

Earthquake probability calculated from paleoseismic observations on the south Hayward fault

by

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Abstract. A recent statewide earthquake probability report issued by the Working Group on California Earthquake Probabilities calculated a mean 19.4% probability of a $M \geq 6.7$ earthquake rupturing the south Hayward fault in the next 30 years. This value was based on earthquake rate calculations inferred from observations of fault slip rate. Here, south Hayward fault probability values are presented that are based solely on the paleoseismic record. A recent consistency test between time dependent and time independent recurrence distributions was made using a Monte Carlo method to replicate the paleoseismic series on the south Hayward fault, which concluded that large Hayward fault earthquakes are quasi-periodic, and are most consistent with a stress renewal process. A by-product of the analysis yielded the full range of recurrence parameters that are consistent with paleoseismic observations. In this paper, these values are used to calculate rupture probability on the south Hayward fault. The resulting mean 10-yr probability (2010-2020) is 6.2%, while the mean 30-year probability (2010-2040) is 17.9%. Taking account of coseismic and post-seismic stress reduction from the 1906 earthquake on the south Hayward fault reduces probabilities to 5.2% in 10 years, and 15.6% in 30 years. Two independent approaches to earthquake probability calculations have now yielded similar, and relatively high mean 30-year results (17.9% and 19.4%). Thus expedient retrofitting of vulnerable structures along the south Hayward fault would be a prudent public investment.

INTRODUCTION

The remarkable paleoseismic sequence (Figure 1) developed by Lienkaemper and Williams (2007) for the southern Hayward fault in the San Francisco Bay area of California (Fig. 2) was examined quantitatively for consistency with time dependent and time independent recurrence models by Parsons (2008a). Individual time dependent distributions produced >5 times more matches to the observed record than the most common time independent distributions (Fig. 2). Within the framework of the test, the most likely south Hayward fault recurrence distribution is time dependent, with mean recurrence interval of $\mu=210$ yrs, and coefficient of variation of $\alpha=0.6$.

This result is somewhat different than the mean of 170 yrs reported by Lienkaemper and Williams (2007) for the reasons described by Parsons (2008a, 2008b). Briefly, the difference arises because the arithmetic mean of a small sample of intervals is likely to be shifted towards the mode (most frequent value) rather than the true mean of a skewed, or asymmetric underlying recurrence distribution. Current consensus is that earthquake intervals distribute with strongly asymmetric shapes (e.g., Nishenko and Buland, 1987; Hagiwara, 1974; Kagan and Knopoff, 1987; Matthews et al., 2002).

In this paper, implications on south Hayward fault rupture probability calculations are explored as caused by: (1) a time-dependent earthquake renewal process, (2) the distribution of allowable recurrence interval and coefficient of variation pairings as found from Monte Carlo analysis, and (3) potential delays caused by static stress transfer and post-seismic viscoelastic relaxation from the 1906 great San Francisco earthquake.

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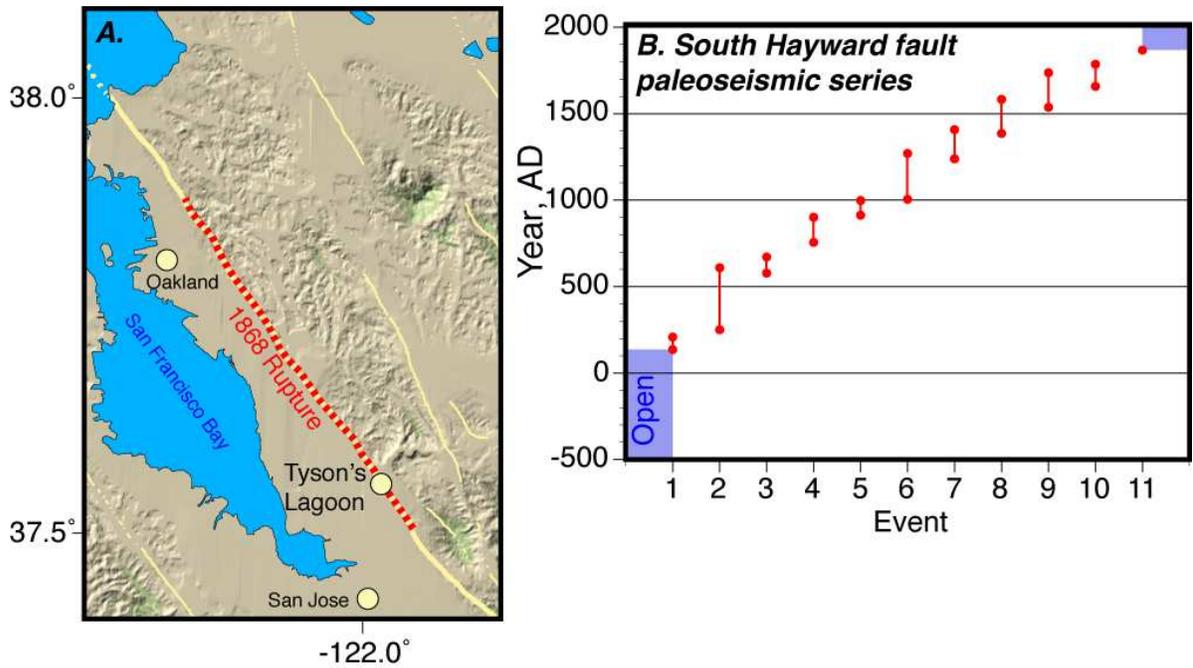


Figure 1. (a) Hayward fault location east of San Francisco Bay with the paleoseismic site at Tyson's Lagoon identified. The extent of the 1868 earthquake rupture is shown according to Yu and Segall (1996). In (b) the 95% confidence bounds on event times are shown from Lienkaemper and Williams (2007). Open intervals before and after the sequence are shaded in blue.

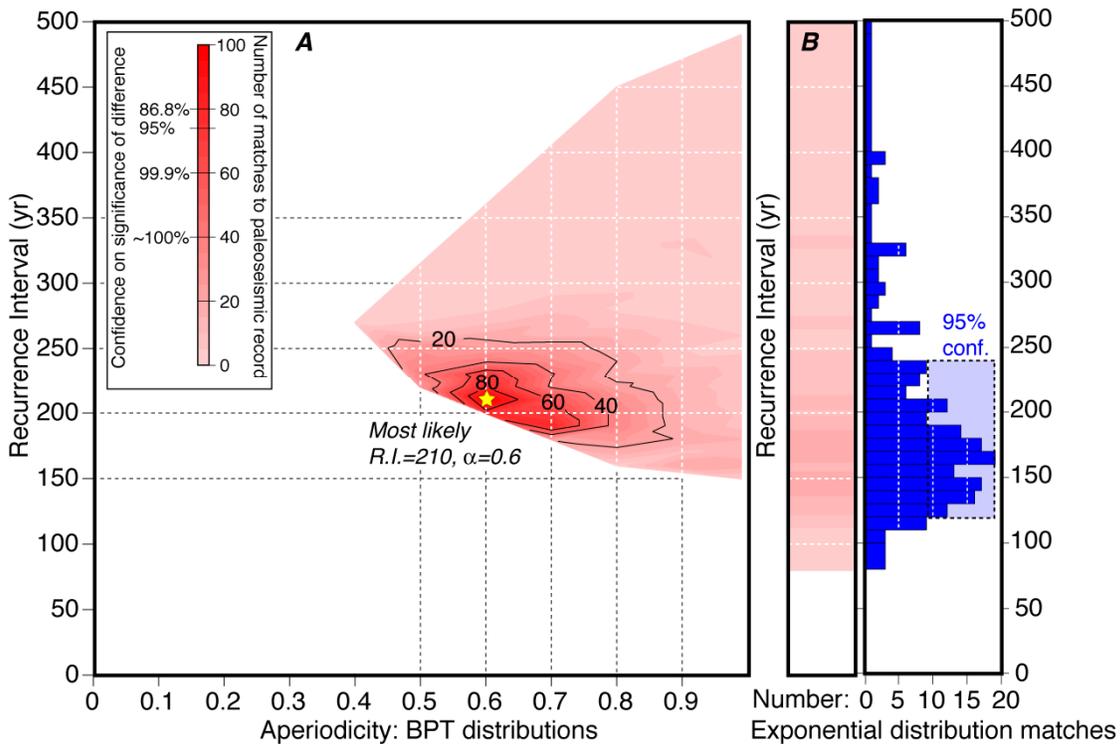


Figure 2. Contours of matches to south Hayward fault paleoseismic event series of different (a) time dependent (Brownian Passage Time) and (b) time independent (exponential) recurrence distributions. The best-fit distributions are time dependent, with recurrence intervals of $m \sim 210$ yr, and coefficient of variation $\alpha \sim 0.6$. Confidence (Z-test) on the significance of relative proportions is keyed to the contour intervals. The best-fit exponential distributions have significantly fewer matches, leading to the conclusion that earthquake recurrence on the south Hayward fault is time dependent, possibly from a stress renewal process (Parsons, 2008a). A histogram of exponential distribution matches is shown in (b), with 95% confidence of significance shaded, which gives the same information as the adjacent contour mapping, but in more detail.

EARTHQUAKE PROBABILITY ON THE SOUTH HAYWARD FAULT

A significant proportion of the most likely earthquake recurrence interval (~210 years) has elapsed since 1868, the year of the last large ($M \sim 7$) earthquake to strike the south Hayward fault. Losses associated with a similar earthquake on the south Hayward fault today could rival or surpass those from Hurricane Katrina (M.L. Zoback, personal communication, 2009). Given the time elapsed, and that a renewal process appears to be operating on the south Hayward fault, there is significant probability gain relative to a time-independent, Poisson process (Figure 3). This is another way of saying that the south Hayward fault is late in its earthquake cycle.

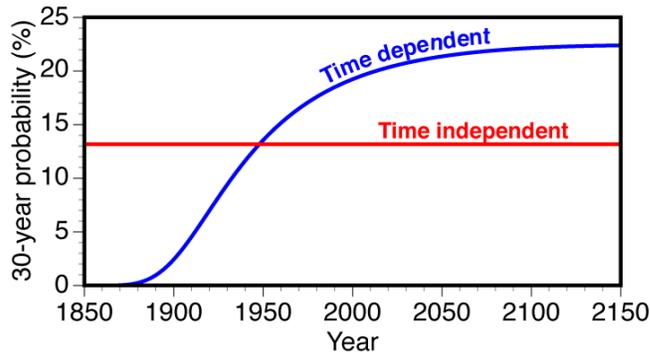


Figure 3. Comparison of time independent (red line) and time dependent (blue line) 30-year earthquake probability calculations for the south Hayward fault made using a 210-yr recurrence interval and a 0.6 coefficient of variation. The difference between the two results is ~7% by 2010.

A recent report by Working Group on California Earthquake Probabilities (WGCEP) (2008) calculated time-dependent probability for major California faults, including the Hayward fault. Their results, which are based primarily on geologically determined fault slip rates, show a mean 30-yr south Hayward fault segment probability of 19.4% for $M \geq 6.7$ earthquakes, with a 95% confidence range of 11% to 38%. WGCEP (2008) used a Brownian Passage Time (inverse Gaussian) recurrence distribution (Kagan and Knopoff, 1987; Matthews et al., 2002) to calculate time dependent probabilities, and also gave 30% weighting to an empirical model, which adjusted probabilities according to observations of lower 20th century regional seismicity rates. The WGCEP (2008) report tested event rates calculated from fault slip data for consistency with paleoseismic information, but did not use paleoseismic information directly.

In this paper, paleoseismic information is the sole basis for determining south Hayward fault earthquake rates and recurrence distribution parameters. Such an approach has advantages and disadvantages as compared with the WGCEP (2008) method. Using paleoseismic information means that the calculations are more directly rooted in empirical observation as compared with inferring earthquake rate from fault slip rate, which requires assumptions about the magnitude-area relation, the maximum seismogenic depth, and the seismic coupling coefficient. On the other hand, paleoseismic observations on strike-slip faults are not very sensitive to magnitude, and they tend only to offer rates at infrequent points along most faults. Preference given to paleoseismic rates for the south Hayward fault may be well justified however; the fault is short relative to the $M \sim 7$ ruptures likely to be detected paleoseismically, meaning that large events identified at the Tyson's Lagoon paleoseismic site probably affected the entire southern part of the fault (Figure 1b). Further, the geologic signature of the historic $M \sim 7$ 1868 shock can be compared with older events in the record (Lienkaemper and Williams, 2007).

Knowledge of the last large earthquake (1868 for the south Hayward fault) and a mean-recurrence-interval/coefficient-of-variation pairing are required to make a time dependent probability calculation. Each set of recurrence distribution parameters plotted in Figure 2a were used to make 10- and 30-year probability calculations for the south Hayward fault, which produced corresponding histograms of possible probability values (Figure 4). The breadth of the histograms can be taken to illustrate calculation parameter uncertainty.

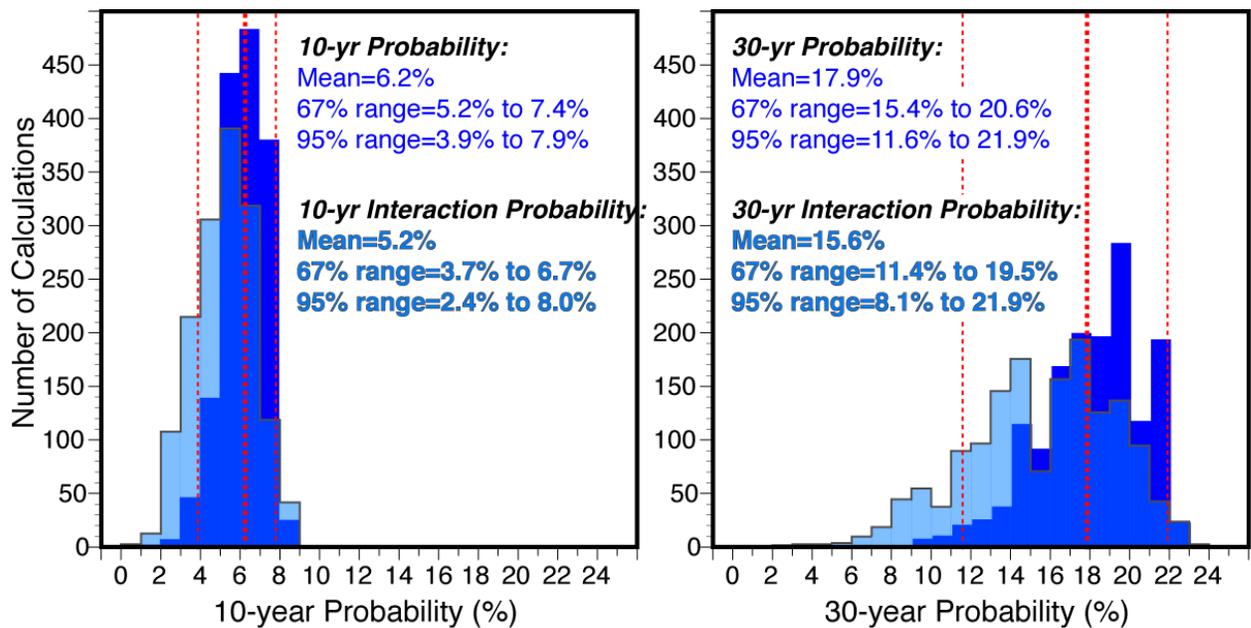


Figure 4. Probability of earthquake rupture on the south Hayward fault inferred from Monte Carlo analysis (Parsons, 2008a) (Figure 2) of the paleoseismic series of Lienkaemper and Williams (2007) (Figure 1). Dark blue histograms show distributions of 10- and 30-year probabilities beginning in 2010, and lighter blue histograms show distributions of interaction probabilities that include the coseismic and postseismic stress decreases on the south Hayward fault calculated as a result of the 1906 earthquake by Parsons (2002). Vertical dashed lines show mean and 95% confidence bounds on probability without the 1906 interaction effects.

Results show 6.2% odds of a large earthquake striking the south Hayward fault in the next 10 years, and 17.9% chance in 30 years. 67% of the calculated 10-year probability values lie within the 5.2% to 7.4% range, and 95% of the values fall between 3.9% and 7.8%. Similarly, 67% of the calculated 30-year probability values lie within the 15.4% to 20.6% range, and 95% of the values fall between 11.6% and 21.9%. The mean 30-year value calculated from paleoseismic observations (17.9%) is slightly lower than the WGCEP (2008) number of 19.4%, but falls within their minimum-maximum range of 10.6% to 38.0%.

It has been noted that 20th century earthquake rates are lower in the San Francisco Bay region than in the preceding decades (e.g., Reasenber et al., 2003; WGCEP, 2003), an effect that may be associated with stress decrease caused by the 1906 earthquake (e.g., Harris and Simpson, 1998; Stein, 1999). Parsons (2002) used a viscoelastic finite element model to calculate both the expected coseismic and post-seismic (mantle and lower crustal relaxation) stress changes and associated earthquake delay times from the 1906 earthquake on all major San Francisco Bay area faults including the south Hayward segment. In that study it was concluded that a ~43 year period would be required to regenerate the stresses relieved by the 1906 earthquake on the south Hayward fault. A simple way of accounting for this delay in time dependent probability calculations is to adjust the last earthquake time ahead by 43 years (the “clock-change” approach of WGCEP (1990)). Interaction probability calculations for the south Hayward fault are thus slightly lower, with mean 10-year odds of a large earthquake being 5.2%, and mean 30-year probability adjusted down to 15.6% (Figure 4).

CONCLUSIONS

The key point of this paper is that calculations of south Hayward fault earthquake probability constrained by completely different data sets result in very similar mean 30-year probability values: 17.9% in this paper compared with 19.4% quoted by WGCEP (2008). These numbers represent some of the highest values calculated for an individual fault segment in the San Francisco Bay Area, and are a quantitative way of expressing a conclusion that the Hayward fault has reached a late point in its earthquake cycle. However, these high probability values are calculated for 30-year spans, which means that there is likely enough time to prepare for the next large Hayward fault earthquake. In particular, given the current poor economy in need of stimulation, reinforcing the dozens of schools and hospitals situated along the fault that are most in need of retrofit would be a prudent investment of public funds.

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