Probabilistic Warning Times for Earthquake Ground Shaking in the San Francisco Bay Area

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INTRODUCTION

Current earthquake mitigation in the United States focuses on long-term characterization of the likely levels of ground shaking and the frequency of occurrence (Frankel *et al.*, 1996). These estimates are the basis for building codes, which aim to prevent collapse during earthquakes. In other countries, including Mexico, Japan, Taiwan, and Turkey, earthquake warning systems (EWS) are used in addition to building codes to further reduce the impact of earthquakes (Espinosa Aranda *et al.*, 1995; Wu *et al.*, 1998; Wu and Teng, 2002; Erdik *et al.*, 2003; Odaka *et al.*, 2003; Boese *et al.*, 2004; Kamigaichi, 2004; Nakamura, 2004; Horiuchi *et al.*, 2005; Wu and Kanamori, 2005). Short-term mitigation actions are taken to reduce both financial losses and casualties.

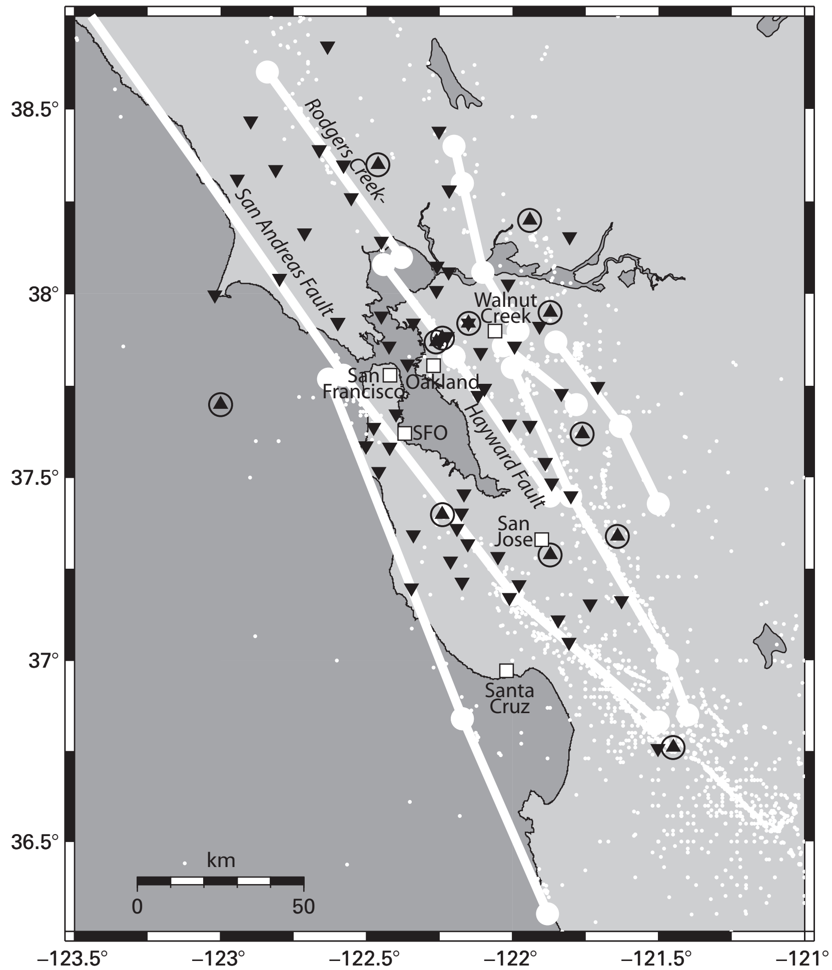
Earthquake warning systems rapidly detect the initiation of earthquakes and warn of the forthcoming ground shaking. For a specific city, such as San Francisco, the warning time could be tens of seconds for some earthquakes but essentially zero seconds for others. Even in situations when San Francisco has zero seconds warning, however, neighboring cities such as Oakland would likely have a few seconds and San Jose would have ~15 seconds warning. Thus, for any earthquake scenario in a densely populated region, such as the San Francisco Bay Area (SFBA), an EWS could provide warning to at least some of the affected population in a damaging earthquake.

Here I present estimates of the warning times that would be available for locations across the SFBA if an EWS were implemented in northern California. These warning times are calculated for identified likely earthquake scenarios in northern California. For each scenario an estimate of the probability of occurrence has been made (WGCEP, 2003), allowing calculation of probabilistic warning times. The warning times were calculated using the existing seismic network geometry in the region and are based on the ElarmS method for earthquake warning (Allen, 2004).

ElarmS

The ElarmS method (Allen, 2004) is designed to predict the distribution of peak ground shaking across the region affected by an earthquake before the beginning of significant ground motion (see `http://www.ElarmS.org/`). This is possible using the first energy to arrive at the surface during an earthquake, the *P* waves, which are generally low energy and do not cause damage. It is the later *S* waves, which travel more slowly, that cause most damage during earthquakes. The *P*-wave arrival times at several seismic stations close to the epicenter can be used to locate the earthquake. The magnitude of the earthquake can be estimated from the frequency content of the first 4 seconds using the method first described by Nakamura (1988). The maximum predominant period observed within 4 seconds scales with magnitude of the event. This has been observed for earthquakes with magnitude ranging from 3.0 to 8.3 from several regions around the world (Allen and Kanamori, 2003; Lockman and Allen, 2005, 2006; Olson and Allen, 2005). These data sets include events that occurred on extensive strike-slip faults like those in northern California, *i.e.*, the Landers (28 June 1992; M_w 7.3), Hector Mine (16 October 1999; M_w 7.1), and Denali (3 November 2002; M_w 7.9) earthquakes. The accuracy of magnitude estimates is a function of the number of stations providing *P*-wave data. Data sets from both southern California (Allen and Kanamori, 2003) and Japan (Lockman and Allen, 2006) show that when using just the closest station to the epicenter the average magnitude error is ~0.75 magnitude units. Once data from the closest two stations are available the error drops to ~0.6, and to ~0.5 magnitude units once data from four stations are available.

Given the location and magnitude of an earthquake, ElarmS estimates the spatial distribution of peak ground shaking using attenuation relations designed for the purpose (Allen, 2004). One second after the first *P*-wave arrival at the station closest to the epicenter, the first estimate of magnitude is available and the attenuation relations provide peak ground acceleration (PGA) as a function of distance from the epicenter. An "AlertMap" showing the distribution of ground shaking hazard can then be generated. As time progresses, more of the *P*-wave arrival from the closest station, plus *P* waves from other stations, become available and the magnitude estimate is updated along with the AlertMap. The accuracy of the hazard prediction therefore increases with time, while the warning time available decreases.



▲ **Figure 1.** Map of the study region showing existing continuous broadband stations in the Bay Area. Broadband velocity seismometers are shown with open circles (operated by UC Berkeley); accelerometers are shown as triangles (UC Berkeley) and inverted triangles (U.S. Geologic Survey). The fault segments identified by the Working Group on California Earthquake Probabilities (WGCEP, 2003) are shown with large white dots at the ends of segments joined by broad white lines. The location of M > 3 earthquakes are shown as small white dots. The six "warning points" included in Figure 2 are shown as white squares.

WARNING TIME ESTIMATES

Here, I calculate the distribution of warning times for many likely earthquakes in northern California. A threshold at which a warning is issued is chosen based on the accuracy of the warning. I use the point in time when 4 sec of *P*-wave data are available at four seismic stations. This point in time is defined as the "alert time" and represents the time when the average error in the magnitude estimate will be 0.5 magnitude units. The warning time is then the difference between the alert time and the estimated time of peak ground shaking for a given location. For the arrival time of peak ground shaking as a function of epicentral distance I use the *S*-wave arrival-time curve out to a distance of 150 km and then a constant moveout of 3.55 km/s, based on the observed moveout of peak ground shaking in California.

Warning times are calculated for a total of 4,070 earthquake epicenters. These epicenters were distributed at 1-km intervals along the faults identified as those most likely to cause damaging earthquakes in northern California by the Working Group on California Earthquake Probabilities (WGCEP, 2003). The study identified seven fault systems, each of which has one or more rupture segments, as shown in Figure 1, that can rupture on their own or with adjacent segments. In all, 35 earthquake rupture scenarios were identified and a probability of occurrence within 30 years was estimated for each. The total probability of one or more of these earthquake scenarios (with magnitudes ranging from 5.8 to 7.9) occurring before 2032 was estimated at 84%. Within the SFBA the faults that are most likely to rupture are the San Andreas Fault and the Hayward-Rodgers Creek Fault, with probabilities of producing a magnitude 6.7 or greater earthquake of 21% and 27% respectively. The aggregate probability of one or more magnitude 6.7 or greater earthquakes within the next 30 years (from 2003 to 2032) in the SFBA is estimated to be 62%.

Each of these earthquake scenarios involves rupture across a finite fault plane. The warning time in a given earthquake is dependent on the epicentral location where the rupture initiates. One does not know the likely point of initiation for the 35 scenarios; I therefore accommodate the uncertainty in epicentral location by distributing epicenters at 1-km intervals along each fault. The probability of an earthquake with each epicentral location within one rupture scenario is set equal, and the aggregate probability of all the epicenters is equal to the scenario probability.

Given the epicenter of an earthquake, the alert time is dependent on the relative locations of seismic stations to detect the *P*-wave arrivals. Several thousand seismic stations are operated in northern California by the California Integrated Seismic Network (CISN), which consists of multiple, complementary seismic networks (see http://www.cisn.org/). The ElarmS method requires data from continuous broadband seismic instruments. In northern California such instruments are operated by the University of California at Berkeley, which contributes a network of 24 stations, each with a broadband velocity seismometer and an accelerometer; and the U.S. Geological Survey, which operates approximately 100 accelerometers, located mostly in the SFBA, and 15 broadband velocity seismometers. In total, approximately 140 seismic stations across northern California could be used in an EWS (Figure 1 and electronic supplement [see http://www.seismosoc.org/]).

The alert time for each earthquake epicenter is calculated as the time at which 4 sec of *P*-wave data are available at the four closest continuous broadband stations plus a fixed telemetry and processing delay of 4.5 sec. A 4.5-sec delay accounts for transmission of waveform data from each station to one of the network operation centers, processing time, and transmission of the warning to the user community. Given the current seismic infrastructure in northern California, the most significant delay is packetization of data before transmission from each station. I introduce a 2.5-sec delay for packetization, which represents the delay at the slowest existing stations. I add 1 sec for transmission to the processing center and 1 sec for transmission of the warning message. The processing time for the data is negligible. The warning time estimates therefore represent what is possible using the existing seismic network hardware. They could be improved through upgrade of telemetry and processing systems as well as the addition of seismic stations.

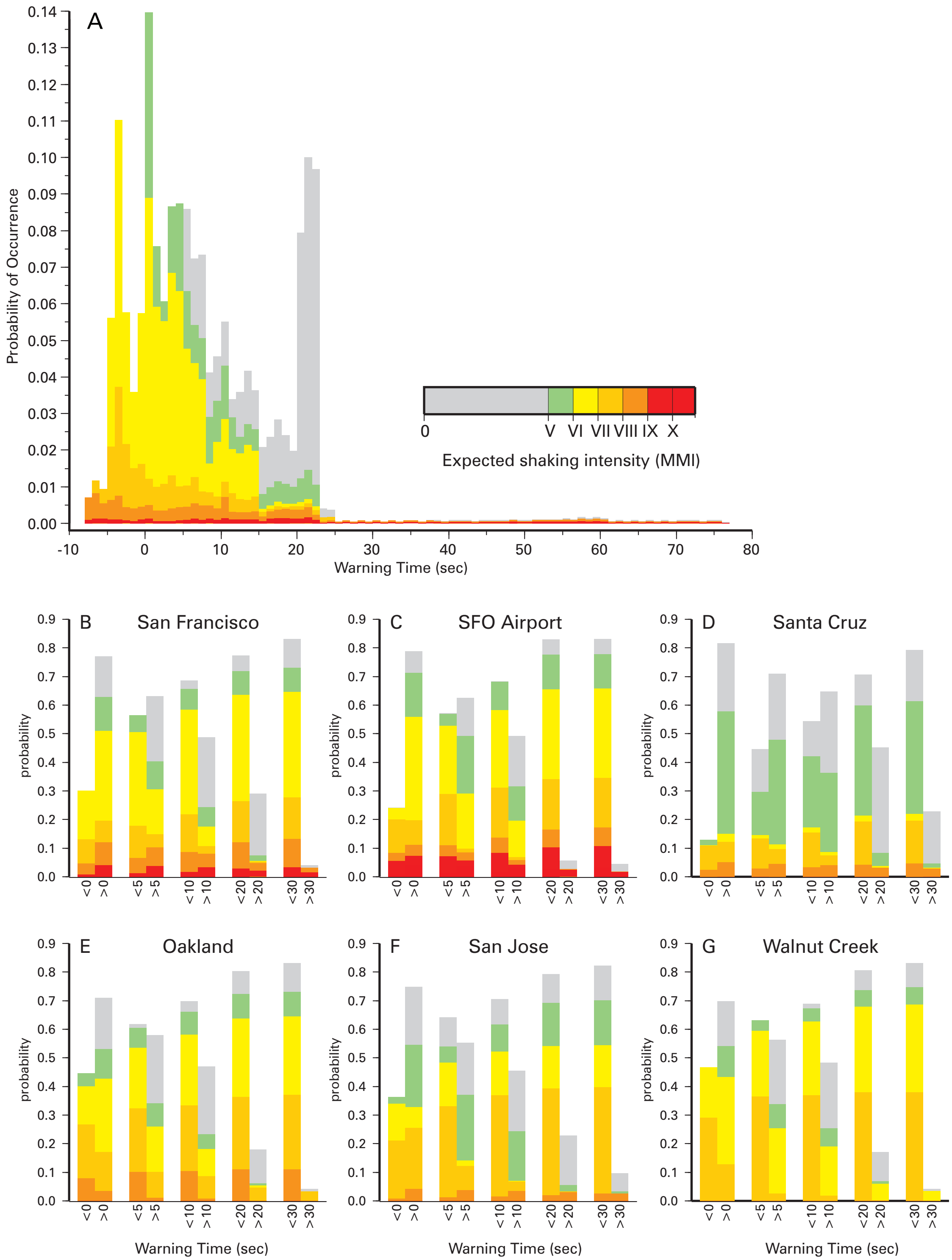
Warning Time Probability Density Function

The warning time probability density function (WTPDF) for the city of San Francisco is shown in Figure 2(A). This WTPDF is specifically for the Civic Center, but it does not vary significantly over the rest of the city. For all the likely damaging earthquakes in the region, San Francisco could receive warnings varying from 77 sec down to −8 sec. Negative warning times mean no warning is possible. The most likely warning times are less than 25 sec; the WTPDF has a long tail which is due to the San Andreas Fault, however. In a repeat of the 1906 earthquake, a 450-km-long segment of the fault could rupture. If the event nucleated off the Golden Gate, there would be little or no warning for San Francisco. Assuming that it is equally likely that rupture nucleated anywhere along the fault, however, it is more likely that the epicenter would be a significant distance from San Francisco. Thus, there could be tens of seconds warning for this most damaging earthquake scenario. It should be noted that the 1906 rupture probably did nucleate off the Golden Gate (Bolt, 1968; Boore, 1977; Zoback *et al.*, 1999; Lomax, 2005). Whether this means that a future rupture would nucleate in the same location is unknown but seems unlikely. An M6 repeating earthquake on the San Andreas Fault was identified near Parkfield in the 1980's (Bakun and Lindh, 1985). The previous two events in 1932 and 1966 were remarkably similar with identical epicenters, magnitudes, fault-plane solutions, and unilateral southeastward ruptures. The most recent event in the sequence occurred in 2004, was also M6.0, and ruptured the same segment of the fault. The epicenter, however, was to the south, and unilateral rupture propagated to the northwest (Dreger *et al.*, 2005; Langbein *et al.*, 2005).

In addition to the warning times for each earthquake, I also estimate the likely intensity of ground shaking at the warning point, *i.e.*, the Civic Center in the case of Figure 2(A). These intensities are derived from ShakeMap scenario calculations (WGCEP, 2003). The gray regions in Figure 2(A) represent earthquakes for which shaking intensity at the Civic Center is less than V on the Modified Mercalli Intensity (MMI) scale (Richter, 1958) and there is unlikely to be damage. Above MMI V the likely damage increases with the severity of shaking, from light (V: unstable objects displaced), to strong (VII: broken furniture and damage to masonry), to violent (IX: masonry seriously damaged or destroyed, frames displaced from foundations).

In the case of the WTPDF for San Francisco (Figure 2(A)), the long tail of large warning times includes a large portion of the earthquake scenarios that will cause violent (MMI > IX) ground shaking. This is because the intensity of ground shaking in a given earthquake depends on the closest distance to the fault rupture, while the warning time depends on the distance to the epicenter. Our warning time estimates are conservative in that they represent the travel time of shear energy directly from the epicenter to the warning point. The true time of peak ground shaking may not occur until the rupture has propagated along the fault to the closest point, which is typically at a velocity less than the shear-wave speed, and radiated energy has traveled from the fault to the warning point at the shear-wave speed.

The probability of one or more earthquakes occurring by 2032 for which more or less than a specific warning time could be available is shown in Figure 2(B–G). The full WTPDF for these locations and other cities and sites of engineering interest are included in the electronic supplement (see http://www.seismosoc.org/). Figure 2(B) shows that there is a 63% probability of one or more earthquakes that will cause some damage (MMI ≥ V) in San Francisco for which a warning would be available, and a 30% chance of a damaging earthquake for which no warning would be available. For the subset of events that cause violent ground shaking (MMI ≥ IX), there is a 3% probability of an earthquake for which more than 10 sec of warning could be available, and a 2% chance of less than 10 sec warning. It is therefore twice as likely that warning would be available in a damaging earthquake and more likely than not



▲ **Figure 2.** Warning time distributions. (A) Warning time probability density function (WTPDF) for the San Francisco Civic Center. The warning times for all likely earthquakes range from –8 sec to 77 sec, where negative warning times mean no warning is possible. Earthquakes are in 1-sec bins, and the vertical axis shows the total probability of one or more earthquakes occurring before 2032 with a given warning time. The color represents the estimated intensity of ground shaking for each event. Damage is unlikely for MMI < V (gray); MMI > IX means violent shaking likely to cause serious damage to buildings (red). (B) Probability that one or more earthquakes will occur by 2032 for which more or less than 0-, 5-, 10-, 20- and 30-sec warning times could be available for the city of San Francisco. The color indicates the intensity of ground shaking expected. Probabilistic warning times for (C) San Francisco International Airport (SFO), (D) Santa Cruz, (E) Oakland, (F) San Jose, and (G) Walnut Creek. The locations of the five cities and airport are indicated in Figure 1. The full WTPDF are included in the electronic supplement (see http://www.seismosoc.org/) along with other locations.

that more than 10 sec warning would be available before violent ground shaking. The WTPDF for San Francisco International Airport (Figure 2(C)) is similar to that for the city, except that the intensity of ground shaking could be greater given the proximity to the San Andreas Fault.

The most severe earthquakes for East Bay cities occur on the Hayward–Rodgers Creek fault. Its proximity to cities such as Oakland (Figure 1) makes for reduced warning times, but also lower intensities due to the shorter length of the fault. It is still more likely than not that a warning would be available for a damaging earthquake (Figure 2(E)). Most of the hazard for San Jose comes from the San Andreas Fault. As with San Francisco, this means there is a high probability of large warning times for the most damaging earthquakes. There is a 3% probability of an event causing MMI VIII in San Jose for which more than 20 sec warning could be available, more than the 2% chance of less than 20 sec warning (Figure 2(F)). In the 17 October 1989, Loma Prieta (M_w 6.9) earthquake, Santa Cruz experienced MMI VIII. There is a 7% probability of a similar intensity of ground shaking by 2032 in Santa Cruz, and a 3% chance of similar ground shaking for which more than 30 sec warning could be available (Figure 2(D)). Finally, the rapidly growing urban areas east of the Berkeley hills, such as Walnut Creek, are as likely to experience damaging ground shaking as San Francisco, although the most severe events have a lower intensity (Figure 2(G)). As is the case for all locations in the SFBA, Walnut Creek could receive a warning before ground shaking starts for the majority of damaging earthquakes.

EARTHQUAKE WARNINGS IN CALIFORNIA?

An EWS for San Francisco was first suggested by Cooper (1868), who proposed that the telegraph cables radiating from the city could transmit warning ahead of ground shaking. He also noted that this would not work if the center of the "shock" was close to the city, but estimated such a scenario to occur less than 1% of the time. His estimate was not far from our current estimates today. A more recent study by Heaton (1985) using a theoretical distribution of earthquakes in southern California concluded that there could be more than a minute of warning for the larger, most damaging earthquakes. Here, I come to a similar conclusion using the set of likely earthquakes and existing seismic stations in northern California.

Active early warning systems are now operational in Mexico, Japan, Taiwan, and Turkey. Like ElarmS, the systems in Japan use the *P*-wave arrival to assess hazard. This approach maximizes the warning time, potentially providing warning in the epicentral region (Odaka *et al.*, 2003; Kamigaichi, 2004; Nakamura, 2004; Horiuchi *et al.*, 2005). In Mexico, the earthquakes which threaten Mexico City are ~300 km away in the coastal region. The Seismic Alert System uses the *P*- and *S*-wave energy recorded by seismometers in the epicentral region and transmits the warning ahead of ground shaking (Espinosa Aranda *et al.*, 1995). Other systems are hybrids between these two approaches. In Taiwan, 10 sec of data are used at stations closest to the epicenter (Wu *et al.*, 1998; Wu and Teng, 2002) and development is underway to use the *P* wave (Wu and Kanamori, 2005). In Turkey, an amplitude threshold must be exceeded at multiple stations close to the fault to trigger an alert (Erdik *et al.*, 2003; Boese *et al.*, 2004).

The warning messages from these active systems are currently used by transportation systems such as rail and metro systems, as well as private industries, including construction, manufacturing, and chemical plants. They are also used by utility companies to shut down generation plants and dams, and by emergency response personnel to initiate action before ground shaking. In addition, schools receive the warnings, allowing children to take cover beneath desks, housing units automatically to switch off gas and open doors and windows, and entire complexes evacuate. Many of these applications would also be appropriate in the SFBA. The WTPDF for the specific location of any user can be calculated to plan automated response. This provides the necessary input for cost benefit analysis of implementation versus anticipated preventable losses over the next 30-year period (Grasso and Allen, 2006).

EWS are no panacea for the mitigation of seismic hazard. While an EWS cannot warn everyone prior to all ground-shaking events, it can offer warning to many affected people most of the time. No approach to natural hazard mitigation is perfect. Building codes are intended to prevent collapse of most structures in most earthquakes. If the mitigation of natural hazards is our intent, it is important to ensure that we continually ask what more could be done, what new technologies can be applied? As the 26 December 2004 tsunami disaster demonstrated most clearly, complacency is not an option. The SFBA has flourished over the last 100 years with few damaging earthquakes. This was not the case in the 100 years prior to the 1906 event, when several moderate to large earthquakes shook the region (WGCEP, 2003). If we are emerging from the stress shadow of the 1906 rupture, as the Loma Prieta earthquake may suggest (WGCEP, 2003), we must work hard to expand our mitigation strategies.

ELECTRONIC SUPPLEMENT

The electronic supplement includes the warning time probability density functions for 26 locations around the San Francisco Bay Area, including cities, airports, and other sites of interest. It also includes a map showing all seismic stations and faults included in the analysis.

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REFERENCES

Allen, R. M. (2004). Rapid magnitude determination for earthquake early warning, in M. Pecce, G. Manfredi and A. Zollo (editors), *The*

Many Facets of Seismic Risk, Napoli: Università degli Studi di Napoli "Federico II", 15–24.
Allen, R. M. and H. Kanamori (2003). The potential for earthquake early warning in southern California, *Science* **300**, 786–789.
Bakun, W. H. and A. G. Lindh (1985). The Parkfield, California, earthquake prediction experiment, *Science* **229**, 619–624.
Boese, M., M. Erdik, and F. Wenzel (2004). Real-time prediction of ground motion from P-wave records, *Eos, Transactions of the American Geophysical Union Fall Meeting Supplement* **85,** Abstract S21A.0251.
Bolt, B. A. (1968). The focus of the 1906 California earthquake, *Bulletin of the Seismological Society of America* **50**, 457–471.
Boore, D. M. (1977). Strong-motion recordings of California earthquake of April 18, 1906, *Bulletin of the Seismological Society of America* **67**, 561–577.
Cooper, J. D. (1868). Earthquake indicator, *Evening Bulletin* **XXVII**, 23.
Dreger, D. S., L. Gee, P. Lombard, M. H. Murray, and B. Romanowicz (2005), Rapid finite-source analysis and near-fault strong ground motions; Application to the 2003 Mw 6.5 San Simeon and 2004 Mw 6.0 Parkfield earthquakes, *Seismological Research Letters* **76**, 40–48.
Erdik, M. O., Y. Fahjan, O. Ozel, H. Alcik, M. Aydin, and M. Gul (2003). Istanbul earthquake early warning and rapid response system, *Eos, Transactions of the American Geophysical Union Fall Meeting Supplement* **84**, Abstract S42B.0153.
Espinosa Aranda, J. M., A. Jimenez, G. Ibarrola, F. Alcantar, A. Aguilar, M. Inostroza, and S. Maldonado (1995). Mexico City seismic alert system, *Seismological Research Letters* **66**, 42–52.
Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E. V. Leyendecker, N. Dickman, S. Hanson, and M. Hopper (1996). *National Seismic Hazard Maps*, U.S. Geological Survey Open-File Report 96-532.
Grasso, V. F. and R. M. Allen (2006). Uncertainty in real-time earthquake hazard predictions, *Bulletin of the Seismological Society of America* (in review).
Heaton, T. H. (1985). A model for a seismic computerized alert network, *Science* **228**, 987–990.
Horiuchi, S., H. Negishi, K. Abe, A. Kamimura, and Y. Fujinawa (2005). An automatic processing system for broadcasting earthquake alarms, *Bulletin of the Seismological Society of America* **95**, 708–718.
Kamigaichi, O. (2004). JMA earthquake early warning, *Journal of the Japan Association of Earthquake Engineering* **4**.
Langbein, J., R. Borcherdt, D. S. Dreger, J. Fletcher, J. L. Hardebeck, J. R. Murray, R. Nadeau, M. J. Rymer, and J. A. Treiman (2005). Preliminary report on the 28 September 2004, M 6.0 Parkfield, California earthquake, *Seismological Research Letters* **76**, 10–26.
Lockman, A. and R. M. Allen (2005). Single station earthquake characterization for early warning, *Bulletin of the Seismological Society of America* **95**, 2,029–2,039; doi:10.1785/0120040241.
Lockman, A. and R. M. Allen (2006). Magnitude-period scaling relations for Japan and the Pacific Northwest: Implications for earthquake early warning, *Bulletin of the Seismological Society of America* (in review).
Lomax, A. (2005). A reanalysis of the hypocentral location and related observations for the great 1906 California earthquake, *Bulletin of the Seismological Society of America* **95**, 861–877.
Nakamura, Y. (1988). On the urgent earthquake detection and alarm system (UrEDAS), *Proceedings of the 9th World Conference on Earthquake Engineering* **VII**, 673–678.
Nakamura, Y. (2004). UrEDAS, urgent earthquake detection and alarm system, now and future, *Proceedings of the 13th World Conference on Earthquake Engineering*, August 2004, Paper No. 908.
Odaka, T., K. Ashiya, S. Tsukada, S. Sato, K. Ohtake, and D. Nozaka (2003). A new method of quickly estimating epicentral distance and magnitude from a single seismic record, *Bulletin of the Seismological Society of America* **93**, 526–532.
Olson, E. and R. M. Allen (2005). The deterministic nature of earthquake rupture, *Nature* **438**, 212–215; doi:10.1038/nature04214.
Richter, C. F. (1958). *Elementary Seismology*, W. H. Freeman, 768 pp.
WGCEP (Working Group on California Earthquake Probabilities) (2003). *Earthquake Probabilities in the San Francisco Bay Region: 2003 to 2031*, U.S. Geological Survey Open-File Report 03-214.
Wu, Y.-M. and H. Kanamori (2005). Experiment on an onsite early warning method for the Taiwan early warning system, *Bulletin of the Seismological Society of America* **95**, 347–353.
Wu, Y. M., T. C. Shin, and Y. B. Tsai (1998). Quick and reliable determination of magnitude for seismic early warning, *Bulletin of the Seismological Society of America* **88**, 1,254–1,259.
Wu, Y.-M. and T.-l. Teng (2002). A virtual sub-network approach to earthquake early warning, *Bulletin of the Seismological Society of America* **92**, 2,008–2,018.
Zoback, M. L., R. C. Jachens, and J. A. Olson (1999). Abrupt along-strike change in tectonic style: San Andreas Fault zone, San Francisco peninsula, *Journal of Geophysical Research* **104**, 10,719–10,742.

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