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The Distribution of Modified Mercalli Intensity in the 18 April 1906 San Francisco Earthquake

by John Boatwright and Howard Bundock

Abstract We analyze Boatwright and Bundock's (2005) modified Mercalli intensity (MMI) map for the 18 April 1906 San Francisco earthquake, reviewing their interpretation of the MMI scale and testing their correlation of 1906 cemetery damage with MMI intensity. We consider in detail four areas of the intensity map where Boatwright and Bundock (2005) added significantly to the intensity descriptions compiled by Lawson (1908). We show that the distribution of off-fault damage in Sonoma County suggests that the rupture velocity approached the *P*-wave velocity along Tomales Bay. In contrast, the falloff of intensity with distance from the fault appears approximately constant throughout Mendocino County. The intensity in Humboldt County appears somewhat higher than the intensity in Mendocino County, suggesting that the rupture process at the northern end of the rupture was relatively energetic and that there was directivity consistent with a subsonic rupture velocity on the section of the fault south of Shelter Cove. Finally, we show that the intensity sites added in Santa Cruz County change the intensity distribution so that it decreases gradually along the southeastern section of rupture from Corralitos to San Juan Bautista and implies that the stress release on this section of rupture was relatively low.

Introduction

Delineating the intensity distribution of the 1906 earthquake was one of the chief goals of the California Earthquake Commission. Although there were earlier isoseismal maps, notably the map drawn by Mallet (1862) for the 1857 Neapolitan earthquake, the abundance of intensity reports and the explicit recognition of soft soil and basin amplification effects made the isoseismal maps in Lawson (1908) benchmarks for a century of subsequent seismological research.

Lawson compiled and edited the felt reports and damage descriptions provided by coauthors, scientific volunteers, and lay contributors into the longest chapter (190 pp.) of the report. This chapter contains reports from more than 600 sites outside San Francisco, although many of these reports are brief. The only section on intensity not compiled by Lawson was the section on the apparent intensity in San Francisco written by his coauthor Wood.

Four sections of felt reports and damage descriptions form the basis for Lawson's efforts, summarized in the fifth and last section of the chapter, to assign and map Rossi–Forel intensity. Plates 21 and 22 in the report show the mapped intensities in San Mateo and Santa Clara Counties, respectively, and plate 23 shows the intensities in California, Nevada, and Oregon. Figure 1a reprints part of plate 23. Lawson's recognition of the amplifying effect of basins is clear from his isoseismal contours, which outline various basins and exclude uplands in northern and central California. Lawson also assigns the fault rupture a uniform Rossi–Forel intensity 10.

Unfortunately, Lawson's use of the Rossi–Forel intensity scale undercut the longevity of his isoseismal maps. The Rossi–Forel scale fell out of seismological favor in part because it does not distinguish intensity differences between moderately and strongly damaged urban areas. Wood and Neumann (1931) introduced the modified Mercalli intensity (MMI) scale, which quickly became the standard seismological intensity scale. Richter (1958) revised the MMI scale: his tabulation of shaking effects by intensity level is the version of the MMI scale most often cited and quoted in the literature.

However, the modern MMI scale was not finally realized until Stover and Coffman (1993), hereafter shortened to S&C93, incorporated a set of further revisions into their isoseismal maps of earthquakes in the United States from 1568 to 1989. They lowered the maximum intensity from MMI 12 to MMI 10 and lowered the intensity associated with chimney damage from MMI 8 to MMI 7. Unfortunately, S&C93 did not tabulate shaking effects by intensity level to show how they had revised Richter's (1958) scale.

The 1906 earthquake was arguably the most important event that S&C93 analyzed: their isoseismal map is reprinted

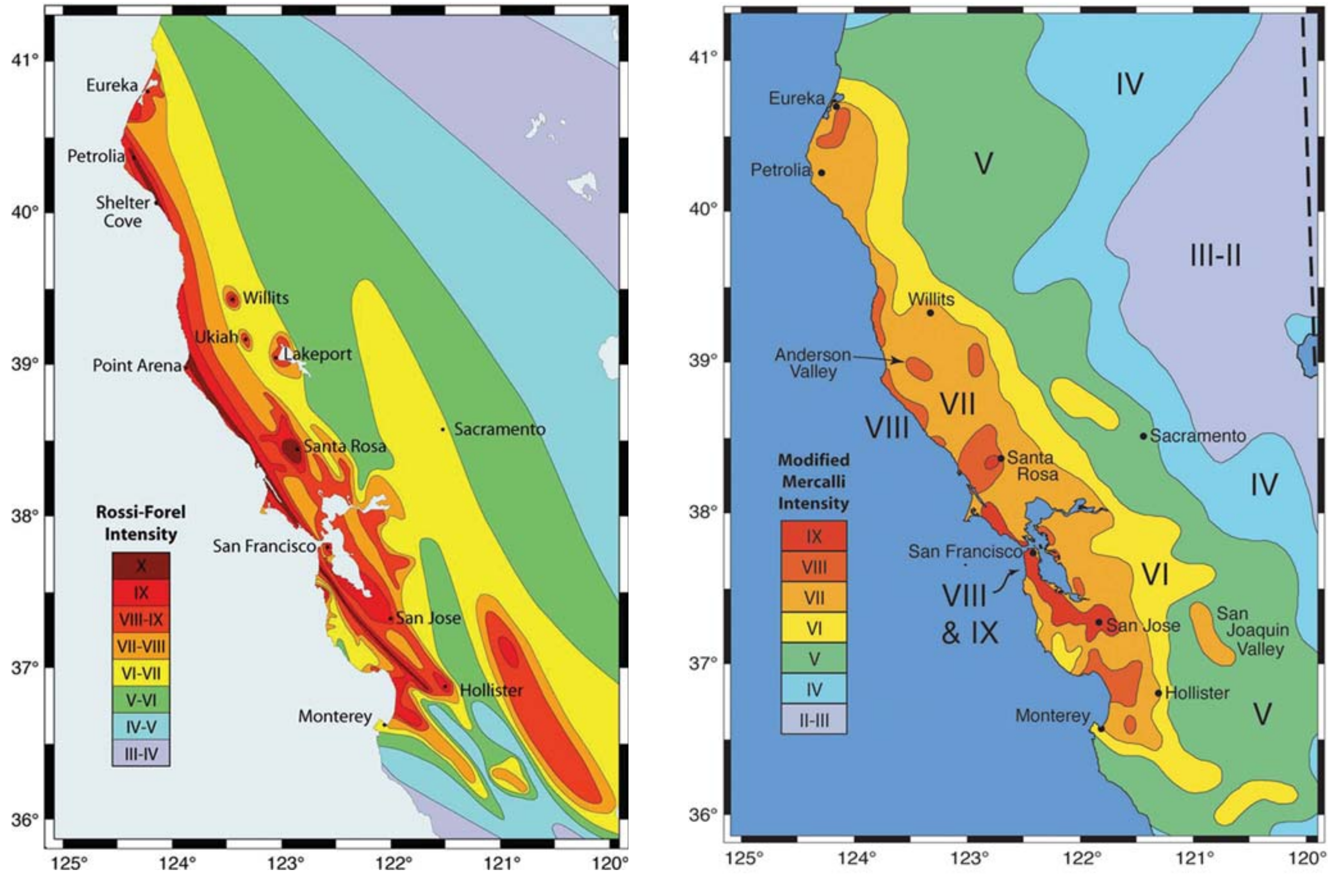

Figure 1. (a) Rossi–Forel (RF) intensity for the 1906 earthquake, reprinted from plate 23 of the report by Lawson (1908). Lawson gives the highest intensities (RF 10) to the fault trace and around Santa Rosa, and extends a line of RF 10 intensity from Shelter Cove through Petrolia. Willits, Lakeport, and Ukiah are contoured as isolated areas of relatively high intensity. (b) MMI for the 1906 earthquake, reprinted from S&C93. S&C93 aggregate the MMI 8 and 9 areas in Marin, San Mateo, and Santa Clara Counties for graphical simplicity. The isolated MMI 7 isoseismal area in the San Joaquin Valley is a contouring error.

in Figure 1b. Although they use the Lawson (1908) intensity reports as their fundamental data, they are more conservative than Lawson: they draw fewer contours and anticipate less amplification in the basins and less intensity along the fault. The resulting isoseismal map differs significantly from Lawson's (1908) map. We note that although the two intensity scales differ, most of the differences between the two maps are interpretive.

Recently, Boatwright and Bundock (2005), hereafter shortened to B&B05, comprehensively reevaluated MMI intensities for all of the sites described in Lawson (1908) and added 65 new sites using information obtained from local newspapers, survivor narratives, and damage to cemeteries. They exploited the ShakeMap methodology devised by Wald *et al.* (1999) to make an interpolated map of MMI for the 1906 earthquake. Their intensity map, plotted in Figure 2, differs from both the Lawson (1908) and S&C93 maps, although it uses the same MMI scale as the S&C93 map.

In this article, we review four areas of the new isoseismal map where B&B05 added critical intensity sites. These areas, outlined on Figure 2, are Sonoma County, where the strongest shaking was reported, Mendocino and Humboldt Counties, where many sites inland from the coast have been added, and finally, Santa Cruz and San Benito Counties, where the intensity decreases abruptly at the southeastern end of the rupture.

A Modified Mercalli Intensity Scale for the 1906 Earthquake

The large moment release and the long duration of the 1906 earthquake modified the phenomenology of the shaking effects: long-period effects such as stopped clocks and seiches and ground failure effects such as ground cracks and lateral spreads occur at lower intensities than in Richter's (1958) MMI scale. Table 1 shows how B&B05 assigned MMI intensities coincident with the S&C93 intensity scale that maintain the correlation of effects reported in Lawson (1908). B&B05 discuss this correlation of earthquake effects in the 1906 Modified Mercalli Scale section of their report.

B&B05 found that the detailed reports in Lawson (1908) allowed intensity to be specified at half-intervals instead of full intervals for MMI ≥ 5. The clearest example is derived

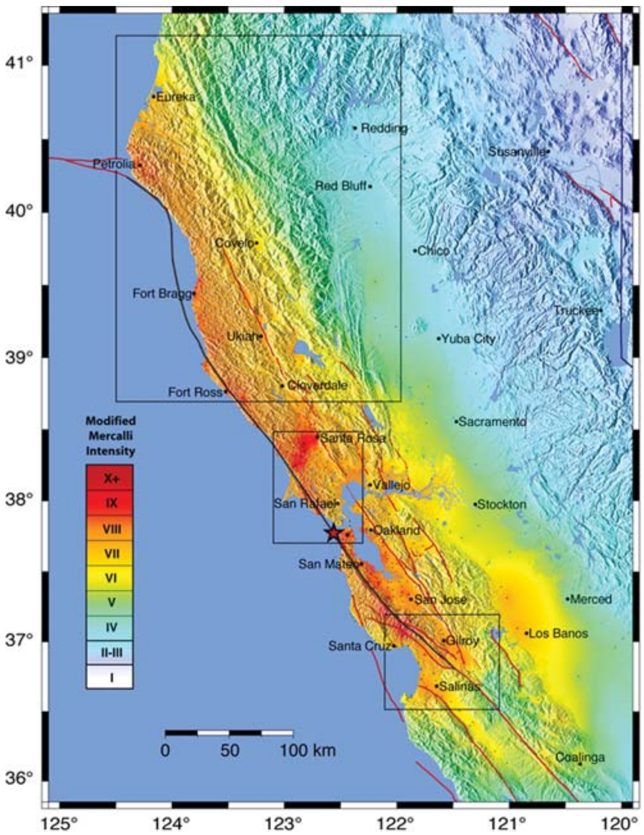

Figure 2. MMI for the 1906 earthquake, reprinted from B&B05. The intensity sites appear as small black dots. Note the isoseismal hole to the southeast of the fault rupture, between Salinas, Los Banos, and Coalinga. The three areas with black outlines are shown in greater detail in later maps. The large upper box contains Mendocino and Humboldt Counties, the middle box contains Sonoma and Marin Counties, and the lower box contains parts of Santa Clara, Santa Cruz, San Benito, and Monterey Counties.

from chimney damage: MMI 6–7, 7, and 7–8 are marked by few chimneys damaged, about half the chimneys damaged, and almost all chimneys damaged, respectively. These half-interval intensity levels are tabulated in Table 1.

The use of these half-intervals does not imply that the intensities are better resolved. B&B05 grade their intensities as A, B, or C, whose uncertainties are estimated to be ± 0.5, ± 0.7, and ± 1.0 intensity unit, respectively. A intensities are generally obtained from large towns with multiple reported effects, B intensities are obtained from towns with one well-quantified effect, and C intensities are obtained from incomplete reports, lay contributions, narratives, or ground failures. The intensities, grades, and Lawson citations are available at http://pubs.usgs.gov/of/2005/1135/1906_locations.html (last accessed March 2006).

Canvassing Rural Cemeteries for 1906 Damage

Spurred by Mallet's (1862) seminal study of the 1857 Neapolitan earthquake, Lawson and his coauthors documented the damage and the direction of fall of monuments in many cemeteries. Unfortunately, they found the direction of fall to be generally random, and they were unable to use Mallet's (1862) technique to locate the focus of the 1906 earthquake. R. S. Holway's observations of cemetery damage in Sebastopol and Tomales (Lawson, 1908) were critical, however, as they showed that these severely damaged cemeteries were located in towns that were also strongly damaged.

Because damaged monuments and headstones can be repaired, but are rarely replaced, much of the damage from the 1906 earthquake is still evident in rural cemeteries throughout northern California. We located and canvassed some 30 cemeteries from San Juan Bautista to Westport. These cemeteries and their damage statistics are complied in Table 2. Our method of quantifying cemetery damage is simple: we count the number of damaged, reset, and undamaged headstones and monuments that predate the 1906 earthquake. Toppled monuments are almost always misaligned when they are reset, and broken headstones are cemented onto their footers. Short headstones (<0.5 m) and metal monuments are not counted. We then calculate D as the damaged and reset pre-1906 monuments and headstones divided by the total number of pre-1906 monuments and headstones.

The first MMI listed in Table 2 is the MMI inferred by B&B05 from the damage and shaking effects reported in Lawson (1908). Among the sites that suffered the strongest shaking (MMI $\geq$ 8–9), the damage in Graton and Sebastopol was particularly well documented. Two Rock and Windsor suffered relatively strong shaking (MMI 7–8 and 8), while Boonville and San Juan Bautista suffered moderate shaking (MMI 7). The damage to nearby cemeteries allows us to associate MMI intensities with our modern observations of cemetery damage. The general equation

$$I_{MM} = 3.33(D + 2.0) \quad \text{for } 7 \leq I_{MM} \leq 9 \qquad (1)$$

associates $D > 0.85$ with MMI 9–10, 0.7–0.85 with MMI 9, 0.55–0.7 with MMI 8–9, 0.4–0.55 with MMI 8, 0.25–0.4 with MMI 7–8, and 0.1–0.25 with MMI 7.

Two processes can confuse this analysis: vandalism and restoration. Vandalism can usually be discerned from damage to post-1906 monuments and headstones. The effect of restoration can be subtle, particularly in well-maintained cemeteries. We indicate where these processes may have affected the apparent damage in Table 2. We note as well that the 1906 earthquake caused an abrupt change in headstone style in northern California. Because of the extensive 1906 damage to marble headstones, post-1906 headstones are shorter and thicker and more often made from granite.

The Distribution of Intensity in Sonoma County

Although parts of San Francisco, San Jose, and Fort Bragg suffered great devastation, Santa Rosa and Sebastopol are generally considered to have suffered the strongest shak-

Table 1
Lawson's (1908) Descriptions of Shaking and Damage Associated with MMI for the 1906 Earthquake

MMI	Description
1	Not felt
2	Felt by people at rest, but not miners at work, lamps and open doors swing,* some pendulum clocks stopped*
2–3	Slight shock
3	Felt by most people, usually for a short duration (<20 sec),* direction of motion described
4	Light shaking, most sleepers awakened, doors and windows rattled, longer duration (>30 sec)* and variability of motion described, water thrown from horse troughs, water tanks, and canals*
5	Moderate shaking, objects shifted, milk spilled from pans,† houses rocked with slight plaster cracking, some water tanks thrown down*
5–6	Trees strongly shaken, grassland and fields appear to move in waves†
6	Heavy shaking, objects moved and thrown from shelves, plaster cracked, windows broken, some weak masonry walls damaged, bricks thrown from parapets, tall monuments shifted
6–7	Ground cracks on roads and hillsides,* some chimneys damaged
7	Many chimneys thrown down or damaged, some masonry but no frame buildings damaged, piles of cordwood overthrown, some headstones overturned,† small landslides and earth lumps
7–8	Liquefaction and large lateral spreads,* most chimneys thrown down
8	Well-built masonry damaged, some frame buildings shifted on their foundations, headstones and stone monuments overturned,† extensive ground failure and settlement, foundations cracked, water and gas pipes broken, railway tracks twisted
8–9	Men, horses, and cattle thrown off their feet,† large boulders dislodged or rolled down hillsides,† trestles and well-braced bridges wrecked,† frame buildings thrown from their foundations
9	Masonry and frame buildings destroyed, massive landslides, pervasive ground failure, large limbs broken from healthy trees†
9–10	Trees topped,† all headstones and stone monuments thrown down†

*MMI intensity associations specific to the 1906 earthquake that differ from Richter's (1958) MMI scale.
†MMI intensity associations identified by B&B05.

ing in the earthquake. One way to investigate the cause of this strong shaking is to consider the spatial distribution of the intensity. To resolve this distribution, B&B05 located 18 new intensity sites in the area around Sebastopol and Santa Rosa, shown in detail in Figure 3.

The five sites added around Santa Rosa were obtained from the detailed reports contributed by R. S. Holway and D. Butler (Lawson, 1908). While the ground shaking in Santa Rosa itself was severe (Santa Rosa had the greatest number of houses thrown from their foundations), it decreases rapidly to the east (MMI 6–7 in Bennett Valley) and the northeast (MMI 7 in the Rincon District), but somewhat more slowly to the north (MMI 8 at the Sonoma County Hospital and MMI 7 at Fulton Road). B&B05 were unable to find new sites to the west of Santa Rosa towards Sebastopol, where the ShakeMap interpolation connects the two areas of high intensity.

The rapid falloff of intensity to the east and northeast, together with Santa Rosa's historic vulnerability to moderate earthquakes (see L. Burbank's comment on p. 205 of Lawson's report), suggests that ground shaking is strongly amplified in Santa Rosa. Recently, McPhee *et al.* (2007) inverted the Bouguer gravity anomaly to image a semicircular sedimentary basin approximately ~0.5-km deep beneath Santa Rosa. This basin and the shallow fluvial deposits beneath downtown Santa Rosa together may yield enough amplification to explain the 1906 damage (Aagaard *et al.*, 2008).

The new sites with the best-determined intensities are three towns to the west and north of Sebastopol. The shaking damage in Graton (MMI 8–9) is described in Lawson (1908) as occurring in "a place 3 miles northwest of Sebastopol." The damage reports for Occidental (MMI 8) and Forestville (MMI 7–8) were obtained from a town history (Hill and Lapham, 1997) and three narratives (Schubert, 2006). The 1906 damage to cemeteries near Graton and Forestville corroborate these intensity estimates.

Three cemeteries to the south of Sebastopol (Pleasant Hill, Canfield, and Macedonia) were severely damaged, suggesting that these sites suffered MMI ~ 9 intensities. This damage is commensurate with the MMI 9 intensity observed for the Bloomfield cemetery and is slightly less than the nearly complete destruction of the Sebastopol cemetery reported by Holway (Lawson, 1908). These cemeteries show that the area of strong shaking was not confined to Sebastopol, but extended south toward Tomales. As these high-intensity sites are on stiff soils, anomalous site amplification probably did not contribute significantly.

The westernmost site that B&B05 added in Sonoma County was Calvary Cemetery, south of Bodega, which was severely damaged (MMI 9) by the earthquake. Nearby Valley Ford (MMI 8–9) was strongly damaged, while Tomales (MMI 9) was the most severely damaged town in Marin County, suffering damage to wood-frame buildings, the complete destruction of masonry buildings, and two cemeteries whose monuments were almost all overturned. The cemetery at Two Rock (MMI 7–8), 10 km east of Tomales, was only moderately damaged.

Tomales, Bloomfield, and Sebastopol lie on an approximate line that intersects the San Andreas fault near the town of Hamlet. This line of high intensity suggests that the fault rupture along Tomales Bay was both transonic and energetic. A transonic rupture velocity, $\beta \leq \nu \leq \alpha$, where α and β are

Table 2

Damage Statistics for Cemeteries in Northern California

Cemetery	Town	MMI	Undamaged	Damaged	Reset	D	MMI_c	Notes
Tomales Presbyterian	Tomales	9	3	29		0.91	9–10	Lawson (1908, p. 198)
Tomales Presbyterian	Tomales	9	16	7	9	0.50	(8)	Restored by church
Tomales Catholic	Tomales	9	4	20		0.83	9	Lawson (1908, p. 198)
Olema		9	5	5	2	0.57	(8–9)	Possibly restored
Bodega Calvary	Bodega	8	5	15	8	0.82	9	Heavy damage
Duncans Mills		8–9	7	1	3	0.36	(7–8)	Restored by caretaker
Seaview	Fort Ross	(8–9)	6	1	0	0.14	7	Very slight damage
Forestview	Forestville	7–8	7	3	3	0.46	8	Moderate damage
Gilliam	Graton	8–9	14	22	2	0.63	8–9	Heavy damage
Green Valley	Graton	8–9	9	13	0	0.59	8–9	Heavy damage
Shiloh	Windsor	8	103	41	17	0.36	7–8	Moderate damage
Fulton	Santa Rosa	7	3	3	2	0.63	(8–9)	Clearly vandalized
Calvary Cemetery	Santa Rosa		19	1		0.50	6–7	Lawson (1908, p. 201)
Memorial Lawn	Sebastopol	9–10				0.90	9–10	Lawson (1908, p. 204)
Macedonia	Sebastopol		5	14	0	0.74	9	Heavy damage
Pleasant Hill	Sebastopol		15	30	36	0.81	9	Many cemented resets
Canfield	Sebastopol		4	13	1	0.78	9	Heavy damage
Bloomfield		9				0.80	9	Lawson (1908, p. 199)
Bloomfield		9	50	84	44	0.72	9	Poorly cemented resets
Two Rock Presbyterian	Two Rock		35	10	3	0.27	7–8	Slight damage
Liberty	Petaluma		30	21	7	0.48	(8)	Possible 1898 damage
Upper Lake		7–8	136	32	6	0.22	7	From photographs
Redwood Valley	Near Ukiah		12	9	2	0.48	(8)	Probably vandalized
Potter Valley	Near Ukiah	6–7	84	9	4	0.13	(7)	Possibly vandalized
Hopland		7	38	2	7	0.19	7	Slight damage
Laytonville		6–7	26	6	2	0.23	(7)	Clearly vandalized
Sherwood	Near Willits	7	7	0	1	0.13	6–7	No apparent damage
Evergreen	Boonville	7	63	3	7	0.18	7	Slight damage
Shields	Philo	6–7	31	0	4	0.11	6–7	Very slight damage
Madronia	Saratoga	(6–7)	26	18	20	0.59	8–9	Possible 1989 damage
Day Valley	Aptos	(7)	6	5	2	0.53	8	Moderate damage
St. Francis	Watsonville	8	25	9	9	0.42	8	Moderate damage
San Juan Bautista		6–7	72	11	3	0.16	(7)	Probable 1890 damage
Fish Rock	Anchor Bay	(8)	8	2	1	0.27	7–8	Slight damage
Westport		(7–8)	8	3	6	0.53	8	Moderate damage

This table contains cemetery damage statistics obtained from postearthquake canvasses conducted by R. S. Holway and described in Lawson (1908), and from recent canvasses conducted by us. The MMI column indicates intensity estimates obtained from damage and shaking descriptions in nearby communities. Poor or distant (> 2-km) estimates are written in parentheses. MMI_c column indicates intensity estimates obtained from cemetery damage. Estimates from cemeteries that have been restored, vandalized, or damaged by a previous earthquake are written in parentheses. Toppozada *et al.* (2002) obtain MMI 8 for Petaluma from the 1898 Mare Island earthquake, and MMI 7–8 for San Juan Bautista from the 1890 Pajaro Gap earthquake.

the *P*-wave and *S*-wave velocities, produces *S*-wave caustics at the angle

$$\vartheta_c = \cos^{-1}(\beta/\nu) \quad (2)$$

from the strike of the fault (Bernard and Baumont, 2005). The line drawn on Figure 3 is at $\vartheta_c = 54.7°$ to the fault strike and corresponds to a rupture velocity equal to the *P*-wave velocity. Santa Rosa lies ~7 km east of this line.

The Song *et al.* (2008) rupture model for the 1906 earthquake obtains 7 m of slip at the north end of Tomales Bay, indicating that the rupture there was very energetic. It is not possible, however, to fix the caustic near the fault, in part because Holway did not report shaking damage for Marshall and Hamlet in Lawson (1908). (He described a lateral spread that carried a hotel at Marshall into the Tomales Bay and a large landslide above Hamlet that “carried away the country road.”) B&B05 estimate MMI 8–9 for Hamlet from a photo of a damaged railroad shack.

The Distribution of Intensity in Mendocino County

F. E. Matthes canvassed geologic effects and shaking damage from Fort Ross to Fort Bragg on the Mendocino

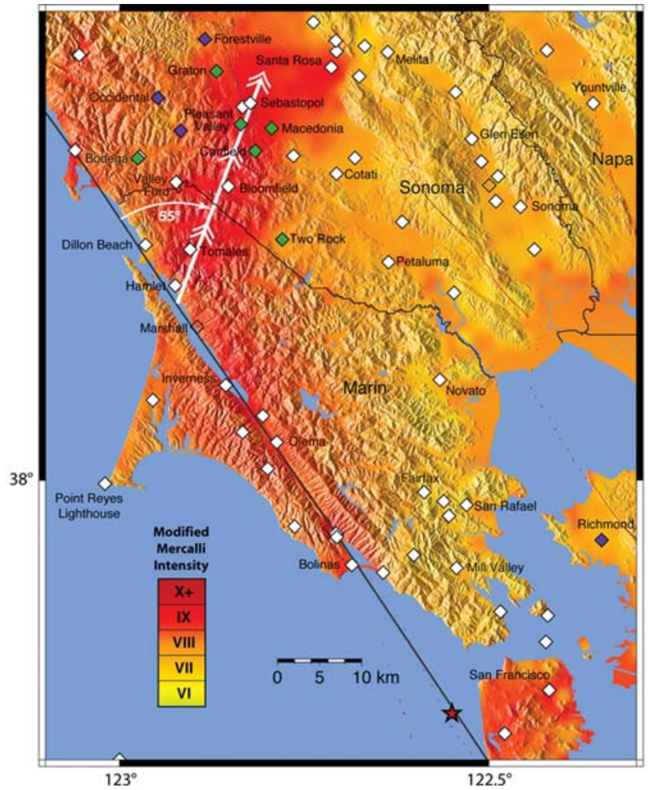

Figure 3. The distribution of MMI in Marin and Sonoma Counties, replotted from B&B05. The white diamonds indicate intensity estimates obtained from the reports in Lawson (1908), the violet diamonds indicate intensity estimates obtained from newspaper accounts and narratives, and the green diamonds indicate intensity estimates obtained from cemetery damage. Empty diamonds indicate sites where the strongest reported effect (for example, the lateral spread at Marshall) was judged to underestimate the actual shaking. The white arrow indicates an alignment of an *S*-wave caustic associated with a rupture velocity of $\nu = \alpha$.

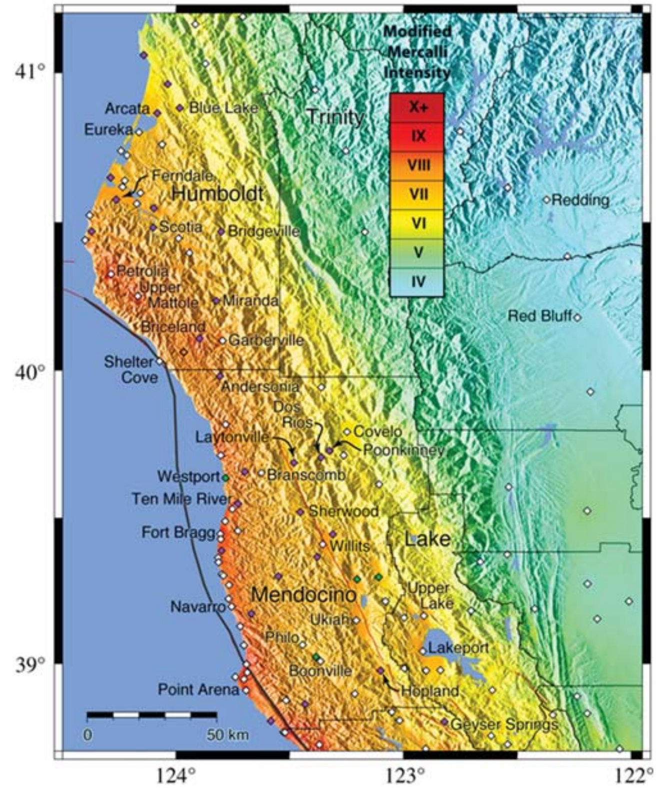

Figure 4. The distribution of MMI Intensity in Mendocino and Humboldt Counties, replotted from B&B05. The color of the diamonds indicates the source of the intensity report, as described in the caption for Figure 3. The empty diamond near Briceland marks Thorn Junction, where the postmaster's report of shaking effects was extremely brief. The Eel River lowlands lie just north of Ferndale. Intensities at the sites in Mendocino County marked with violet diamonds were obtained from narratives compiled by Bartley (2006): Muir Canyon and Tree Rock Valley are just southwest and northeast of Willits.

Coast (Lawson, 1908). The intensity along the coast varied from MMI 7–8 to MMI 9, as shown on Figure 4. The area around Fort Bragg suffered some of the greatest damage, despite being 10–15 km east of the fault trace. Inland, however, full reports were only obtained from large towns. B&B05 were able to add 19 intensity sites in Mendocino County, primarily from narratives compiled by Bartley (2006), that help determine the falloff of intensity with distance from the fault.

Two effects distort the falloff of ground motion with distance: basin amplifications and critically reflected *S* waves (Somerville and Yoshimura, 1990). Because the earthquake was an extended source, and the large towns in Mendocino and Lake County are in valleys, we expect basin amplification to play the larger role. For example, Lakeport (MMI 8) and Upper Lake (MMI 7–8) were more strongly damaged than Hopland (MMI 7), despite being farther from the fault. Ukiah (MMI 7–8) is at the same fault distance as Hopland, but is situated in a large valley and was shaken more strongly.

The relatively low intensities obtained in Anderson Valley provide an interesting counterexample: Boonville (MMI 7) and Philo (MMI 6–7) suffered damage to chimneys, but not to wood-frame and masonry buildings. The slight damage observed at two cemeteries (MMI 6–7 and 7) located between these towns (see Table 2) corroborates these intensity estimates. The MMI 8 area S&C93 draw in northern Anderson Valley (see Figure 1b) is derived from their mislocation of the abandoned town of Navarro (MMI 8–9).

Further north, Willits (MMI 8) suffered damage to many masonry and some wood-frame buildings and the partial collapse of a hotel. Nearby sites to the southwest (Muir Canyon, MMI 7), to the northeast (Tree Rock Valley, MMI 7), and to the northwest (Sherwood, MMI 6–7), were less strongly shaken. This comparison suggests that the ground motion in Willits was strongly amplified, as might be expected for a small but relatively deep (~0.5 km) alluvial basin mantled by Quaternary sediments (Woolace *et al.*, 2005).

The narratives from Bartley (2006) allow us to construct a transect from Westport to Covelo. The cemetery in Westport (MMI 8) was moderately damaged, commensurate with the damage to chimneys reported in Lawson (1908). To the east, horses and cattle standing on a hillside were thrown down near Branscomb Road (MMI 8), but only a few chimneys were damaged in Branscomb and Laytonville (MMI 6–7). The shaking strained a barn and knocked down a tree limb near Dos Rios (MMI 7). No damage to chimneys was reported in either Poonkinney or Covelo (MMI 6). Lawson's coauthor E. S. Larsen mapped a number of ground cracks in the hills around Covelo: B&B05 assigned MMI 6–7 to these sites.

The variable falloff of intensity with distance obtained from this transect is similar to the falloff of intensity with distance for all of Mendocino County, plotted in Figure 5a. The intensities are approximately constant (MMI 8 to MMI 8–9) within 15 km of the fault, and decrease gradually to MMI 6–7 at 60 km, and then decrease more rapidly. The shoulder at 50–60 km is suggestive of a critically reflected *S*-wave (Somerville and Yoshimura, 1990). Most of the sites at this distance are not situated in alluvial basins.

Figure 4 shows few streaks of high intensity off the fault, similar to the one in Sonoma County, that might indicate transonic fault rupture. The only suggestion of a high-intensity streak is aligned north–northeast along the coast from Fort Bragg to Ten Mile River. We note, however, that to generate an off-fault streak, the fault rupture must have both a transonic rupture velocity and a locally high slip rate. The slip in the Song *et al.* (2008) rupture model is approximately constant along the Mendocino coast.

The Distribution of Intensity in Humboldt County

Lawson (1908) obtained few reliable reports from Humboldt County. B&B05 were able to add 12 sites using reports from local newspapers, in particular, the *Blue Lake Advocate* and the *Ferndale Enterprise*. These additional sites are indicated in Figure 4. Petrolia (MMI 9) suffered the strongest shaking in Humboldt County: houses were thrown from their foundations, every headstone in the cemetery was overturned, and there was a large landslide on the south side of the Mattole River. Houses were thrown from their foundations in Upper Mattole (MMI 8–9) and Briceland (MMI 8–9), but the damage was less severe in Garberville (MMI 8). To the south, the logging operation at Andersonia (MMI 8) was badly damaged by landslides.

The intensity in Humboldt County appears to fall off more slowly to the north than to the east. To the north, Ferndale (MMI 8) was badly damaged, and there were extensive lateral spreads throughout the Eel River lowlands (MMI 7–8). Chimneys and windows were broken in both Eureka and Arcata (MMI 7). A letter from Eureka (Tracy, 1992) describes the shaking as building slowly and continuing violently for perhaps as long as a minute. To the east, both Scotia and Miranda (MMI 7) were moderately damaged, and further east, one chimney in Bridgeville (MMI 6–7) was knocked down.

Analysis of the intensity in Humboldt County is hindered by the uncertainty of the location and extent of the rupture. Matthes mapped a splay of the 1906 rupture that came onshore at Shelter Cove (Lawson, 1908, p. 55). Although there was substantial ground failure in the area, there was little damage to a nearby farm. Lawson (1908) extended the high-intensity zone associated with surface faulting through Upper Mattole and Petrolia (see Fig. 1a). However, the rupture mapped by Matthes ends about three miles inland, and there is no other onshore exposure of the rupture in Humboldt County (Prentice *et al.*, 1999), although the terrain is extremely difficult.

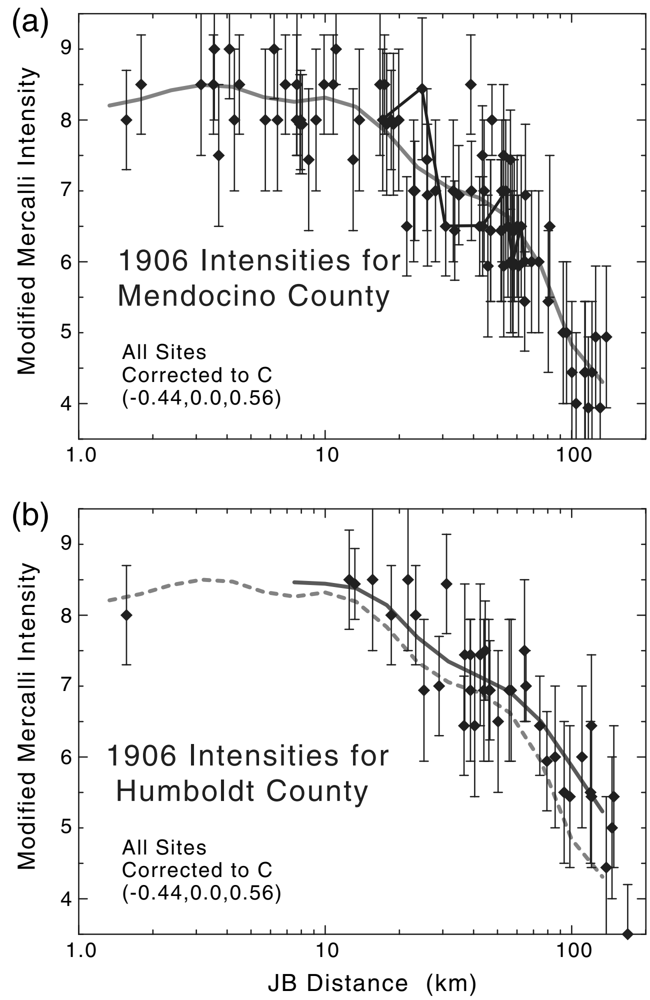

Figure 5. (a) The fall off of MMI plotted as a function of distance from the fault rupture for sites in Mendocino County. The intensity estimates are corrected for site response by binning the sites by the National Earthquake Hazards Reduction Program (NEHRP) soil categories as B&BC, C&CD, D&E, and correcting the B&BC sites by $\Delta I = 0.44$ and the D&E sites by $\Delta I = -0.56$. The solid line connects the corrected intensities for the transect from Westport to Covelo, discussed in the text. The shaded curve is the average intensity, smoothed over logarithmic intervals from $r_{JB}/2$ to $2r_{JB}$, where r_{JB} is the distance to the fault. (b) The fall off of MMI plotted as a function of distance from the fault rupture for sites in Humboldt County. The dashed curve is the average intensity for Mendocino County, replotted from Figure 5a.

Locating the San Andreas fault offshore is difficult as well: marine seismic lines cannot be shot within 10 km of the Humboldt coast. Griscom (1973) used magnetic and Bouguer gravity anomalies to infer that the fault follows the shoreline from Shelter Cover to Punta Gorda. A recent aeromagnetic survey shows a broad anomaly west of Shelter Cove that constrains the San Andreas fault to lie close to the coast (R. C. Jachens, personal comm., 2007). Thatcher *et al.* (1997) used Griscom's (1973) fault location to analyze the 1906 geodetic data.

The intensities in southern Humboldt County are in good agreement with this location: Upper Mattole and Petrolia are both about 14 km from this fault section. Both these towns were shaken severely, suggesting that rupture on this fault section was energetic. It is unlikely that this damage was caused by rupture of the section south of Shelter Cove: if the rupture was subsonic, Briceland and Upper Mattole should have been shaken more strongly than Petrolia, and if the rupture was transonic with an *S*-wave caustic near Petrolia, there should be an *S*-wave caustic aligned north–northeast toward Garberville and Miranda.

Figure 5b compares the intensity in Humboldt County against the intensity in Mendocino County, plotted as a function of distance from the fault. Surprisingly, the intensities in Humboldt County exceed those in Mendocino County ($\Delta I \sim 0.3$ intensity units), for sites 20–100 km from the fault. We attribute this difference to fault geometry and directivity. The long duration of shaking reported in Eureka necessarily contained ground motion radiated by the 150-km-long section of the San Andreas south of Shelter Cove, in addition to ground motion radiated by the 35-km-long section along the southern Humboldt coast. A rapid but subsonic ($\nu \approx 0.8\beta$) rupture along this north-trending section of the fault would amplify the ground motion radiated towards Humboldt County more than enough to compensate for the greater source-receiver distance and would add significantly to the total ground motion.

The Distribution of Intensity in Santa Cruz and San Benito Counties

G. A. Waring mapped the rupture and canvassed damage extensively for the 1908 Lawson Report. His damage reports for sites in San Benito, Santa Clara, and Monterey Counties are generally thorough. In particular, he documented the abrupt change in intensity between Chittenden (MMI 9), where freight cars were thrown off the tracks and bridges were damaged, and San Juan Bautista (MMI 6–7), where a weak adobe wall fell in the Mission and only "one or two chimneys in the village fell."

Waring's damage reports for Santa Cruz County are incomplete, however: he fails to report damage in either Corralitos or the Casserly school district despite visiting these areas as he searched for the fault rupture (Prentice and Schwartz, 1991). B&B05 used newspaper reports of damage to wood-frame churches and houses to infer intensities in Corralitos (MMI 8–9), Casserly (MMI 8–9), and Aromas (MMI 8–9). An extensive landslide dammed Eureka Canyon (MMI 8–9) above Corralitos (Youd and Hoose, 1978). In addition, B&B05 found that both the Day Valley and St. Francis cemeteries (MMI 8) were moderately damaged by the earthquake. These additional sites fill in the intensities between Summit Ridge and Chittenden. Although these added intensities are less than the MMI 9–10 intensities inferred near Summit Ridge, rupture on the fault segment near Corralitos appears somewhat energetic.

The most striking aspect of Figure 6 is the rapid decrease of intensity to the southeast of San Juan Bautista, along the strike of the fault. Tres Pinos (MMI 5–6), Paicines (MMI 6), and Cienega (MMI 5–6) suffered little or no damage. Milk was barely spilled from pans in Los Muertos (MMI 5) and Browns Valley (MMI 5), while objects were thrown from shelves in Mulberry (MMI 5–6). The falloff of intensity along the fault strike is appears more rapid than the falloff normal to the fault, which is the opposite of what we expect from directivity. Although there was off-fault damage in both Salinas (MMI 8) and Hollister (MMI 8), it seems likely that this damage was the result of basin amplification, as both of these towns are situated on relatively deep sedimentary basins (Brocher, 2005).

Because the shaking was so severe at Summit Ridge, we conclude that the rupture through Summit Ridge was rapid, possibly faster than the *S*-wave speed, but that the rupture slowed as it continued past Corralitos. The rupture of the fault section from Chittenden to San Juan Bautista may have been nearly aseismic. This scenario corresponds with the seismic history of this section of the San Andreas. Bakun (1999) located four **M** ~6 earthquakes (1883, 1890, 1892, and 1899) along the San Andreas north of Cienega. The isoseismals for the **M** 6.3 earthquake of 24 April 1890 suggest that this earthquake ruptured from Chittenden to Corralitos (Toppozada *et al.*, 2002). Thus, the slip in the 1906 earthquake on this section may have been semiseismic (i.e., a relatively small stress release accompanied by a large amount of slip driven by the stress redistribution from the rupture to the northwest). This semiseismic model also fits the 3.5-m estimate of fault slip obtained by Fumal *et al.* (2003) at the Arano Flat trench shown on Figure 6.

Discussion

Song *et al.* (2008), hereafter shortened to Sea08, simultaneously fit geodetic length changes and teleseismic recordings to determine a kinematic model for the 1906 earthquake. They discretize the rupture into 48 patches that are 10-km long and 12-km wide, and invert for the slip on each patch. They aggregate these patches into five larger segments, which range from 40- to 120-km long, and invert for the average rupture velocity of these segments.

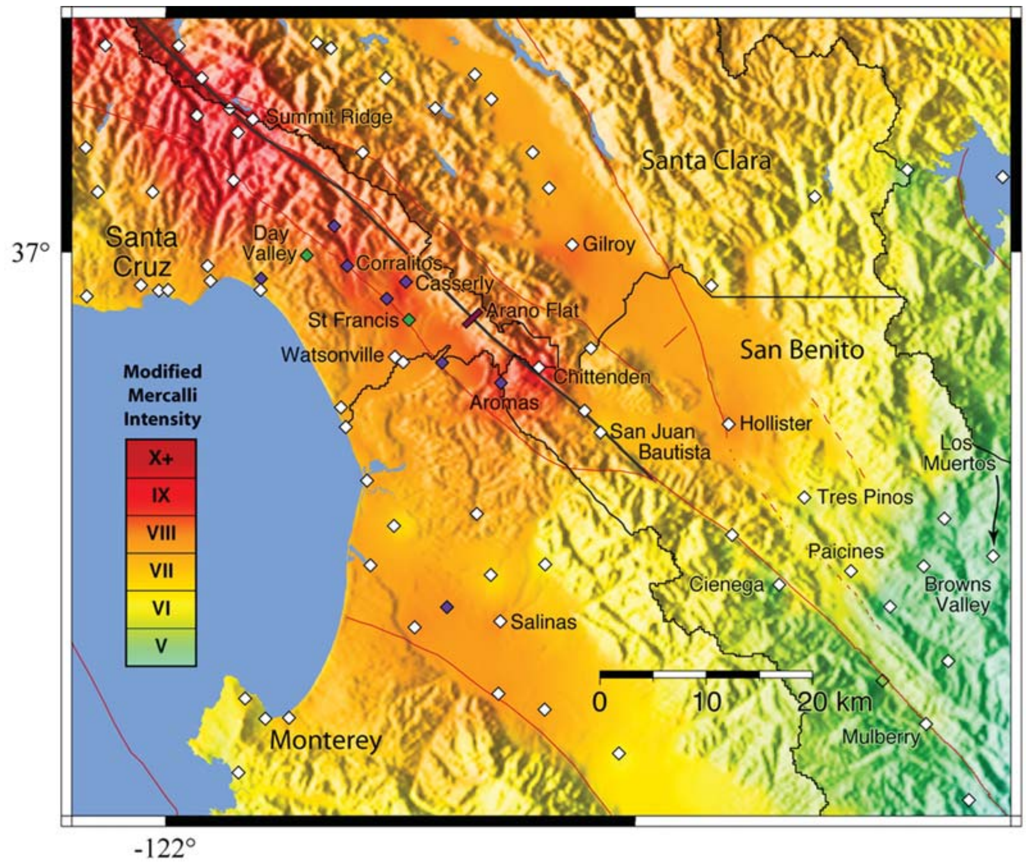

Figure 6. The distribution of MMI Intensity in Santa Clara, Santa Cruz, San Benito, and Monterey Counties, replotted from B&B05. The color of the diamonds indicates the source of the intensity report, as described in the caption for Figure 3. The purple bar on the fault indicates the Arano Flat trench, where Fumal *et al.* (2003) found 3.5 m of slip for the 1906 earthquake.

Sea08 find the fastest rupture velocity ($\nu \approx 1.31\beta$) for the segment that encompasses the epicenter and extends northwest beyond Bodega Head, and the next-fastest rupture velocity ($\nu \approx \beta$) for the segment that extends along the Mendocino coast. They obtain a fast but subsonic rupture velocity ($\nu \approx 0.95\beta$) on the segment that runs from Fort Bragg to Punta Gorda. Sea08 point out that these fast rupture velocities are driven by the relatively short duration of the teleseismic waveforms, combined with the geodetic evidence for substantial slip on the northernmost segment.

Sea08's fastest rupture velocity corresponds reasonably with our inference of a transonic rupture from the intensity in Sonoma County shown in Figure 3, except we see the rupture accelerating to the *P*-wave velocity ($\nu \approx 1.73\beta$) only along Tomales Bay. If the rupture were initially transonic, both San Rafael (MMI 7) and Petaluma (MMI 7–8) would have been more strongly damaged. If the rupture velocity from the epicenter to Bolinas (MMI 9) were subsonic but relatively fast, say $\nu = 0.8\beta$, the average velocity for this segment could approximate Sea08's estimate of $\nu \approx 1.31\beta$. Unfortunately, the intensity sites in Sonoma County north of Bodega are sparse and yield little constraint on the rupture process there.

The intensity distribution in Mendocino County shown in Figure 4 gives less constraint on the rupture velocity along the Mendocino coast. There are no clear off-fault streaks of high intensity that indicate transonic ruptures, but the Sea08 slip is relatively smooth on this segment, other than a three-patch section of low slip south of Point Arena. We note that the rupture velocity $\nu = \beta$ is not stable for in-plane ruptures (Andrews, 1976), so it would be natural to expect the rupture to vary between subsonic and transonic sections. But no transonic rupture velocity jumps are apparent in the off-fault intensity distribution.

The geometry of the San Andreas fault offshore of Mendocino County, where Humboldt County lies in the direction of rupture and Mendocino County is normal to the fault, allows us to use the intensity distribution in Humboldt and northern Mendocino Counties to estimate the rupture velocity of this section. In particular, the intensities in Humboldt County exceed the intensities in Mendocino County by $\Delta I \leq 0.5$ or by about a factor of 1.5 in ground motion. Correcting this factor for the greater distance to this fault section, where Humboldt County is approximately two to three times farther from the fault, yields a directivity factor of 3 to 5.

The Ben-Menahem (1961) directivity factor

$$D = (1 - \nu/\beta \cos \vartheta)^{-1} \quad (3)$$

associated with a rupture velocity of $\nu = 0.9\beta$ is a factor of 10: the very fast rupture ($\nu \approx 0.95\beta$) that Sea08 obtain for the section south of Shelter Cove would have produced MMI ≥ 8–9 for most of Humboldt County. This fast rupture velocity would also shorten the duration of the ground motion in Eureka to <25 sec (see Aagaard *et al.*, 2008, figures 9 and 16).

Finally, Sea08 obtain their slowest average rupture velocity, $\nu \approx 0.77\beta$, for the segment that extends southeast from Los Gatos to San Juan Bautista. The intensity distribution in Santa Cruz County suggests that this average rupture velocity is made up of a relatively fast rupture past Summit Ridge that starts to decelerate near Corralitos and slows to become nearly aseismic from Chittenden to San Juan Bautista.

Conclusions

B&B05 added many sites to the set of Lawson (1908) intensity sites that were analyzed and contoured by S&C93. These new sites help to resolve the distribution of shaking intensity in the near and intermediate field of the earthquake. In particular, the resolution of intensity in Sonoma, Mendocino, and Humboldt Counties has been significantly improved. The added sites reveal an intensity distribution in Sonoma and Marin Counties that suggests a transonic rupture near Tomales Bay, an approximately uniform intensity distribution in Mendocino County, and stronger shaking in Humboldt County than previously mapped. Sites added near Santa Rosa and Willits confirm that ground motion in these areas was amplified by basin effects. Low intensities in Santa Cruz and San Benito Counties suggest that the rupture decelerated on the southeastern segment of the fault, possibly becoming aseismic as it reached San Juan Bautista.

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References

Aagaard, B. T., T. M. Brocher, D. Dolenc, D. Dreger, R. W. Graves, S. Harmsen, S. Hartzell, S. Larsen, K. McCandless, S. Nilsson, N. A. Petersson, A. Rodgers, B. Sjögreen, and M. L. Zoback (2008). Ground-motion modeling of the 1906 San Francisco earthquake, part II: Ground-motion estimates for the 1906 earthquake and scenario events, *Bull. Seismol. Soc. Am.* **98,** no. 2, 1012–1046.

Andrews, D. J. (1976). Rupture velocity of plane strain shear cracks, *J. Geophys. Res.* **81,** 5679–5687.

Bakun, W. H. (1999). Seismic activity of the San Francisco Bay region, *Bull. Seismol. Soc. Am.* **89,** 764–784

Bartley, S. E. (2006). *The 1906 Earthquake on California's North Coast*, Fort Bragg-Mendocino Coast Historical Society and Mendocino Museum, Fort Bragg, California.

Ben-Menahem, A. (1961). Radiation of seismic surface-waves from finite moving sources, *Bull. Seismol. Soc. Am.* **51,** 401–435.

Bernard, P., and D. Baumont (2005). Shear Mach wave characterization for kinematic fault rupture models with constant supershear rupture velocity, *Geophys. J. Int.* **162,** no. 2, 431–447.

Boatwright, J., and H. Bundock (2005). Modified Mercalli intensity maps for the 1906 San Francisco earthquake plotted in ShakeMap format, *U.S. Geol. Surv. Open-File Rept. 2005-1135*.

Brocher, T. M. (2005). A regional view of urban sedimentary basins in northern California based on oil industry compressional-wave velocity and density logs, *Bull. Seismol. Soc. Am.* **95,** 2093–2114.

Fumal, T. E., G. F. Heingartner, L. Samrad, T. E. Dawson, J. C. Hamilton, and J. N. Baldwin (2003). Photomosaics and logs of trenches on the San Andreas fault at Arano Flat near Watsonville, California, *U.S. Geol. Surv. Open-File Rept. 2003-450*.

Griscom, A. (1973). Tectonics at the junction of the San Andreas fault and the Mendocino fracture zone from gravity and magnetic data, in *Proc. of the Conference on Tectonic Problems of the San Andreas Fault System*, R. L. Kovach and A. Nur (Editors), Vol. 13,, Stanford University, Publications in the Geological Sciences, 383–390.

Hill, A., and H. Lapham (1997). An historical and anecdotal walking tour of the small (but fascinating) village of Occidental, Occidental, California.

Lawson, A. C. (Editor) (1908). The California earthquake of April 18, 1906 (reprinted in 1969 by the Carnegie Institution of Washington, D.C.).

Mallet, R. (1862). Great Neapolitan earthquake of 1857, in *The First Principles of Observational Seismology*, Chapman and Hall, London.

McPhee, D. K., V. E. Langenheim, S. Hartzell, R. J. McLaughlin, B. T. Aagaard, R. C. Jachens, and C. McCabe (2007). Basin structure beneath the Santa Rosa Plain, northern California: implications for damage caused by the 1969 Santa Rosa and 1906 San Francisco earthquakes, *Bull. Seismol. Soc. Am.* **97,** no. 5, 1449–1457.

Prentice, C. S., and D. P. Schwartz (1991). Re-evaluation of 1906 surface faulting, geomorphic expression, and seismic hazard along the San Andreas fault in the southern Santa Cruz Mountains, *Bull. Seismol. Soc. Am.* **81,** no. 5, 1424–1479.

Prentice, C. S., D. J. Merritts, E. C. Beutner, P. Bodin, A. Schill, and J. R. Muller (1999). Northern San Andreas fault near Shelter Cove, California, *Geol. Soc. Am. Bull.* **111,** 512–523.

Richter, C. (1958). *Elementary Seismology*, W. H. Freeman, San Francisco.

Schubert, J. (2006). West County quake memoirs, in *Sonoma Historian*, Vol. **1**, Simone Wilson (Editor), Sonoma County Historical Society, Santa Rosa, California.

Somerville, P. G., and J. Yoshimura (1990). The influences of critical Moho reflections on strong ground motions recorded in San Francisco and Oakland during the 1989 Loma Prieta earthquake, *Geophys. Res. Lett.* **17,** 1203–1206.

Song, S., G. C. Beroza, and P. Segall (2008). A unified source model for the 1906 San Francisco earthquake, *Bull. Seismol. Soc. Am.* **98,** no. 2, 823–831.

Stover, C. W., and J. L. Coffman (1993). Seismicity of the United States, 1568–1989 (Revised), *U.S. Geol. Surv. Profess. Pap. 1527*.

Thatcher, W., G. Marshall, and M. Lisowski (1997). Resolution of fault slip along the 470-km-long rupture of the great 1906 San Francisco earthquake and its implications, *J. Geophys. Res.* **102,** 5353–5367.

Toppozada, T. R., D. M. Branum, M. S. Reichle, and C. L. Hallstrom (2002). San Andreas fault zone, California: M 5.5 earthquake history, *Bull. Seismol. Soc. Am.* **92,** 2555–2601.

Tracy, E. E. (1992). The earthquake of 1906, in *Humboldt Historian*, Vol. **4**, Humboldt County Historical Society, Eureka, California.

Wald, D. J., V. Quitoriano, T. Heaton, H. Kanamori, C. W. Scrivner, and C. B. Worden (1999). TriNet "ShakeMaps": rapid generation of instrumental ground motion and intensity maps for earthquakes in southern California, *Earthq. Spectra* **15,** 557–564.

Wood, H. O., and Neumann (1931). Modified Mercalli intensity scale of 1931, *Bull. Seismol. Soc. Am.* **21,** 277–283.

Woolace, A. C., H. M. Kelsey, A. M. Sarna-Wojcicki, and G. Simpson (2005). Late Neogene and Quaternary stratigraphy and structure of Little Lake (Willits) Valley, Northern Coast Range, California (abstracts with programs), *Geol. Soc. Am.*, **37,** no. 4, 68.

Youd, T. L., and S. N. Hoose (1978). Historical ground failures in northern California triggered by earthquakes, *U.S. Geol. Surv. Profess. Pap. 993*.

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