revised MMI scale (Wald et al., 1999). This common basis allows us to compare ShakeMaps derived from MMI data with ShakeMaps derived from ground motion data, and allows us to invert the MMI estimates for moment magnitude.

The reports of strongest shaking in the earthquake are from Dublin. We take the description of "several persons thrown violently to the ground" at J.W. Dougherty's house and the extensive damage to the two-story adobe built by Jose Maria Amador to indicate PGA > 0.5*g* and MMI 8-9. The damage to the St. Raymond church is estimated to be MMI 7-8, while the shifting of the Fallon house is estimated to be MMI 8. To the north, the chimneys at Joel Harlan's house were described as "destroyed" and Harlan himself thrown against a wall and injured, which we estimate as MMI 7-8.

The reports of the damage to the F.S. Alviso adobe suggest MMI 7-8: the building was repaired after the earthquake. In contrast, Hendry and Bowman (1945) locate an "old adobe house" owned by Jose Dolores Pacheco 0.37

miles north of the F.S. Alviso house. This adobe is marked on surveys published in 1860 and 1862, but disappeared in the 1860s, suggesting it was damaged by the 1861 earthquake and subsequently razed.

The damage reports for the Agustin and Juan Pablo Bernal adobes near Pleasanton are brief: fortunately, the USC Digital Archive contains four 1937 photographs of the A. Bernal adobes. Figure 2 shows shear cracking and incipient corner failure in the older building that we estimate to be MMI 7-8. Because the J.P. Bernal residence was situated much further from the Calaveras fault, we estimate the damage there as MMI 7. The John Kottinger adobe house and stable, just 0.25 miles south, were not reported as damaged.

The description of the pronounced motion of the Contra Costa Courthouse ("the whole solid structure of bricks and stone shook like a ship coming in stays, her sails shivering in the wind" *Contra Costa Gazette* of July 6, 1861) in Martinez is estimated to be MMI 5-6, while the "sharply felt" ground motion at Petaluma and Santa Cruz is estimated as MMI 4-5 (see Toppozada and Branum, 2002). The "violent" intensity felt at Stockton is estimated as MMI 5. These re-evaluations slightly increase the overall intensities and, in turn, increase the estimated size of the earthquake.

ShakeMap Data from the 2004 Parkfield Earthquake

Three elements are needed to determine an MMI ShakeMap: a set of intensity estimates, an attenuation relation for these estimates, and an epicenter, intensity centroid, or rupture extent for the earthquake. The attenuation relation connects the intensity estimates to the fault rupture and interpolates the intensity in areas without nearby intensity sites. Boatwright and Bundock (2005 and 2008) amended the Boore et al. (1997) attenuation relations for *PGA* and *PGV* to fit the attenuation of intensity at regional distances for the 1906 and 1868 earthquakes.

Because there are so few intensity sites for the 1861 earthquake, it is important to make sure the attenuation relation is appropriate for the earthquake size and location. We are fortunate to have a recent event we can use as an analog for the 1861 earthquake: the **M**6.0 Parkfield earthquake that occurred on September 28, 2004, was recorded by ~60 accelerographs within 20 km of the fault and another ~60 instruments within 300 km. The similarity between the 1861 and 2004 earthquakes is remarkable: they are strike-slip earthquakes of nearly the same size, M~6, situated within a broad range of hills that extend ~45 km northeast of each earthquake to the Great Valley.

Figures 3a and 3b show the attenuation of *PGA* and *PGV* with distance from the 2004 Parkfield earthquake. We fit these peak motions using the attenuation function incorporated into the northern Californian ShakeMap

$$PGA \text{ or } PGV = A_o S\, e^{-\eta r} / g(r, r_o, \gamma) \tag{1a}$$

where A_o is the source amplitude, *S* is the *PGA* amplification for the NEHRP site class from Boore et al. (1997), *r* is the distance from the fault rupture to the station, and $g(r, r_o, \gamma)$ is the geometrical spreading function

$$g(r, r_o, \gamma) = \begin{cases} r & r \le r_o \\ r_o (r / r_o)^{\gamma} & r > r_o \end{cases} \tag{1b}$$

with $\gamma = 0.7$ and $r_o = 27.5$ km (Boatwright et al., 2003). The fault rupture in the Parkfield earthquake has been modeled as mostly occurring below 6 km depth (Liu et al. 2006), so the rupture distance is limited as $r > 6$ km. We note that equation (1a) does not include the effect of soil non-linearity.

ShakeMap uses the regression results of Boatwright et al. (2003),

$$\eta = \begin{cases} 0.0073x10^{-0.3(\mathrm{M}-5.5)} & \text{for } PGA \\ 0.0063x10^{-0.3(\mathrm{M}-5.5)} & \text{for } PGV \end{cases} \tag{2}$$

to estimate the attenuation for **M** > 5.5 earthquakes. These relations give $\eta = 0.0052\,\text{km}^{-1}$ for *PGA* and $0.0045\,\text{km}^{-1}$ for *PGV* for an M6.0 earthquake. These attenuation curves are plotted in Figures 3a and 3b where the source amplitude has been fit to the data and the peak motions are corrected to NEHRP-C. Fitting the Parkfield data for η, we obtain $\eta = 0.0053\,\text{km}^{-1}$ for *PGA* and $0.0042\,\text{km}^{-1}$ for *PGV*, close to values used by ShakeMap.

For comparison, we plot Boore and Atkinson's (2007) predictions for *PGA* and *PGV* from an M6.0 strike-slip earthquake at a NEHRP-C site. The curvature as the rupture distance approaches $r = 6$ km is derived from Boore and Atkinson's (2007) use of the distance to the surface projection of the fault instead of the distance to the buried rupture. We note these predicted ground motions are not rescaled to fit the Parkfield data, as are the ShakeMap attenuation curves, so the fit to the overall amplitude is excellent.

Wald et al. (1999) determine an approximation of the Modified Mercalli Intensity, the Instrumental Intensity, I_{mm}, using arithmetic regressions of $\log(PGA)$ and $\log(PGV)$ where $I_{mm} \propto \log(PGV)$ for $I_{mm} \geq 7$ and $I_{mm} \propto \log(PGA)$ for $I_{mm} \leq 5$. These intensity estimates are then interpolated and mapped by ShakeMap. We use these same regressions to estimate I_{mm} for each record of the 2004 Parkfield earthquake and plot these estimates against rupture distance in Figure 4; the smooth curve is the Instrumental Intensity predicted from the attenuation relations for *PGA* and *PGV*, for a NEHRP-C site.

Rupture Length and Magnitude of the 1861 Earthquake

The attenuation relations in ShakeMap depend on two source parameters: the rupture extent and the moment magnitude. Assuming the 1861 rupture occurred on the Calaveras fault reduces our uncertainty to finding the ends of the fault and the magnitude. We estimate these parameters by fitting the estimates of I_{mm} to the MMI intensities compiled in Table 1 and plotted in Figure 4, calculating

$$\chi^2 = \sum_i \left(MMI_i - I_{mm}(\mathbf{M}, R_i, S_i)\right)^2 \Big/ \sigma_i^2 \tag{3}$$

for each set of different endpoints and tracking the moment magnitude that minimizes equation (3) for each pair of endpoints. Here R_i is the Joyner-Boore (1981) distance from the fault trace to the station and S_i is the site correction. We amend the Boore et al. (1997) relations for *PGA* and *PGV* with the exponential factors in equation (2) to estimate $I_{mm}(\mathbf{M}, R_i, S_i)$.

The set of intensities for the Amador Valley earthquake are barely sufficient to determine the extent of the faulting: the MMI 7-8 intensities at the F.S. Alviso and A. Bernal adobes require that the southern end of the fault approach, but not reach, these locations. The next intensity site to the south is San Jose, which reported a relatively weak intensity (MMI 4). Minimizing equation (3) fixes the end of the fault 3 km south of Dublin.

At the northern end of the fault, the weaker intensities at Dr. Labaree's and Porter's indicate that the rupture did not reach Dr. Labaree's residence. We estimate this end of the rupture after fixing the southern end. The relatively strong intensities at San Leandro, Martinez, and Benicia contribute to the northern location of this end of the rupture. We note, however, that the locations of both ends of the rupture are very poorly resolved: the minima are so shallow that we cannot estimate confidence intervals.

The ShakeMap for the earthquake is plotted in Figure 5. The 12 km long rupture corresponds with the length of the fault scarp reported in the *Contra Costa Gazette*, although it extends further north into Contra Costa County than that report suggests. We note too that it would have been hard to trace the scarp though the hills north of Dublin: the fault itself is difficult to map there (Rodgers and Halliday, 1992).

The moment magnitude is determined in the process of minimizing equation (3) for the rupture extent. The resulting estimate of **M** = 6.3±0.3 depends on the calibration of the attenuation relation used to calculate the instrumental intensities $I_{mm}(\mathbf{M}, R_i, S_i)$: in this case, the amended Boore et al. (1997) relations for *PGA* and *PGV*. We test this calibration by fitting the abundant Parkfield 2004 data shown in Figures 3a and 3b to estimate **M**

$$\chi^2 = \sum_i \left(PG_i - PG_{BJF}(\mathbf{M}, R_i, S_i)\right)^2 \Big/ \sigma_{PG}^2 \tag{4}$$

for both *PGA* and *PGV*, where $PG_{BJF}(\mathbf{M}, R_i, S_i)$ is *PGA* or *PGV* predicted by Boore et al. (1997). These fits give **M** = 6.31 and 6.29, respectively. The moment magnitude of the 2004 Parkfield earthquake was **M** = 6.0 (Langbein et al., 2007), so this recalibration obtains a moment magnitude for the Amador Valley earthquake of **M** = 6.0±0.3.

Fault Slip in the 1861 Earthquake

The standard method of estimating the average fault slip is the relation

$$\overline{u} = \frac{M_o}{\mu L W} \ . \tag{5}$$

The seismic moment is $M_o = 1.3x10^{18}$ Nm: we estimate the uncertainty as $0.44 < M_o < 3.5x10^{18}$ Nm. The rupture width $W = 8$ km is estimated from Manaker et al. (2003), who geodetically image shallow and deep aseismic slip on the northern Calaveras. The rupture length of L = 12 km is estimated by locating the ends of the fault using equation (3). Together, these estimates yield an average fault slip of $\overline{u} = 44$ cm. We cannot estimate the uncertainty for this fault slip, however, because we cannot estimate the uncertainty for the fault length.

We can quantify the uncertainty by considering the correlation of seismic moment and fault slip. Somerville et al. (1999) obtain the relationship

$$\bar{u} = 3.36x10^{-5} M_o^{1/3} \quad (6)$$

between the seismic moment in Nm and the fault slip in cm. Substituting our estimate of the seismic moment gives an average fault slip of 37 cm, which is close to our direct estimate. Carrying the uncertainty for M_o through equation (6) yields $26 < \bar{u} < 51$ cm, which appears to underestimate the uncertainty.

Despite the lack of resolution, these estimates of fault slip appear reasonable. Both estimates are larger than the coseismic fault slip of 20-30 cm estimated by Johanson et al. (2007) for the 2004 Parkfield earthquake. We note that both the 1966 and 2004 Parkfield earthquakes had small (< 10 cm) co-seismic surface slip and much larger (20-30 cm) postseismic surface slip (Lienkaemper et al., 2006). The larger estimate of fault slip for the Amador Valley earthquake suggests a greater stress drop and a greater likelihood of coseismic surface slip.

Recurrence on the Northern Calaveras

Manaker et al. (2003) model geodetic strain to image aseismic slip on the Calaveras fault. On the San Ramon segment of the fault, they estimate 6.7±1.7 mm/yr for the deep ongoing slip and ~2 mm/yr for the shallow slip. Dividing the estimated fault slip of 44 cm by this deep slip rate yields a recurrence of 66 years for this earthquake. The 1861 earthquake occurred almost 150 years ago: two recurrence intervals have elapsed since. Either the strain accumulation on the northern Calaveras fault is less than estimated by Manaker et al. (2003) or a recurrence of the 1861 earthquake is overdue.

This recurrence interval is much shorter than the recurrence interval estimated for large earthquakes on the northern Calaveras. Kelson et al. (1996) found evidence for as many as five paleo-earthquakes in a set of trenches at Leyden Creek, ~2 km north of the Calaveras reservoir. On the basis of this set of events and a Holocene slip rate of 5 mm/yr, they proposed that **M**~7 earthquakes rupture the length of the northern Calaveras fault with a recurrence time of 250-850 years. Subsequently, the USGS Working Group on Bay Area Earthquake Probabilities (2003) revised the earthquake size to **M**=6.8 and refined the recurrence time to 284 years.

The location and the timing of the Amador Valley earthquake conflict with this characteristic model for the northern Calaveras. While the characteristic model allows a small population of sub-segment failures, the rupture in 1861 occurred on a fault segment that is loaded more slowly than the Sunol segment to the south. Unless the poorly located M~6 earthquakes of March 5 and May 21, 1864, (Toppozada et al., 1981) ruptured the Sunol segment, the rupture segment of the 1861 earthquake appears to be out of phase with the rest of the northern Calaveras fault.

The 1861 earthquake occurred seven years before the 1868 Hayward earthquake, in the middle of a remarkable 10-year burst of moderate seismicity in the east and south Bay (see Toppozada and Branum, 2002). This timing suggests that the northernmost Calaveras fault may be tuned to the southern Hayward fault rather than the Sunol segment of the Calaveras fault, and that a recurrence of the Amador Valley earthquake could precede the recurrence of the next Hayward earthquake.

Conclusions

The road from Sunol north through Danville was a locus of Mexican and American pioneer settlement of the Amador and San Ramon Valleys. Because this road followed the northern Calaveras fault, shaking in the 1861 earthquake damaged a series of three adobe houses and three wood-frame buildings. Combining this near-fault damage with felt reports from more distant towns allows us to estimate the magnitude of the earthquake and approximately locate the fault rupture.

We use the 2004 Parkfield event twice to calibrate these estimates: first, to fix the attenuation of *PGA*, *PGV*, and I_{mm} out to 300 km, and second, to adjust the estimated moment magnitude of the 1861 earthquake for the bias introduced by the Boore et al. (1997) attenuation relations. The resulting estimate of **M** = 6.0±0.3 is slightly higher than the M = 5.8 estimates of both Toppozada et al. (1981) and Bakun (1999).

A rupture length of 12 km was determining by locating the ends of the fault from the MMI distribution. Although this rupture extent corresponds with the reported length of the scarp, we cannot estimate confidence limits for these locations or the length between them. The 44 cm estimate of fault slip in the earthquake is similarly uncertain, but in agreement with Somerville et al.'s (1999) correlation of fault slip and moment magnitude for strike-slip earthquakes.

The fault segment that ruptured in 1861 subtends the northernmost third of the combined San Ramon-Sunol segments of the northern Calaveras fault. Kelson et al. (1996) and WG02 propose that these segments fail together in **M**~7 earthquakes at intervals from 250 to 850 years. The timing of the Amador Valley earthquake suggests that this segment may be out of phase with the rest of the northern Calaveras fault.

Acknowledgments

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Table 1. Modified Mercalli Intensities

Location	Toppozada MMI	Re-evaluated MMI	Notes
Benicia	5-6	5-6 ± 1	plaster falling
Dublin			
J.W. Dougherty	8	8-9 ± 0.7	people knocked to the ground
St. Raymond Church		7-8 ± 0.7	
E.M. Fallon		8 ± 1	house shifted
Martinez	5	5-6 ± 1	courthouse shaken
Petaluma	F	4-5 ± 1	
Pleasanton			
F.S. Alviso	8	7-8 ± 1	
A. Bernal	6	7-8 ± 1	extensive cracking
J.P. Bernal		7 ± 1.5	
Redwood City	5-6	5-6 ± 1	
Sacramento	2-3	3 ± 1	
San Francisco	5-6	5-6 ± 1	
San Jose	L	4 ± 1.5	
San Leandro	6-7	6-7 ± 1	
San Ramon			
J. Harlan	7	7-8 ± 0.7	chimneys destroyed
Dr. Labaree		7 ± 1	faulting/ground failure
Porter		6-7 ± 1.5	new spring
Santa Cruz	F	4-5 ± 1	
Stockton	4-5	5 ± 1	

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Figure Captions

Figure 1a. Map of the Pleasanton, Dublin, and San Ramon area, showing the Calaveras and Hayward faults and the location of the two inset sections of older maps. Figure 1b. An inset from Hoffman's 1873 map of the Dublin and San Ramon area: intensity sites identified on the map are re-colored in red. Figure 1c. 1878 map of the Pleasanton area: intensity sites are relabeled in red with the owners in 1861, except for the J.D. Pacheco adobe which was located by Hendry and Bowman (1940).

Figure 2. 1937 Charles Pierce photograph of the south wall of the older A. Bernal adobe building, showing shear cracking, incipient corner failure, and stabilization efforts. The USC Digital Archive attributes the buildings to J.P. Bernal, but Hendry and Bowman's (1940) description of the two A. Bernal adobe buildings located on the Baldwin Ranch corresponds exactly with the four photographs of the buildings.

Figure 3a. Peak accelerations from the 2004 Parkfield main shock plotted against rupture distance. The peak accelerations are corrected for site amplification to a NEHRP-C site condition. The solid curve is the attenuation relation used by ShakeMap, while the dashed line is the attenuation of the mean horizontal component PGA obtained by Boore and Atkinson (2007). Figure 3b. Peak velocities from the 2004 Parkfield main shock plotted against rupture distance. The peak velocities are corrected for site amplification to a NEHRP-C site condition. The solid curve is the attenuation relation used by ShakeMap, while the dashed line is the attenuation of the mean horizontal component PGV obtained by Boore and Atkinson (2007).

Figure 4. Instrumental Intensity, determined from the peak acceleration and velocity at each station recording the 2004 Parkfield main shock, plotted against rupture distance. These intensity estimates are not corrected for site amplification. The shaded curve is the Instrumental Intensity for a NEHRP-

C site, predicted from the fitted attenuation curves in Figures 3a and 3b. The apparent misfit from 50 to 200 km is the result of a preponderance of soft soil sites in the Great Valley and the Salinas Valley at these distances. The open symbols are the MMI estimates for the 1861 earthquake.

Figure 5. ShakeMap for the 1861 Amador Valley earthquake. The solid line indicates the extent of fault rupture as determined by minimizing equation (3). The yellow triangles are the intensity sites compiled in Table (1).