# Appendix K: *A-Priori* Rupture Models for Northern California Type-A Faults


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USGS Open File Report 2007-1437K
CGS Special Report 203K
SCEC Contribution #1138K
Version 1.0

2008

**U.S. Department of the Interior**
**U.S. Geological Survey**

**California Department of Conservation**
**California Geological Survey**



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Suggested citation:
Wills, C.J., Weldon, R.J., II, and Field, E.H. 2008, *A-priori* rupture models for northern California Type-A faults, *Appendix K in* The Uniform California Earthquake Rupture Forecast, version 2 (UCERF 2): U.S. Geological Survey Open-File Report 2007-1437K and California Geological Survey Special Report 203K, 7 p. [http://pubs.usgs.gov/of/2007/1437/k/].

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# Appendix K
# *A-Priori* Rupture Models for Northern California Type-A Faults

By Chris Wills, Ray Weldon, and Edward Field

## Introduction

This appendix describes how *a-priori* rupture models were developed for the northern California Type-A faults. As described in the main body of this report, and in Appendix G, "*a-priori*" models represent an initial estimate of the rate of single and multi-segment surface ruptures on each fault. Whether or not a given model is moment balanced (*i.e.*, satisfies section slip-rate data) depends on assumptions made regarding the average slip on each segment in each rupture (which in turn depends on the chosen magnitude-area relationship). Therefore, for a given set of assumptions, or branch on the logic tree, the methodology of the present Working Group (WGCEP-2007) is to find a final model that is as close as possible to the *a-priori* model, in the least squares sense, but that also satisfies slip rate and perhaps other data. This is analogous the WGCEP- 2002 approach of effectively voting on the relative rate of each possible rupture, and then finding the closest moment-balance model (under a more limiting set of assumptions than adopted by the present WGCEP, as described in detail in Appendix G). The 2002 Working Group Report (WCCEP, 2003, referred to here as WGCEP-2002), created segmented earthquake rupture forecast models for all faults in the region, including some that had been designated as Type B faults in the NSHMP, 1996, and one that had not previously been considered. The 2002 National Seismic Hazard Maps used the values from WGCEP-2002 for all the faults in the region, essentially treating all the listed faults as Type A faults. As discussed in Appendix A, the current WGCEP found that there are a number of faults with little or no data on slip-per-event, or dates of previous earthquakes. As a result, the WGCEP recommends that faults with minimal available earthquake recurrence data: the Greenville, Mount Diablo, San Gregorio, Monte Vista-Shannon and Concord-Green Valley be modeled as Type B faults to be consistent with similarly poorly-known faults statewide. As a result, the modified segmented models discussed here only concern the San Andreas, Hayward-Rodgers Creek, and Calaveras faults.

Given the extensive level of effort given by the recent Bay-Area WGCEP-2002, our approach has been to adopt their final average models as our preferred a-prior models. We have modified the WGCEP-2002 models where necessary to match data that were not available or not used by that WGCEP and where the models needed by WGCEP-2007 for a uniform statewide model require different assumptions and/or logic-tree branch weights. In these cases we have made what are usually slight modifications to the WGCEP-2002 model. This Appendix presents the minor changes needed to accomodate updated information and model construction. We do not attempt to reproduce here the extensive documentation of data, model parameters and earthquake probablilities in the WG-2002 report.

For each Type-A fault considered by the present WGCEP, we construct three apriori models: 1) a geologic-insight model; 2) a minimum-rate model; and 3) a maximum-rate model. The geologic-insight model represents the preferred, best-estimate *a-priori* model. Again, given the level of work conducted by the WGCEP-2002, these models are essentially the final average models defined by the WGCEP-2002, but with whatever modifications are needed to satisfy new data. The minimum-rate model minimizes the total rate of events, essentially by maximizing the rate of the largest events, while honoring all other constraints (*e.g.*, historical events and recurrence rates, where available). Similarly, the maximum rate model effectively maximizes the rate of single-segment ruptures, while accommodating any larger events if conclusive evidence for their occurrence exists (such as a historical event). The minimum- and maximum-rate models represent unlikely but nevertheless possible end members.

The most significant difference between WGCEP-2007 and WGCEP-2002 is the treatment of the unsegmented or “floating earthquake” model. In the WGCEP-2007 model, we allow the possibility that faults do not only generate “characteristic earthquakes” on identifiable segments; thus an unsegmented model is a viable basis for constructing earthquake rupture forecasts. As a result, we have constructed an “unsegmented” model from the range of earthquake magnitudes and locations that are possible on a given fault, ranging from M 6.5 up to the maximum magnitude possible based on the fault area. WGCEP-2002 included such events, but only over a relatively narrow range of magnitudes (*e.g.* M 6.9 +/- 0.24 on the northern San Andreas fault). Because the segmented models and unsegmented models are both considered viable alternatives, both are completely developed, then the completed models weighted in a logic tree. In order to do this based on the WGCEP-2002 model, we have removed the “floating earthquakes” from the segmented WGCEP-2002 model. We now outline the specific steps taken in developing each model. Only a qualitative description of the calculations are given here, as numerical details are available in the sheet for each fault in the Excel spreadsheet available at:

http://www.WGCEP.org/resources/documents/ERM2_2_Report/A_FaultsSegmentData_v23.xls

# Hayward-Rodgers Creek Fault

In constructing the *a-priori* models for this fault, we seek to match the one mean recurrence interval estimate available for this fault: 150 years on the Hayward South (HS) segment (Lienkaemper and Williams, 2006, an update of Lienkaemper et al, 2002), rather than the 161 years used by WGCEP-2002, which corresponds to a total segment event rate of 0.00667. (Note that event rates are given here to three significant digits for consistency with our spreadsheets, few of these values are known to this level of precision).

## Geologic Insight *A-Priori* Model:

Table 1 lists the WGCEP-2002 average magnitude and rate of each single and multi-segment rupture for the Hayward-Rodgers Creek fault (see caption for important details). Their model is, on average, moment balanced with respect to the various logic_tree branches they accommodated. Because we treat the floating earthquakes differently, as discussed above, our first step is to remove these floating earthquakes from the model.

We then reestablish the overall moment rate. This is done by multiplying the rate of each rupture by the total moment rate (summed over all ruptures) and dividing by the total moment rate excluding the floating earthquakes (and setting the rate of floating earthquakes to zero). Summing the rate of all ruptures that include the HS segment, we get a total segment rate of 0.00667 events/year, or a mean recurrence interval of 150 years. Remarkably, this matches the available recurrence-interval estimate exactly, meaning no further adjustments are necessary.

### Maximum-Rate *A-Priori* Model:

The maximum rate model assumes that only single-segment ruptures occur. The average rate for HS events is one over the available recurrence interval estimate, or 1/150 = 0.00667. The other two segments have no estimates, so the rates of these events are taken as the average segment moment rates divided by moment implied by the average WGCEP-2002 magnitude for the single-segment rupture.

### Minimum-Rate *A-Priori* Model:

Normally the minimum rate model would permit only full fault ruptures. However, because the HS segment is know to have had a single-segment rupture in 1868, we give that event a nominal rate of 0.001 (once every thousand years), and set the rate of the full fault rupture to be the difference between rate estimate for that segment and the nominal single-segment rate (1/150 – 0.001 = 0.00567). We acknowledge that the nominal rate is arbitrary, but is consistent with the assumption that in a minimum rate model the single segment rupture is an unlikely event, and by WGCEP-2007 rules, an “unlikely” event occurs approximately 10% as often as the lowest occurring rupture in the model.

## Calaveras *A-Priori* Models

In constructing the *a-priori* models for this fault, we seek to match the one mean recurrence interval estimate available for this fault: 484 years on the Calaveras North (CN) segment (Kelson et al, 1996) which corresponds to a total event rate of 0.00207 per year. We note that this data was available to WGCEP-2002, but they did not use it as a constraint in their model. In general, WGCEP-2002 used recurrence data to check the results of their model, rather than as constraints within the model. In this case, we are treating data available to WGCEP-2002 differently than they treated it, but are doing this to maintain a consistent statewide treatment of similar data.

### Geologic Insight *A-Priori* Model:

Table 1 lists the WGCEP-2002 average magnitude and rate of each single and multi-segment rupture for the Calaveras fault (see caption for important details). The first step is to remove the floating earthquakes while preserving moment rate, which was done exactly as described for the Hayward-Rodgers Creek fault above. Summing the rate of all ruptures that include the CN segment gives a total segment event rate of 0.00599, which is higher than the event rate estimate for this segment. Therefore, the event rate of single-segment CN ruptures was simply reduced by the amount needed to match the observed value of 0.00207 per year, leading to the final geologic insight model listed in Table 1.

## Maximum-Rate *A-Priori* Model:

The maximum rate model assumes that only single-segment ruptures occur. The rate for CN events is set by the rate estimate for that segment (0.00207). The other two segments have no rate estimates, so the rates of these events are taken as the average segment moment rates divided by moment implied by the average WGCEP-2002 magnitude for the single-segment rupture.

## Minimum-Rate *A-Priori* Model:

This minimum-rate model assumes only full fault ruptures occur, and so these are given a rate of 0.00207 according the rate estimate for the CN segment.

# Northern San Andreas *A-Priori* Models

In constructing the *a-priori* models for this fault, we seek to match the one mean recurrence interval estimate available for this fault: 248 years on the North Coast (SAN) segment (Zhang et al, 2006), which corresponds to a total segment event rate of 0.00403 per year. This rate represents the most recent update on rates at that site by the same group that provided the rate information that was used by WG-2002. This rate is also within the range of earthquake recurrence calculated from detailed paleoseismology at Fort Ross (Kelson et al, 2006) and from detailed dating of turbidites that may have been triggered by earthquakes on the North Coast segment of the San Andreas (Goldfinger et al, 2007).

The most important potential change in earthquake rate in northern California is based on recurrence studies on the Santa Cruz Mountains segment of the San Andreas Fault. Recent work by Fumal (1999, 2003) has documented an ~105-year recurrence of surface-rupturing earthquakes. This contrasts with the rate of earthquakes predicted by the WG02 model of about one every 225 years. Following presentations and extensive discussion at a WGCEP workshop in November, 2006, the preponderance of views was the Arano Flat earthquakes could represent the full segment ruptures, multi-segment ruptures, or floating earthquakes allowed by the existing model. Once this new data is fully peer-reviewed, it may require significant modifications of the WGCEP-2002 model. Those would involve doubling the rate of earthquakes on the Santa Cruz Mountains segment and possibly increasing the rate on the Peninsula segment to be consistent with the recurrence at Arano Flat. At this time, WGCEP-2007 does not include constraints based on the Arano Flat data in the model because it would require a significant revision of the WGCEP-2002 based on data not yet fully vetted in the peer-reviewed literature.

## Geologic Insight *A-Priori* Model:

Table 1 lists the WGCEP-2002 average magnitude and rate of each single and multi-segment rupture for the N. SAF fault (see caption for important details). The first step is to remove the floating earthquakes while preserving moment rate, which was done exactly as described for the Hayward-Rodgers Creek fault above. Summing the rate of all ruptures that include the SAN segment gives a total segment event rate of 0.00442, which is higher than the event-rate estimate for this segment. Unfortunately, even zeroing out the rate of single SAN segment events doesn't bring the total segment rate to the estimated value of 0.00403. Therefore, one-third of the rate discrepancy was taken from the rate of SAN events, and the other two-thirds was taken from the rate of SAN+SAO events. The rate of single SAO segment events was then increased by two-thirds of the rate discrepancy to preserve the total rate of events on the SAO segment (and to bring the model back toward moment balance). The rate of the SAN+SAP event, which was set as zero by the WGCEP-2002, was changed to “Unlikely” to be consistent with how such events are treated in the other geologic-insight models (we don’t assign zero rates for any events in *a-priori* models, but rather designate them as either “Unknown” or “Unlikely”) as described in Appendix B and Appendix G. Finally, verification of a lower average recurrence interval for the Santa Cruz section (Fumal et al. 1999; 2003) or confirmation of an historical Peninsula section rupture would require a modification of this model in the future.

## Maximum-Rate *A-Priori* Model:

Because full-fault events are known to occur (*i.e.*, the 1906 event), the maximum rate model cannot merely assume that only single-segment ruptures occur. Therefore, we give full-fault events a nominal rate of 0.001, and set the rate of single-segment SAN events to be the observed rate minus the nominal rate (0.00403 – 0.001 = 0.00303). [As discussed above for the Hayward we should use our 10% rule for consistency; again, the logic is that in a maximum rate model, 1906 is “unlikely” thus it would get 10% as with all other “unlikely” events] The other three segments are given single-segment rupture rates computed as the average segment moment rates divided by moment implied by the average WGCEP-2002 magnitude for those single-segment ruptures (which effectively ignores the moment-rate contribution from the full-fault ruptures).

## Minimum-Rate *A-Priori* Model:

This minimum-rate model assumes only full fault ruptures occur, and so these are given a rate of 0.00403 according the rate estimate for the SAN segment. Given the current state of knowledge on the recurrence of surface rupture on all other sections of the fault it is possible that only full fault rupture occurs. However, verification of a lower average recurrence interval for the Santa Cruz section (Fumal et al. 1999; 2003) or confirmation of an historical Peninsula section rupture would require a modification of this rate in the future.

**Table 1.** The "WG02" rates and magnitudes listed here come from the NSHMP-2002 implementation of the WGCEP-2002 model (provided by Michael Blanpied via email). These rates are ~6% higher than those listed in Table 4.8 of the WGCEP-2002 report because the latter were reduced to account for moment released in the "Gutenberg-Richter tail" earthquakes (whereas the NSHMP-2002 put no moment rate into such events).

**N. San Andreas**

| Rupture | WG02 Ave Rate | WG02 Ave Mag | Geologic Insight Rate | Minimum Rate | Maximum Rate |
|---|---|---|---|---|---|
| SAO | 2.34E-04 | 7.29 | 4.93E-04 | 0.0 | 1.08E-02 |
| SAN | 1.48E-04 | 7.45 | 2.09E-05 | 0.0 | 3.03E-03 |
| SAP | 5.27E-04 | 7.15 | 5.31E-04 | 0.0 | 9.27E-03 |
| SAS | 7.58E-04 | 7.03 | 7.64E-04 | 0.0 | 1.08E-02 |
| SAO+SAN | 1.31E-03 | 7.70 | 1.07E-03 | 0.0 | 0.0 |
| SAN+SAP | 0.0 | 7.65 | Unlikely | 0.0 | 0.0 |
| SAP+SAS | 1.03E-03 | 7.42 | 1.03E-03 | 0.0 | 0.0 |
| SAO+SAN+SAP | 8.15E-05 | 7.83 | 8.21E-05 | 0.0 | 0.0 |
| SAN+SAP+SAS | 2.50E-05 | 7.76 | 2.52E-05 | 0.0 | 0.0 |
| SAO+SAN+SAP+SAS | 2.81E-03 | 7.90 | 2.84E-03 | 4.03E-03 | 1.00E-03 |
| floating | 9.63E-04 | 6.90 | | | |

**Calaveras**

| Rupture | WG02 Ave Mag | WG02 Ave Rate | Geologic Insight Rate | Minimum Rate | Maximum Rate |
|---|---|---|---|---|---|
| CN | 3.74E-03 | 6.78 | 1.03E-03 | 0.0 | 2.07E-03 |
| CC | 5.78E-03 | 6.23 | 7.66E-03 | 0.0 | 2.82E-02 |
| CS | 7.93E-03 | 5.79 | 1.05E-02 | 0.0 | 3.46E-02 |
| CN+CC | 9.70E-05 | 6.90 | 1.29E-04 | 0.0 | 0.0 |
| CC+CS | 1.96E-03 | 6.36 | 2.60E-03 | 0.0 | 0.0 |
| CN+CC+CS | 6.84E-04 | 6.93 | 9.07E-04 | 2.07E-03 | 0.0 |
| floating | 3.21E-03 | 6.20 | | | |
| floating CS+CC | 1.28E-02 | 6.20 | | | |

**Hayward-Rodgers Creek**

| Rupture | WG02 Ave Mag | WG02 Ave Rate | Geologic Insight Rate | Minimum Rate | Maximum Rate |
|---|---|---|---|---|---|
| RC | 4.26E-03 | 6.98 | 4.36E-03 | 0.0 | 6.04E-03 |
| HN | 3.40E-03 | 6.49 | 3.48E-03 | 0.0 | 1.12E-02 |
| HS | 3.64E-03 | 6.67 | 3.72E-03 | 1.00E-03 | 6.67E-03 |
| RC+HN | 5.10E-04 | 7.11 | 5.22E-04 | 0.0 | 0.0 |
| HN+HS | 2.58E-03 | 6.91 | 2.64E-03 | 0.0 | 0.0 |
| RC+HN+HS | 3.02E-04 | 7.26 | 3.09E-04 | 5.67E-03 | 0.0 |
| floating | 3.02E-04 | 6.90 | | | |

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