Reevaluation of the Macroseismic Effects of the 1887 Sonora, Mexico Earthquake and its Magnitude Estimation

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Abstract

The Sonora, Mexico, earthquake of 3 May 1887 occurred a few years before the start of the instrumental era in seismology. We revisit all available accounts of the earthquake and assign Modified Mercalli Intensities (MMI), interpreting and analyzing macroseismic information using the best available modern methods. We find that earlier intensity assignments for this important earthquake were unjustifiably high in many cases. High intensity values were assigned based on accounts of rock falls, soil failure or changes in the water table, which are now known to be very poor indicators of shaking severity and intensity. Nonetheless, reliable accounts reveal that light damage (intensity VI) occurred at distances of up to ~200 km in both Mexico and the United States. The resulting set of 98 reevaluated intensity values is used to draw an isoseismal map of this event. Using the attenuation relation proposed by *Bakun* (2006b), we estimate an optimal moment magnitude of M_w7.6. Assuming this magnitude is correct, a fact supported independently by documented rupture parameters assuming standard scaling relations, our results support the conclusion that northern Sonora as well as the Basin and Range province are characterized by lower attenuation of intensities than California. However, this appears to be at odds with recent results that L_g attenuation in the Basin and Range province is comparable to that in California.

Introduction

The 3 May 1887 earthquake, which occurred in the Teras Mountain region of the state of Sonora, Mexico is one of the largest historic earthquakes in the Basin and Range physiographic province and is the longest recorded normal-fault surface rupture in historic times (*Suter*, 2006) (Figure 1.). As described by *Suter* (2006), the earthquake was large enough to disturb the magnetograph operated by the Coast and Geodetic Survey in Los Angeles and might have been recorded by the early seismometers installed at Lick Observatory located on Mt. Hamilton in the Diablo Range, east of San Jose, California.

Compiled records from accurate clocks operated by railroads and telegraph operators establish a reasonably precise origin time of 22:13 UTC. Unfortunately, no seismograms are available to perform a quantitative analysis of this event. Nevertheless, a significant number of archival accounts of macroseismic effects were compiled by *DuBois and Smit*h (1980), who assigned Modified Mercalli Intensity (MMI) values for 214 locations in Mexico and in the United States.

The accounts compiled by *Dubois and Smith* (1980) provide a good overview of the effects of the earthquake which was felt over a large area. Locally, the earthquake caused significant damage in towns close to the epicenter. In the town of Bavispe, located about 20 kilometers from the surface rupture of the Pitáycachi segment, most private dwellings were destroyed and the church collapsed; it is estimated that 42 people were killed out of a population of 700 (*Goodfellow*, 1887b; *DuBois and Smith*, 1980). In the Teras Range and in several other locations in Arizona, the earthquake caused numerous landslides, rockfalls, ground fissures and hydrological changes.

A detailed first-hand account of the earthquake from the town of Tepic, 6 miles south of Cumpas (29.983N, 109.783W), describes "earthwaves" rolling across a plaza (*MacDonald*, 1918). The waves were reportedly "2 ft. high and 20' apart", and moving as rapidly as waves approaching seashore. Shaking in this location was severe enough to leave the walls and roof of every house, all of which were of "squatty" adobe construction, "shattered." *MacDonald* (1918) describes many houses "wrecked in the same manner" in Moctezuma, 20 miles south of Tepic, and reported that the effects of the earthquake were “strongly manifested for a distance of up to 100 miles south of the town. *García Acosta and Suárez* (1996) collected additional macroseismic information from sources in Mexico. This information is used to complement the data of *DuBois and Smith* (1980).

As documented by *Suter* (2006), the surface rupture of the Sonora earthquake was investigated in detail by two individuals immediately after the event occurred: George Emory Goodfellow (*Goodfellow*, 1887a, 1887b, 1888) and José Guadalupe Aguilera Serrano (*Aguilera*, 1888; *Aguilera*, 1920). The rupture maps produced by these studies are among the earliest detailed surface rupture maps. The mapped fault rupture is fragmented into three main segments, with a total length of approximately 102 km.

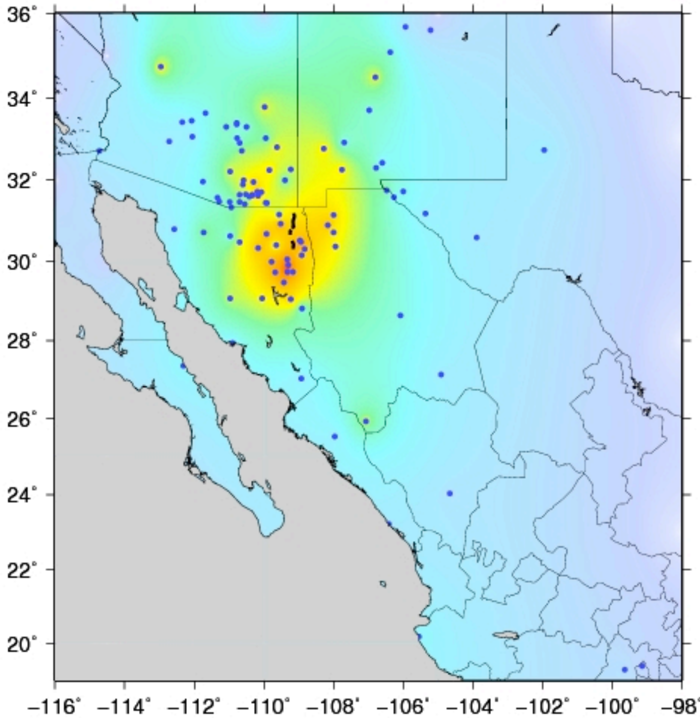
Based on Aguilera’s and Goodfellow’s investigations, as well as on later studies of the fault scarp, *Natali and Sbar* (1982) estimated an average displacement of 3 m with a maximum of 4.5 m. These authors assumed an 80-km rupture length, a rupture depth of 16 km, and a shear modulus of 3.3×10^{11} *dyne*-cm. Based on these parameters, *Natali and Sbar* (1982) estimated the magnitude of the 1887 earthquake to be $M_w7.4$. Assuming the rupture length extends to a total length of 102 km, the scaling relations of *Wells and Coppersmith* (1994) yield a magnitude of $M_w7.5 \pm 0.3$.

Dubois and Smith (1980) estimated a magnitude of 7.2 for the Sonora event based on a qualitative interpretation of the intensity data. More recent published estimates, based on rupture length as well as macroseismic data, have been consistently close to $M_w7.5$. These include a recent study by *Bakun* (2006b), who infers an optimal $M_w7.5$ based on a reinterpretation of MMI values using a subset of only 27 macroseismic reports of the 214 sites for which accounts were reported by *DuBois and Smith* (1980). Most of the sites used by *Bakun* (2006b) in his analysis are in the United States, to the northwest of the rupture zone and at an average distance of over 200 km from the source area.

Reevaluation of the Intensity Data

The approximate magnitude of the Sonora earthquake does not appear to be in question. Nevertheless, we note that in spite of the extensive archival search of *DuBois and Smith* (1980) and the relatively large number of macroseismic accounts of the event, no intensity map is available for this important earthquake that makes use of all the available macroseismic information. The map produced by *DuBois and Smith* (1980) reveals some aspects of the intensity field, including the extent of the shaking felt. However, in this study intensities were assigned according to practices that recent studies have shown to be problematic or erroneous. In particular, *DuBois and Smith* (1980) assign a large number of high intensity values based on accounts of landslides, rockfalls, ground fissures, liquefaction, and documented hydrological disruptions, such as changes in the course of rivers or water source flow. A number of recent studies have shown that such effects are not reliable indictors of shaking intensity (*e.g.*, *Ambraseys and Bilham*, 2003). According to traditional intensity scales, observations of liquefaction correspond to a MMI value of at least VIII. Nevertheless, recent studies have documented liquefaction in earthquakes as small as $M3.5$ (*Musson*, 1998). Furthermore, *Hough and Elliott* (2004) find that rockfalls occurred commonly following the 1892 Laguna Salada, Mexico, earthquake, in regions that experienced an estimated shaking intensity of only MMI VI.

For our investigation the data of *DuBois and Smith* (1980) is complemented with macroseismic information collected by *García Acosta and Suárez* (1996). These authors report additional macroseismic information from some new locations and, in some locations, data that complement those reported originally by *DuBois and Smith* (1980). Because both the Sonora region and Arizona were sparsely populated at the time, many of the accounts that describe environmental effects do not provide sufficient information to assign MMI based on effects to structures or even shaking intensity as perceived by humans. Nonetheless, we are able to assign reliable intensity values for 98 locations that provide good azimuthal coverage of the intensity field around the fault rupture (Table 1; Figure 1).



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18–34	34–65	65–124	>124
PEAK VEL.(cm/s)	<0.1	0.1–1.1	1.1–3.4	3.4–8.1	8.1–16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1. Ninety eight intensity data points considered of quality 1 for the 1875 Sonora earthquake are shown as blue dots. The colored contours are drawn using a gridding algorithm from the Generic Mapping Tools (*Wessel and Smith*, 1991), according to the color scale shown in the lower part of the figure. Notice the large area where intensities MMI V or higher were felt, spanning a distances in a NW-SE direction of up to 1000 km.

The farthest location towards the west for which an intensity value was determined is Yuma, Arizona, where we infer MMI IV based on accounts that the shaking was distinctly felt and strong enough to cause hanging objects to sway. This report suggests that the shaking should have been felt throughout southern California as well. This inference appears to be supported by a number of newspaper accounts, for example a report in the 6 May 1887 *Decatur Daily Review* that “the shock was felt from Centerville, California, through Arizona and New Mexico, to El Paso, Tex,” and a report in the 5 May 1887 *Hamilton Daily Democrat* that, “violent shocks were felt in Arizona and Southern

California." However, the 5 May 1887 *Galveston Daily News* notes that a heavy earthquake was felt in Centerville, California, on the morning of May 3.

This account is clearly problematic. First the time does not correspond to the time of the Sonora earthquake, which occurred on the afternoon of May 3. Furthermore, Centerville is in central California at latitude 36.73N. If the earthquake was felt strongly in this location it should have been widely felt throughout southern California, in which case we would expect to find abundant archival documentation from other locations. From this evidence we conclude that the account from Centerville is unreliable, and that it was likely the source of later, derivate articles in other newspapers; a practice common in those days. Considering the accounts from Arizona and the absence of reliable, primary accounts from California, we conclude that shaking was probably felt weakly in the sparsely populated southeastern corner of California and probably not felt in the early settlements along the California-Mexico border, 100 or more km west of Yuma (Figure 2).

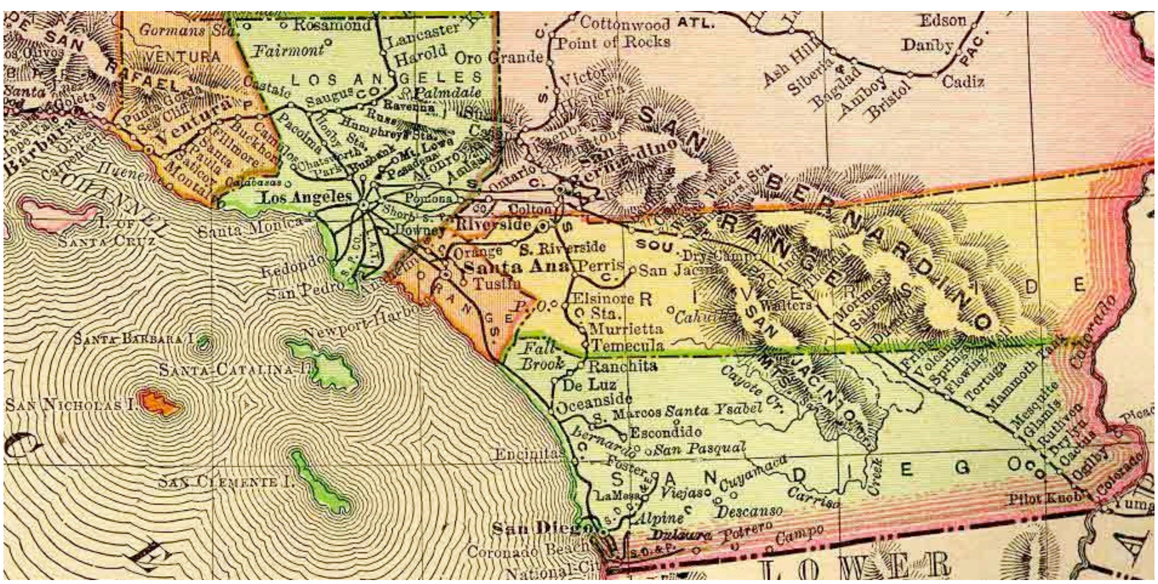


Figure 2.   An 1895 Rand-McNally map of California (Humboldt State Univ. Library). By 1877 the Southern Pacific Railroad extended from Los Angeles to Yuma, but the corridor remained sparsely populated through the southeastern desert region, with only tiny railroad stops along the route between Yuma and San Bernardino.

Table 1 presents a summary of the macroseismic information used to estimate the intensity values reported. A subjective quality factor of 1 or 2 is included in the table for all intensity data points. A quality value of 1 indicates that the descriptions of the felt reports corresponds clearly to specific entries in the Modified Mercalli Scale and as a result yield highly reliably intensity data points. A value of 2 indicates that the available information is less precise, ambiguous or does not clearly correspond to entries in the MMI scale. Thus the corresponding MMI values are less reliable.

The isoseismal contours shown in Figure 1 were calculated by the gridding algorithm used in the "surface" utility of the Generic Mapping Tools (*Wessel and Smith*, 1991). This algorithm uses a tension factor, T, to control the degree of curvature. The minimum curvature solution, T=0 can generate unrealistic oscillations, while T=1 will generate a solution with no maxima or minima away from control points. As a compromise, here we use a value of T=0.5.

Figure 1 reveals a relatively complex distribution of intensities and the extent of the felt area is not well constrained. Nonetheless, as we noted before, one can reasonably infer that strong shaking was not generally felt in California beyond the sparsely populated southeastern corner of the state. Strong and damaging shaking extended over 200 kilometers north and south of the epicentral region, with isolated locations at greater distances experiencing light damage. The damage pattern reveals the expected correlation with near-surface geology. For example the cluster of intensity VI-VII in southeastern Arizona are all from towns located on sediment-filled basins within the Basin and Range province. In general, early settlements in the region were within basins rather than ranges (*e.g.*, Figure 3).

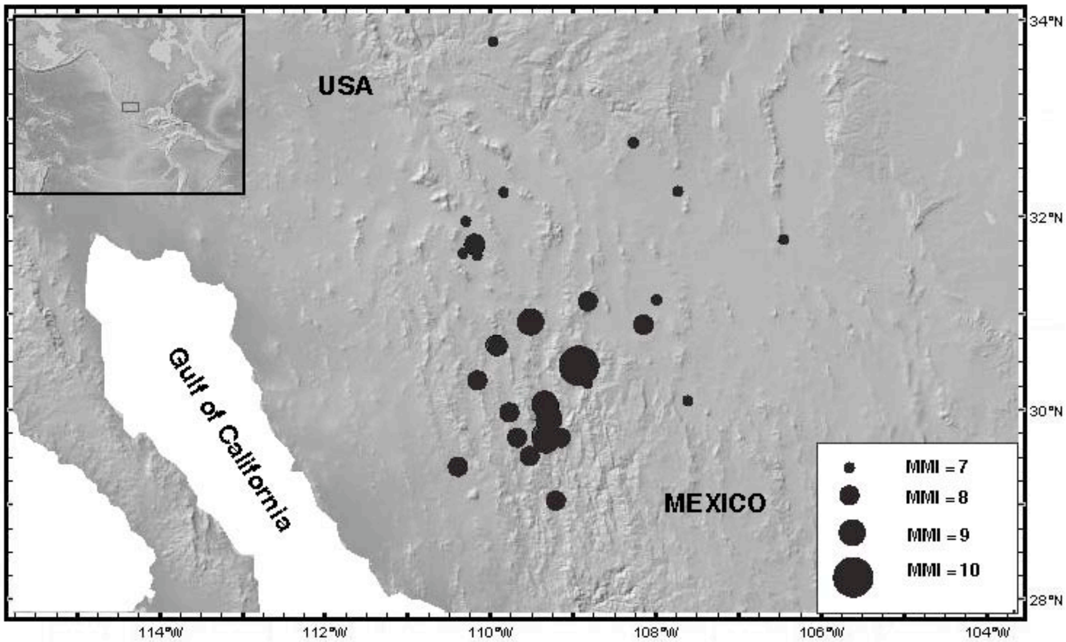


Figure 3. Shaded topographic relief map of the Basin and Range province including locations reporting damaging intensities (black circles).

Interpretation

Bakun and Wentworth (1997) (hereinafter BW97) present a method to determine magnitude from the decay of MMI values as a function of distance from the epicenter for earthquakes in western North America. *Bakun* (2006b) determines an attenuation relation for intensities of earthquakes in the Basin and Range province. The BW97 method estimates an optimal magnitude and epicentral location using observed MMI values as a function of distance, using calibrations established for the region from a set of instrumentally recorded earthquakes with known magnitudes and epicentral locations. The method yields a magnitude estimate, M_I, that is expected to correspond to M_w if M_w values are used as calibration events to determine the local attenuation relation. The method of BW97 does not use isoseismal contours per se, but instead involves a regression of intensity versus distance at each and every data point, given previously estimated attenuation calibration curves.

Using a set of instrumentally recorded calibration events in the Basin and Range provnice, *Bakun* (2006b) determines the attenuation relation,

$$MMI(M_I,r)=0.44 + 1.7M_I - 0.0048r - 2.73\log(r) \qquad \text{Eq. (1)}$$

The relationship determined by *Bakun* (2006a) for California is

$$MMI(M_I,r) =1.64 + 1.41M_I - 0.00526r - 2.63\log(r) \qquad \text{Eq (2)}$$

Applying the BW97 method and using the Basin and Range attenuation model of *Bakun* (2006b) to our 98 reinterpreted intensity values, we estimate an optimal magnitude of M_w7.8 and an optimal centroidal location of 29.7N, 110.0W. This location is significantly south and west of the Pitaycachi segment of the rupture (Figure 4) and reveals that the optimal location is not well constrained by the intensity distribution. If we constrain the epicenter to be at 31.07N, 109.12W, the location where *Suter* (2006) concludes that slip reached 4.4 m, the optimal magnitude estimate is M_I7.6. The BW97 method assumes a point source and might therefore yield biased results for long ruptures such as the one observed during the Sonora earthquake. However, the magnitude is largely constrained by the far-field intensity distribution and Figure 4 reveals that the preferred estimate remains 7.5-7.6 for any epicenter along the mapped trace of the surface rupture.

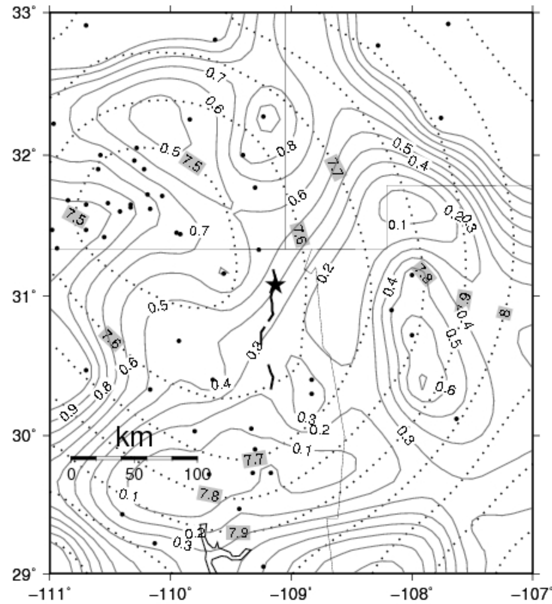


Figure 4. The results of a grid-search regression for optimal location and magnitude using the method of Bakun and Wentworth (1997) and the attenuation relation of Bakun (2006b). The rms misfit value and magnitude results over the grid of trial locations are contoured with solid and dotted lines, respectively. The preferred epicenter is assumed to be at the location of maximum slip along the mapped rupture trace (star.)

In order to investigate possible biases associated with less reliable MMI values we also estimated magnitude and location using only intensity data points with a quality factor of 1 as well as using the complete data set of 98 observations. No substantial difference is observed in the resulting epicentral location or in the magnitude. Nor do we find a significant change if intensity assignments with a quality factor of 1 are double-weighted in the inversion. These results suggest that the estimated magnitude is not dependent on the set of intensity data points used or unduly influenced by values that are relatively uncertain.

If one uses the California attenuation relation of *Bakun* (2006a) to determine magnitude, the optimal value increases significantly, to 8.2. Assuming this to be an unrealistically high value, this confirms the conclusion of *Bakun* (2006b) that attenuation of intensities is significantly lower in the Basin and Range province than in California.

Attenuation in the Basin and Range

Our preferred magnitude estimate is slightly higher than previously published estimates inferred from the shaking distribution (e.g., *Bakun*, 2006b) as well as from the predictions of scaling relations based on the extent of the mapped surface rupture (*Dubois and Smith*, 1980; *Natali and Sbar*, 1982). Our estimate, like that of *Bakun* (2006b), is based on a Basin and Range attenuation model characterized by significantly lower attenuation than California. We note, however, that recent investigations of L_g attenuation in the Basin and Range yield relatively low values of Q at 1 Hz (*Benz et al.*, 1997). *Aleqabi and Wysession* (2006) report values of Q=192 and 267, respectively. Both studies conclude that the Basin and Range province is characterized by interplate rather than intraplate attenuation, which *Aleqabi and Wysession* (2006) note to be consistent with expectations for an active tectonic region.

Thus the intensity attenuation relation of *Bakun* (2006b) may be apparently inconsistent with regional L_g attenuation values determined from instrumental data. This discrepancy could indicate that the intensity values for the calibration earthquakes used by *Bakun* (2006b) are systematically inflated. In this case, assuming the intensities estimated in this study are not similarly inflated, the true magnitude of the Sonora earthquake would be higher—potentially significantly higher—than our preferred estimate.

A recent study of attenuation in the vicinity of the Sonora earthquake (*Castro et al.*, 2008) concludes that, in the region around the 1887 rupture, the crust is characterized by stronger attenuation (i.e., lower Q) than the regional average. The results of *Castro et al.* (2008) are consistent with the Lg studies referenced above. Castro (personal communication, 2008) suggests that the broad damage pattern of the 1887 earthquake can be explained by high Q values at mid-crustal depths. However, *Hough and Anderson* (1988) also conclude that Q is high at mid-crustal depths in California.

An alternative interpretation is that there are significant, systematic differences in sources in the Basin and Range versus those in California, such that earthquakes in the former region generate higher ground motions at the frequency range that controls damage and perceptability. Comparing intensity distributions from small-to-moderate events in the central/eastern United States and California, *Atkinson and Wald* (2007) conclude that intraplate events have higher near-field intensities than interplate events, and attribute this to higher stress drops in intraplate regions.

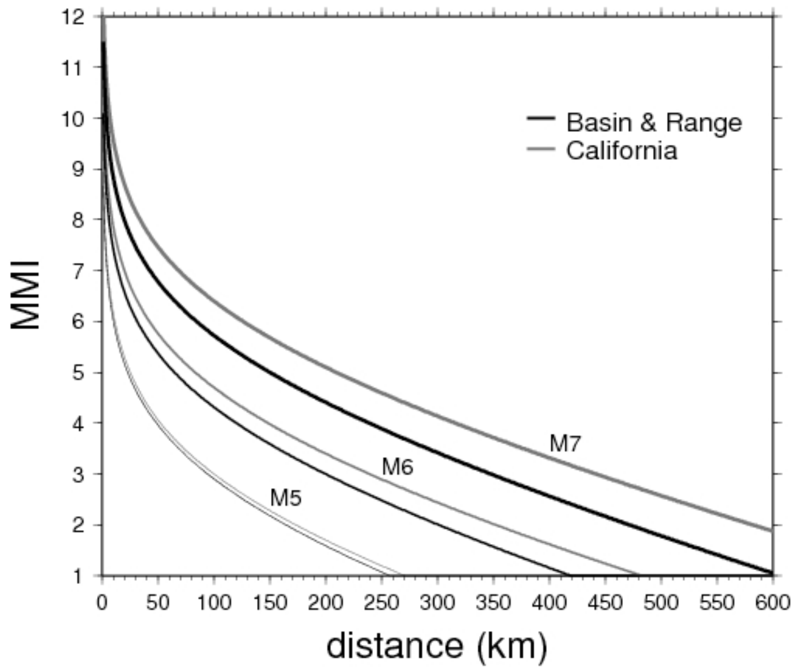


Figure 5. Predicted MMI(r) values from equations (1) and (2) for magnitude 5.0 (thin lines), M6 (medium lines), and M7 (thick lines).

The attenuation relations determined by *Bakun* (2006a) and *Bakun* (2006b) (e.g., equations (1) and (2)) have different magnitude scaling (Figure 5.) Although the curves predict comparable MMI(r) for M5.0 earthquakes, they predict significantly higher MMI(r) for M7.0 earthquakes in the Basin and Range than in California. If this apparent difference is not due to systematic biases in intensity, we suggest that large earthquakes in California might generally occur on mature faults and thus have lower stress drop than large (M7+) earthquakes in the Basin and Range, which tend to be complex faulting events. The higher stress drop of Basin and Range earthquakes would produce stronger shaking at regional distances than earthquakes occurring on well-developed faults in California. This fact could help explain the shaking effects of 1872 Owen's Valley earthquake, which both early studies (e.g., *Richter*, 1958) and the recent investigation of

Hough and Hutton (2007) conclude were more severe at regional distances than shaking from the 1906 San Francisco earthquake.

Conclusions

We have reviewed all available macroseismic information for the 3 May 1887 Sonora, Mexico, earthquake. The resulting isoseismal map shows that the earthquake was clearly felt at distances of up to 500 km north of the rupture and at even greater distances to the south. The earthquake generated damaging shaking over a broad area in Sonora as well as southern Arizona. These felt and damage reports highlight the effect that a future comparable earthquake could have today, when the population density and the number of constructions has substantially increased in the region. We present a set intensity values at 98 locations that we consider to be reliable subset of MMI intensity estimations for the 1887 Sonora event. Using recently developed methods to invert for the magnitude of historical events, the best estimate of the magnitude of the Sonora earthquake of 1887 is M_w7.6. The magnitude estimate appears to be robust and is independent of the subset of intensity values used in the inversion.

Our results are predicated on the ground motion relations determined by *Bakun* (2006b), which reveal significantly lower attenuation of intensities for large earthquakes in the Basin and Range compared to comparable events in California. This result remains enigmatic in light of recent studies showing that the Basin and Range is characterized by relatively high regional L_g attenuation. The apparent discrepancy could indicate a systematic difference between stress drops of large Basin and Range earthquakes versus large earthquakes on well developed faults in California. A definitive resolution of this discrepancy is beyond the scope of this study. We note, however, that in any case the intensity distribution of the 1887 Sonora earthquake was more dramatic at regional distances than the distribution expected for a *Mw*7.6 earthquake in California.

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References

Aguilera, J.G. (1888). Etudio de los fenómenos séismicos del 3 de mayo de 1887, *Anales del Ministerio de Fomento de la República Mexicana*, **10**, 5-56.

Aguilera, J.G. (1920). The Sonora earthquake of 1887, *Bull. Seism. Soc. Am*., **10**, 31-44.

Aleqabi, G.I. and M.E. Wysession (2006). QLg distribution in the Basin and Range Province of the western United States, *Bull. Seism. Soc. Am.*, **96**, 348-354.

Ambraseys, N., and R. Bilham (2003). Reevaluated intensities for the great Assam earthquake of 12 June 1897, Shillong, India, *Bull. Seism. Soc. Am*., **93**, 655-673.

Atkinson, G.M. and D.J. Wald (2008), "Did you feel it"? Intensity data: A surprisingly good measure of earthquake ground motion, *Seism. Res. Lett.* ***78,*** 362-368.

Bakun, W.H. (2006a) Estimating locations and magnitudes of earthquakes in southern California from modified Mercalli Intensities, *Bull. Seism. Soc. Am.* **96**, 1278-1295.

Bakun, W.H. (2006b). Modified Mercalli Intensity attenuation and historical earthquakes in the Basin and Range Province of western North America, *Bull. Seism. Soc. Am*. **96**, 2206-2220.

Bakun, W.H. and C.M. Wentworth (1997). Estimating earthquake location and magnitude from seismic intensity data, *Bull. Seism. Soc. Am*., **87**, 1502-1521.

Benz, H.M., A. Frankel, and D.M. Boore (1997). Regional Lg attenuation for the continental United States, *Bull. Seism. Soc. Am*. **87**, 606-619, 1997.

DuBois, S.M. and A.W. Smith (1980). The 1887 earthquake in San Bernardino Valley, Sonora: Historic accounts and intensity patterns in Arizona, *State of Arizona Bureau of Geol. and Mineral Technology, Special Paper no. 3*, 112 pp.

Castro, R.R., C. Condori, O. Romero, C. Jacques, and M.Suter, (2008). Seismic attenuation in northeastern Sonora, Mexico, *Bull. Seism. Soc. Am*. **98**, 722-732.

García Acosta, V. and G. Suárez (1996). Los Sismos en la Historia de México, Fondo de Cultura Económica, México D.F., 718pp.

Goodfellow, G. E. (1887a). The Sonora earthquake, *Science*, **9**, 483-484.

Goodfellow, G. E. (1887b). The Sonora earthquake, *Science*, **10**, 81-82.

Goodfellow, G. E. (1888). The Sonora earthquake, *Science*, **11**, 162-166.

Hough, S.E. and J.G. Anderson (1988). High frequency spectra observed at Anza, California: Implications for Q structure, Bulletin of the Seismological Society of America 78, 692-707.

Hough, S.E., and A. Elliott (2004). Revisiting the 1892 Laguna Salada earthquake, *Bull. Seism. Soc. Am., **94**,*

Hough, S.E. and K. Hutton (2008). Revisiting the 1872 Owens Valley, California earthquake, *Bull. Seism. Soc. Am.* **98**, 931-949.

MacDonald, B. (1918). Remarks on the Sonora earthquake—Its behavior at Tepic, Sonora, etc, *Bull. Seism. Soc. Am*. **8**, 74-78.

Musson, R.M.W. (1998). The Barrow-in-Furness earthquake of 15 February 1865: Liquefaction from a very small magnitude event, *Pure Appl. Geophys*., **152**, 733-745.

Natali, S.G., and M.L. Sbar (1982). Seismicity in the epicentral region of the 1887 northeastern Sonoran earthquake, Mexico, *Bull. Seism. Soc. Am.* **72**, 181-196.

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

Suter, M. (2006). Contemporary studies of the 3 May 1887 Mw7.5 Sonora, Mexico (Basin and Range Province) earthquake, *Seism. Res. Lett.*, **77**, 134-147.

Wald, D.J., V. Quitoriano, T.H. Heaton, and H. Kanamori (1999). Relationships between peak ground acceleration, peak ground velocity, and modified Mercalli intensity in California, *Earthq. Spectra*, **15**, 557-564.

Wells, D. and Coppersmith (1994). New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. Seism. Soc. Am*., **84**, 974-1002.

Wessel, P., and W.H.F. Smith (1991). Free software helps map and display data, *Eos Trans. AGU*, **72**, 441, 445.