Earthquake Probabilities in the San Francisco Bay Region:
2002–2031

By Working Group On California Earthquake Probabilities
Open-File Report 03-214

2003

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U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY
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EXECUTIVE SUMMARY

Drawing on new data and new methodologies, we have concluded that there is a 0.62 probability (i.e., a 62% probability) of a major, damaging earthquake striking the greater San Francisco Bay Region (SFBR) over the next 30 years (2002–2031). Such earthquakes are most likely to occur on seven main fault systems identified in this study, but may also occur on faults that were not characterized as part of the study (i.e., in the “background”) (Figure ES.1). Our results come from a comprehensive analysis lead by the USGS and involving input from a broad group of geologists, seismologists, and other earth scientists representing government, academia and the private sector. The results of this study are appropriate for use in estimating seismic hazard in the SFBR, and estimating the intensity of ground shaking expected for specified “scenario” earthquakes. In addition, they provide a basis for calculating earthquake insurance premiums, planning and prioritizing expenditures for seismic upgrades of structures, and developing building codes.

Introduction

Earthquakes in the San Francisco Bay Region result from strain energy constantly accumulating across the region because of the northwestward motion of the Pacific Plate relative to the North American Plate (Figure ES.2). The region experienced large and destructive earthquakes in 1838, 1868, 1906, and 1989, and future large earthquakes to relieve this continually accumulating strain are a certainty. For our study we define the SFBR as extending from Healdsburg on the northwest to Salinas on the southeast. It encloses the entire metropolitan area, including its most rapidly expanding urban and suburban areas. We have used the term "major" earthquake as one with $M \geq 6.7$ (where $M$ is moment magnitude). As experience from recent earthquakes in Northridge, California ($M6.7$, 1994, 20 killed, $\$20B$ in direct losses) and Kobe, Japan ($M6.9$, 1995, 5500 killed, $\$147B$ in direct losses), earthquakes of this size can have a profound impact on the social and economic fabric of densely urbanized areas.

Figure ES.1. Probabilities of one or more major ($M \geq 6.7$) earthquakes on faults in the San Francisco Bay Region during the coming 30 years. Color indicates the probability that each fault segment will rupture in such a quake.
Working Group probability study

To evaluate the probability of future large earthquakes in the San Francisco Bay Region, the U.S. Geological Survey has established a series of Working Groups on California Earthquake Probabilities (hereafter referred to as WG88, WG90, WG99). Each of these Working Groups has expanded on the work of its predecessors, applying, in turn, the data and methodology available at the time and drawing on input from broad cross-sections of the earth science community.

WG88 and WG90 established a framework for estimating earthquake probabilities based on simple physical models for the San Andreas and Hayward faults in the Bay Area, and on the San Andreas, San Jacinto, and Imperial Faults in southern California. WG99 extended this framework into a more comprehensive, regional one for the SFBR based on a greatly expanded set of geological and geophysical observations. In its calculations, WG99 combined the results of multiple viable models when a single consensus model did not exist. Summaries of WG99 methods and results were published in 1999 on the tenth anniversary of the Loma Prieta earthquake, as U.S. Geological Survey Open-File Report 99-517, and USGS Fact Sheet 151-99.

The present study (hereafter referred to as WG02) is a continuation and extension of WG99 and updates the results of that study. WG02 adopts the basic framework used by WG99 and expands on it by:

- incorporating additional data;
- more fully analyzing the possible effects of the 1906 earthquake (the “stress-shadow” effect) on the current earthquake potential in the SFBR;
- more fully developing the uncertainties associated with the calculated probabilities;
- exploring some of the implications for earthquake hazard in SFBR;
- making available a full documentation of the methods and computer codes used.

Figure ES.2. Faults and plate motions in the San Francisco Bay Region. Faults in the region, principally the seven faults shown here and characterized in this report, accommodate about 40 mm/yr of mostly strike-slip motion between the Pacific and North American tectonic plates. Yellow lines show the locations of the 1868 M6.8 earthquake on the southern portion of the Hayward Fault and the 1989 M6.9 Loma Prieta earthquake near the San Andreas fault northeast of Monterey Bay.

Broadened modeling approach

This WG02 report builds on previous analyses of earthquake likelihood, modifying some of the methodologies used in those studies and introducing new ones. The earthquake probabilities presented here are the product of model calculations consisting of three basic elements. The first element is the SFBR earthquake model, which determines the average magnitudes and long-term rates of occurrence

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1 Computer codes will be released in a separate USGS publication.
of earthquakes on the principal faults and for the region as a whole. These average long-term rates of earthquakes lead to average, time-independent probabilities of earthquakes at or above a particular magnitude level of interest (e.g., $M \geq 6.7$).

The second element consists of a suite of time-dependent earthquake probability models, which incorporate physical aspects of the causes and effects of earthquakes that vary with time. The two most important of these are the progression of faults through the “earthquake cycle” and the interactions of faults, through which the stress released by an earthquake on one fault is transferred in part to other faults or adjacent fault segments. The most significant interaction effect—that produced by the 1906 earthquake—figures prominently in the modeling. There is no consensus within the earth science community, or within this Working Group, as to whether the SFBR remains within the 1906 stress shadow (as suggested by seismicity data for the past 96 years), is now emerging from it (as suggested by the occurrence of the Loma Prieta earthquake and by calculations based on models of viscous flow in the lower crust and mantle), or has emerged from it (as suggested by simple elastic fault interaction models). The addition of a suite of probability models to represent this range of thinking represents the most substantial difference between the analysis reported by WG99 and that reported here.

The third new element introduced in our calculations is the characterization of the rate of occurrence of “background” earthquakes—earthquakes in the Bay region that do not occur on the principal faults. The probability for these events is based on seismicity rates known since 1836, extrapolated to $M \geq 6.7$ events. Background earthquakes include events such as the September 2001 M5.1 Napa earthquake, and the 1989 M6.9 Loma Prieta earthquake.

WG02 has devoted considerable effort to defining and quantifying uncertainties in all data, models, and parameters used in the analysis. In the calculations, estimates of uncertainty from all parts of the model are carried through to the end, providing an objective basis for assessing the reliability of the model calculation results and pointing to critical research needed to increase the precision and reliability of future assessments.

**Summary of main results**

1. **Regional earthquake probability.** There is a $0.62^2$ probability (i.e., a 62% probability) of at least one magnitude 6.7 or greater earthquake in the 3-decade interval 2002-2031 within the SFBR. Such earthquakes are most likely to occur on the seven fault systems characterized in the analysis, but may also occur on faults that were not characterized in this study (i.e., in the “background”). This result is consistent with regional 30-year probability estimates made by WG88 (0.5), WG90 (0.67), and WG99 (0.70), given the differences among these studies and their uncertainty ranges.

<table>
<thead>
<tr>
<th>Source fault</th>
<th>Probability</th>
<th>95% Confidence Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFBR region</td>
<td>0.62</td>
<td>[0.37 to 0.87]</td>
</tr>
<tr>
<td>San Andreas</td>
<td>0.21</td>
<td>[0.02 to 0.45]</td>
</tr>
<tr>
<td>Hayward/Rodgers Crk</td>
<td>0.27</td>
<td>[0.10 to 0.58]</td>
</tr>
<tr>
<td>Calaveras</td>
<td>0.11</td>
<td>[0.03 to 0.27]</td>
</tr>
<tr>
<td>Concord/Green Valley</td>
<td>0.04</td>
<td>[0.00 to 0.12]</td>
</tr>
<tr>
<td>San Gregorio</td>
<td>0.10</td>
<td>[0.02 to 0.29]</td>
</tr>
<tr>
<td>Greenville</td>
<td>0.03</td>
<td>[0.00 to 0.08]</td>
</tr>
<tr>
<td>Mt. Diablo thrust</td>
<td>0.03</td>
<td>[0.00 to 0.08]</td>
</tr>
<tr>
<td>Background</td>
<td>0.14</td>
<td>[0.07 to 0.37]</td>
</tr>
</tbody>
</table>

This result, like virtually every other result in this report, is associated with a confidence range that reflects uncertainties in the analysis. The 95% confidence bounds for the regional probability is [0.37 to 0.87] (Table ES.1).
2. Geographic distribution of probability. The earthquake likelihood is distributed broadly across the SFBR, from the San Gregorio fault on the west to the Green Valley and Greenville faults on the east (Figure ES.1). The easternmost faults along the rapidly developing Interstate 680 corridor in central and eastern Contra Costa and Alameda Counties have a mean combined probability for $M \geq 6.7$ earthquakes of 0.19$^3$. Combining this with the contributions from the Hayward-Rodgers Creek fault, the central and southern parts of the Calaveras fault, and half the background earthquake likelihood, the probability for $M \geq 6.7$ earthquakes east of San Francisco Bay is 0.46 [0.17 to 0.64]. West of San Francisco Bay, the San Andreas and San Gregorio faults have a mean combined probability for a $M \geq 6.7$ earthquake of 0.32. With half of the background probability included, this part of the SFBR has a probability of 0.34 [0.05 to 0.57] for one or more $M \geq 6.7$ earthquakes in 2002-2031.

3. Highest-probability faults. Consistent with previous probability estimates, the Hayward-Rodgers Creek and San Andreas fault systems have the highest probabilities of generating a $M \geq 6.7$ earthquake before 2032. The Hayward fault is of particular concern because of the dense urban development along and directly adjacent to it and the major infrastructure lines (water, electricity, gas, transportation) that cross it.

4. Background earthquakes. The probability of a sizeable earthquake on a fault not characterized by WG02 (i.e., an earthquake in the “background”) is substantial. For events $M \geq 6.7$, the likelihood is 0.14 [0.07 to 0.37], greater than that on any individual fault system other than the Hayward-Rodgers Creek and San Andreas faults. Many of the significant recent earthquakes in California, including the 1989 Loma Prieta event, have occurred on faults that were not recognized at the time of their occurrence.

5. Larger earthquakes ($M > 7.0$, $M > 7.5$). The magnitude of an earthquake is directly related to the size of the fault rupture. Our analysis suggests a 30 year probability of an earthquake $M > 7.5$ or larger striking the region is only 0.10 (0.02 to 0.20). Only the San Andreas and San Gregorio faults, both lying west of San Francisco Bay, have sufficient length to generate such a large event. When the magnitude threshold is dropped to $M > 7$, the probability is considerably larger, 0.36 (0.17 to 0.60) and is concentrated on faults adjacent to the most developed parts of the region, the San Andreas, Hayward-Rodgers Creek, and San Gregorio fault systems.

6. Smaller earthquakes ($M > 6.0$). We estimated the probability of a moderate earthquake ($M > 6.0$, $M > 6.7$) over the next 30 years to be at least 0.80 (at least four times as likely to happen as not). As the recent past has demonstrated, earthquakes of this magnitude and smaller can produce significant damage over localized areas. For example, the 1984 $M = 6.2$ Morgan Hill earthquake on the southern Calaveras fault caused $10$ million damage, while a $M = 5.1$ earthquake that occurred in September 2000 in a rural area 10 miles northwest of Napa caused $70$ million damage to that community.

7. Stress shadow. Probability estimates for the next 30-year interval depend critically on the degree to which the SFBR has emerged from the seismic quiescence that followed the great 1906 San Francisco earthquake. The quiescence is thought to be caused by a region-wide drop in stress produced by that earthquake. Regional seismicity rates from the last few decades of the 20th century (Figure ES.3) suggest that the SFBR has been emerging from this quiescence, but has not returned to the high rate of earthquakes experienced in the 1800’s. Until a better understanding of the evolution of the 1906 “stress shadow” is developed, this fundamental uncertainty will continue to ham-

$^3$ Probabilities are combined according to Equation (5.9) of this report.
per the accuracy of time-dependent probability estimations in the SFBR.

Figure ES.3. Earthquakes $M \geq 5.5$ in the SFBR since 1850. The decrease in rate of large earthquakes in the 20th century has been attributed to a region-wide drop in stress due to the 1906 M7.8 earthquake, the "stress shadow" hypothesis.

8. Reliability of results. Generally speaking, the larger the spatial and temporal scales, the more reliable the results. The earthquake probabilities for the SFBR as a whole, for example, are more reliable than those for any individual fault. Similarly, earthquake probabilities for several decades are more reliable than those for the next year.

Implications for earthquake hazard

Earthquake probabilities are one key component in estimating the seismic hazard in a region, but not the only one. Most earthquake damage is caused by strong, sustained ground shaking. The strength and duration of shaking at a particular location depends on the earthquake's size, its distance from the location, soil conditions at the location, and details about the rupture itself and the propagation of the seismic waves from it.

WG02 has identified 35 potential earthquake rupture sources on the seven faults characterized in this study. For each potential source, a "scenario" map of the expected shaking intensity was constructed, using existing knowledge about the expected propagation and site effects in the SFBR. Figure ES.4 shows the expected shaking intensity distribution related to a M6.9 event on the southern Hayward fault, a likely repeat of the 1868 earthquake. This particular event has a likelihood of occurrence of 0.11 over the next 30 years.

Figure ES.4. Scenario ShakeMap illustrating the strength and regional extent of shaking that can be expected from a future M6.7 earthquake on the southern Hayward fault.

The full suite of 35 potential earthquake sources (and their probabilities) have been combined with the likelihood of background earthquakes to produce regional shaking hazard maps (Figure ES.5). These shaking hazard maps quantify the expected shaking in terms of modified Mercalli intensity (MMI), a scale that is related to damage. These maps represent average expectations and do not attempt to characterize details of the distribution of ground shaking and damage expected in any individual earthquake. The hazard map shown in Figure

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ES.5 depicts the MMI shaking level\(^4\) at a given site with a 50% chance of being exceeded in 30 years. This type of information is used as the input into the seismic design criteria in building codes.

Both the scenario shaking intensity maps and regional shaking hazard maps show that future earthquakes, regardless of where they occur in the San Francisco Bay region, are expected to produce damaging ground motions over broad areas and at substantial distances from their locations. Furthermore, the hazard maps show that sites located on rock have even odds in 30 years of experiencing up to MMI VII shaking, which is likely to damage only weak structures. In contrast, most sites on soft soils surrounding San Francisco Bay and the Sacramento River Delta generally have even odds in 30 years of experiencing MMI VIII or stronger shaking, which is expected to cause significant damage in engineered structures.

\[\text{Figure ES.5. Shaking hazard of the SFBR, expressed as the modified Mercalli Intensity (MMI) having even odds of being exceeded in 30 years. Shaking hazard is high throughout the region, and especially pronounced on the soft-soil areas surrounding the bay.}\]

\(^4\) The MMI scale is described and tabulated at http://neic.usgs.gov/neis/general/handouts/mercalli.html.
Working Group Participants

The ’99 and ’02 incarnations of the Working Group on California Earthquake Probabilities solicited the participation and open discussion of the earthquake research community. Participants included scientists from Federal and State governments, private industry, consulting firms, and academia. Thirteen people were voting members of the WG02 Overview Group, which had responsibility for guiding the study and completing this report:

- Michael Blanpied, co-chair .............U.S. Geological Survey
- David Schwartz, co-chair .............U.S. Geological Survey
- Norm Abrahamson ......................Pacific Gas & Electric
- William Bakun ............................U.S. Geological Survey
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- Paul Reasenberg .........................U.S. Geological Survey
- Michael Reichle .........................California Geological Survey

The following persons also participated in the WG99 and/or WG02 studies:

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Glenn Borchardt, Soil Tectonics
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Mary Lou Zoback, U.S. Geological Survey
CHAPTER 1: INTRODUCTION

In Earth, as in all Nature’s vast domain,
    A cycle rules events as night and day,
And powerful quakes like those that struck before,
    Will soon again shake San Francisco Bay.

When joined in sum the region’s numerous faults
    Portend disastrous earthquakes yet to be,
With strength enough to shake foundations loose,
    Disrupting all in our society.

While science can’t predict when earthquakes strike,
    We know enough to know we’d best prepare.
For in the end, the future looks toward us
    To heed those facts of which we are aware.

— Paul Reasenberg

This report presents probabilities for the occurrence of one or more $M \geq 6.7$ earthquakes, where $M$ denotes moment magnitude, in the San Francisco Bay Region (SFBR) for the 30-year period 2002–2031. The models and inputs presented here revise and update those given in Working Group on California Earthquake Probabilities (1999) (hereafter WG99) as U.S. Geological Survey Open-File Report 99-517 in October 1999. The results presented here supersede those of WG99. The Working Group on California Earthquake Probabilities (2002) (hereafter WG02) has taken into account new geologic, seismologic, and geodetic information developed since 1999, and extends the previous analysis through a keener appreciation of the “stress shadow” cast by the 1906 earthquake and the influence it has likely had on SFBR seismicity from 1906 to the present—and may continue to have on SFBR seismicity for the next 30 years. This study, like WG99’s, has involved a broad spectrum of the earthquake-science community in its analysis, including government, university and private-sector scientists.

This report

- Documents the data, methods, and assumptions used to calculate SFBR earthquake probabilities.
- Presents a long-term model for the occurrence of earthquakes in the SFBR (a modification of the WG99 model) based on the currently available geologic information.
- Quantifies the likelihood of damaging earthquakes occurring on major faults, on segments of these faults, and throughout the entire SFBR.
- Quantifies and discusses the uncertainty in these probability estimates.
- Estimates the intensity of ground shaking expected for some of the most likely anticipated earthquakes in the SFBR.
• Estimates the earthquake hazard for the SFBR in terms of the expected intensity of ground shaking.

WG02 is the latest in a series of analyses of earthquake probabilities for California. Each of these studies has advanced the modeling of earthquake generation. The first Working Group on California Earthquake Probabilities (1988) (hereafter WG88) produced the initial report on earthquake probabilities for the San Andreas Fault system. WG88 developed a fault-segmentation model for the San Andreas, Hayward, San Jacinto, and Imperial Faults; used slip rates to calculate average earthquake recurrence intervals; and employed the time-predictable model to estimate fault segment probability. WG88 concluded that the probability of one or more large (M~7) earthquakes in the SFBR during the next 30 years (1988-2017) was at least 0.5 (50%). This was based on an analysis of information about the earthquake history and behavior of only two SFBR faults, the San Andreas and Hayward Faults.

Following the damaging M=6.9 1989 Loma Prieta earthquake, the Working Group on California Earthquake Probabilities (1990) (hereafter WG90) was convened and charged with re-evaluating SFBR earthquake probabilities in light of that event. Using new slip-rate information from the Rodgers Creek Fault, and adding this fault to the estimate, WG90 found the 30-year earthquake probability to be 0.67 (67%). WG90 noted that other earthquake sources pose a threat to the region, including the Calaveras, San Gregorio, Concord-Green Valley, and Greenville Faults. However, these were not included in the analysis at that time because of insufficient information, particularly slip-rate data. WG90 added sophistication to the probability calculations by considering alternative rupture scenarios for the Peninsula segment of the San Andreas Fault and the effects of stress changes associated with the Loma Pieta earthquake. A principal limitation of the WG88 and WG90 models, however, was in the limited number and variety of the ruptures it characterized.

A major effort to re-evaluate earthquake probabilities in southern California was completed in 1995 by the Southern California Earthquake Center (SCEC Phase II report, 1994; Jackson and others, 1995). That study attempted to include the earthquake contributions from all faults in the region, added geodetic estimates of fault slip rates to the geologic estimates, and developed a method for calculating recurrence intervals for multiple-segment ruptures on the southern San Andreas Fault (the Cascade model). WG95 raised issues about the need to carefully compare regional seismic moment release and earthquake recurrence rates based on historical seismicity, geodesy, and the geological observations.

The WG99 report built on many of the concepts pioneered in these earlier California probability studies. In particular, WG99 expanded the use of multiple-segment ruptures in its long-term model for the occurrence of earthquakes in the SFBR by including 18 segments on the San Andreas, Hayward-Rodgers Creek, San Gregorio, Calaveras, Concord-Green Valley, Greenville and Mt. Diablo Faults and providing for 35 different possible ruptures of them. Their model balanced the long-term earthquake activity with observations of historical seismicity and the observed rate of tectonic plate motion. WG99 also expanded the use of formalized expert opinion and logic-trees to account for uncertainty in each stage of the probability calculations. And whereas WG88 and WG90 exclusively used the time-predictable model for calculating
earthquake probabilities, WG99 employed a weighted combination of several alternative probability models. Using this approach, WG99 found a 0.70 (70%) likelihood of at least one M>6.7 earthquake in the SFBR from 2002 through 2031.

The present report (WG02) adopts, with minor modifications, WG99’s methods, including multiple-segment-based long-term earthquake model and multiple probability models. Key differences include a more fully developed model for the “stress-shadow” effect of the 1906 earthquake in calculating the current probabilities of earthquakes. We also expand the results to include the probability of earthquakes for a range of magnitudes and time intervals; and explore implications for earthquake hazard in the SFBR.

Since the 1989 Loma Prieta earthquake, much new geologic, geodetic, and seismologic information has been obtained for SFBR faults. Some of this information was reviewed and summarized in 1996 by the Working Group on Northern California Earthquake Potential (WGNCEP 96) as input to the California seismic hazard map (Petersen and others, 1996) and US National Seismic Hazard map (Frankel and others, 1996), and both WG99 and WG02 built on these efforts. Specifically:

- Geologic slip rates and information on earthquake recurrence are now available for the northern Calaveras Fault, San Gregorio Fault, Concord-Green Valley Fault, and Greenville Fault.

- Understanding of the San Andreas Fault has improved with reevaluation of the distribution of slip in the 1906 earthquake coupled with paleoseismic slip rate and recurrence studies in Marin County, on the San Francisco peninsula, and in the Santa Cruz Mountains.

- Interpretation of the earthquake history of the Hayward Fault has significantly changed with recognition that a large earthquake in 1836 was not on the northern segment of the fault, but likely occurred southeast of San Francisco Bay.

- Knowledge of contractional deformation across the region has greatly improved, particularly the locations of reverse, thrust, and blind thrust faults and their associated slip rates.

- The effect of the 1906 earthquake, which relaxed the major faults in the SFBR and lowered the rate of seismicity for much of the 20th century, can now be estimated in several ways and incorporated into probability calculations.

- Several of the SFBR strike-slip faults exhibit aseismic slip or creep. The role played by fault creep in determining the seismogenic behavior of these faults is recognized here and incorporated into estimates of potential earthquake magnitude and recurrence rate.

- New analytical approaches to estimate the size and improve the location of historical earthquakes have resulted in a more complete catalog of SFBR M≥5.5 earthquakes back to 1850. Furthermore, the likelihood that specific historical earthquakes are associated with specific faults has been estimated.
• Global Positioning System (GPS) measurements of crustal deformation now provide a more precise estimate of the present day rate of deformation across the region, which is an important constraint on earthquake recurrence calculations.

An overview of the WG02 model is presented in Chapter 2. Chapter 3 summarizes on a fault-by-fault basis much of the geologic and geophysical data utilized in this study, and additional data and models are contained in the Appendices. Chapter 4 describes and constructs the SFBR earthquake model, which determines the average rate of earthquake occurrence for the faults characterized herein and for the region as a whole. Chapter 5 describes the five probability models used to determine earthquake probabilities in the SFBR for the coming decades. Chapter 6 presents the results of these calculations and discusses their uncertainties and sensitivity to key modeling assumptions. Chapter 7 explores some of the implications of these calculations for probabilistic seismic hazard as well as strong ground motion from probable future earthquakes in the SFBR. Finally, Chapter 8 summarizes the issues that matter most to the results presented here in the form of directions for future research.
CHAPTER 2: OVERVIEW OF MODELS AND METHODOLOGY

The San Francisco Bay region (SFBR) sits within the Pacific-North American plate boundary (Figures 2.1, 2.4). About 80 percent of the total plate boundary slip occurs across a 150 km-wide zone extending from the Farallon Islands to the west edge of the Central Valley, with most of this deformation occurring in an even narrower (50 km-wide) zone spanning the San Andreas and Calaveras Fault zones. The SFBR has the highest density of active faults and the highest rate of seismic moment release per km² of any urban area in the United States. The SFBR has experienced many sizeable and damaging earthquakes, including six magnitude $M \geq 6.5$ events in 1836, 1838, 1865, 1868, 1906, and 1989 (Figure 2.2) with magnitudes of 6.5, 6.8, 6.5, 6.8, 7.8, and 6.9, respectively.

The earthquake history of the SFBR has been documented in detail by Bakun (1999) and is believed to be complete for $M \geq 5.5$ events since 1850 (Figure 2.2), when the population of the SFBR increased greatly due to the discovery of gold in the Sierra foothills east of Sacramento. In the context of this study, three important observations can be made of this earthquake history. First, four $M \geq 6.7$ earthquakes have occurred in the historical record. Four events since 1838 corresponds to a rate of occurrence for $M \geq 6.7$ events in the SFBR of between 0.020/yr and 0.024/yr. Second, Bakun (1999) has shown that the size distribution of earthquakes in the SFBR corresponds to $b=0.9$ in the Gutenberg-Richter representation, both for the larger events since 1850 and for smaller events in the 20th Century.

Finally, the rate of earthquakes in the SFBR was considerably higher before 1906 than after (Figure 2.2). For the 70 years before 1906, 17 $M \geq 6$ earthquakes occurred in the SFBR while in the 95 years after 1906 there have been only five (Ellsworth and others, 1981; Bakun, 1999). We estimate the chance of this change in rate being due to random fluctuations to be less than 5%. The post-1906 seismic quiescence is thought to be due to a “stress shadow” cast by the 1906 earthquake over much if not all of the SFBR (Harris and Simpson, 1998). Both large and small earthquakes can be suppressed by the occurrence of a nearby earthquake, and can remain suppressed until the faults in the region are sufficiently reloaded (e.g., Harris and Simpson, 1998). In the SFBR, reloading occurs as the Pacific Plate moves northwestward past the North American Plate. In the SFBR, most of the major faults were relaxed to some degree by the 1906 earthquake, owing to the great length of its rupture and the sub-parallel, strike-slip geometry of these faults (R.W. Simpson, Appendix F).

There is no consensus within WG02, however, as to whether the SFBR remains within the 1906 stress shadow, as suggested by seismicity data for the past 96 years; is now emerging from it, as suggested by calculations based on rheological models of the crust and uppermost mantle; or has emerged from 1906 effects, as suggested by the simplest elastic interaction models. This area of uncertainty has led to substantial differences between the analysis reported by WG99 and that reported here. Put another way, the stress shadow cast over the SFBR by the 1906 San Francisco earthquake has, in turn, cast a considerable cloud of uncertainty over the deliberations and findings of Working Group 2002.
Uncertainty is no stranger to assessments and projections in the Earth Sciences, but it has rarely been an honored guest at these functions. WG02 has devoted considerable effort to defining uncertainties in the data, models, and parameters exercised here; quantifying these uncertainties; and tracking them throughout the calculations. In any model, there may be two types of uncertainty: *aleatory uncertainty* and *epistemic uncertainty*. Aleatory uncertainty refers to the random variability that occurs in the natural world. The throwing of dice is the classic example, perhaps because the word aleatory has its etymological origins in the Latin word for dice. Epistemic uncertainty refers to what we don’t know about the natural world, our ignorance of how the Earth works to manufacture earthquakes of a certain size at a certain place and time, for example. The differing opinions on the present-day effects of the 1906 stress shadow are a measure of epistemic uncertainty about this matter. To the extent a process is knowable, its epistemic uncertainty is reducible. Aleatory uncertainty, on the other hand, while quantifiable through direct observation of the phenomena of interest, is irreducible. WG02 uses models (sometimes more than one) to calculate quantities, and these models are defined by parameters that must be estimated. Both the choice of models and estimation of their parameters have uncertainty associated with them. These model uncertainties and parameter uncertainties are, in general, of both the aleatory and epistemic types. Finally, WG02 uses expert opinion to decide a number of matters in this report. Differing expert opinion also represents uncertainty. Insofar as such differences arise from differing evaluations or perceptions of available but incomplete knowledge (for example, the varying interpretations of the present-day effects of the 1906 stress shadow), this uncertainty is of the epistemic type.

Almost all of the uncertainty considered in this report, including that arising from diverse expert opinion, is treated as epistemic uncertainty. (The only exceptions are the event-to-event variability that we associate with magnitude distributions, natural variability in which fault segments combine to create earthquakes, and the aleatory component of the uncertainty in our time-dependent probability models.) Confronted with a range of possibilities for a parameter (for example, the length of a fault segment) or a relation (for example, the relation between segment area and earthquake magnitude) or a probability model, WG02 uses multiple choices with weights assigned to reflect the uncertainty. To sample systematically among the vast number of combinations of the weighted choices for input data and models, WG02 employs a Monte Carlo technique (also described as a logic-tree approach) in which thousands of complete calculations for SFBR earthquakes and their probability are made. From the distribution of the calculation results, we obtain various mean values (for example, long-term rupture rates or 30-year earthquake probabilities) and their 90% and 95% confidence bands.

An example of how weighted choices are used to represent uncertainty is shown in **Figure 2.3** for the case of estimating the seismogenic area and seismic moment rate (and their uncertainties) for the North Hayward Fault segment, given sets of weighted choices for segment length $L$, segment width $W$, seismic slip factor $R$ and slip rate $v$. (This calculation is described more fully in **Chapter 4**.) The result calculated using the preferred values is near or at the maximum of the distribution function for all possible results, as we would expect. Uncertainties in the calculated results can be large, however, if high confidence levels are imposed on the results. Every result presented in **Chapter 6** is stated as a mean value and its 95% confidence band, as inferred from the Monte Carlo sampling.
The earthquake probabilities reported here are the results of a set of model calculations consisting of three basic elements. The first element is the SFBR earthquake model (described more fully in Chapter 4) which determines the average, long-term rate of earthquakes on the principal faults. The second element is the set of “background” earthquakes, those earthquakes that occur in the SFBR on faults either uncharacterized or unrecognized by this study, the probability for which is based on historical seismicity rates extrapolated to $M \geq 6.7$ events. The third element of these calculations is a suite of probability models, which are described in Chapter 5. The probability models range from the simplest (a time-independent Poisson model) to those that incorporate certain time-dependent physical aspects of the causes and effects of earthquakes, such as the progression of faults through an “earthquake cycle” and the interactions of faults through their stress fields.

Because of the inclusive approach taken by WG02 toward all forms of uncertainty and differing expert opinion, the model used by WG02 to calculate earthquake probability is complex. This complexity notwithstanding, certain assumptions and parts of the model play critical roles in the calculation and strongly affect the results, while others affect the results only a little. In the remainder of this chapter, we introduce the key elements of the WG02 model, paying particular attention to those things that matter most in calculating the earthquake probabilities in the SFBR.

**SFBR Earthquake Model**

For the purposes of this study, the San Francisco Bay Region (SFBR) is a rectangular region, extending from Santa Rosa on the north to Monterey on the south, which trends parallel to the northwesterly strike of the principal faults of the San Andreas system and which includes them all (Figure 2.4). From west to east, they are the San Gregorio, San Andreas, Hayward-Rodgers Creek, Calaveras, Concord-Green Valley, and Greenville Faults, plus the Mt Diablo Thrust, a blind thrust lying between the northern end of the Calaveras Fault and the southern end of the Concord-Green Valley Fault. These seven faults are referred to as the characterized faults in this study.

Attached to the SFBR is a panhandle extending along the San Andreas Fault to Cape Mendocino. This extension is needed to mechanically accommodate in our model long ruptures of the San Andreas Fault, such as that which occurred in 1906. However, when we report results for the SFBR herein, they reflect only earthquakes occurring in or extending into the rectangular SFBR region.

The SFBR earthquake model is fundamentally a geologic model in that both its geometry and long-term behavior are defined and constrained by geologic observation. The model incorporates complexity that leads to a wide spectrum of earthquake sizes, and includes both fault-by-fault and regional constraints on the frequency of occurrence of these earthquakes based on geologic and geodetic observations of slip rate. The basic elements of the SFBR earthquake model are introduced in the box below, and more fully discussed in Chapters 3 and 4.
The SFBR Earthquake Model

Fault segments
The SFBR model is built upon the seven characterized faults mentioned above. Each fault is divided into as many as four, non-overlapping segments – 18 segments in all. These segments are the basic building blocks for earthquake ruptures on each fault. Each fault segment has length $L$, width $W$, geologic slip velocity $v$, and seismogenic scaling factor $R$, which accounts for any part of the geologic slip that is aseismic (Figure 2.5, Table 3.8).

Rupture sources
Unlike WG90, which considered only single-segment ruptures, the present study allows for the simultaneous rupture of two or more adjacent segments of a fault. Each possible combination of segments is a rupture source. These rupture sources—35 in all—are listed in Table 4.8. A mean magnitude is computed for each rupture source based on its seismogenic area $A$ (determined by $L$, $W$ and $R$ on each of its segments) through “$M$–log $A$” relations, as described in Chapter 4.

Floating earthquakes
Each fault (except Mt. Diablo) is host to floating earthquakes—earthquakes of a specified magnitude but without a fixed location. Floating earthquakes, which allow for the fact that some earthquakes are not represented by the prescribed segmentation, are also classified and treated as rupture sources and are listed in Table 4.3.

Rupture scenarios
A rupture scenario is a combination of rupture sources that describes a possible mode of failure of the entire fault during one earthquake cycle. For example, in one rupture scenario the Hayward-Rodgers Creek Fault fails only in 3-segment ruptures, in another it fails only in single-segment ruptures, and in a third scenario it fails in combinations of 1-segment and 2-segment ruptures (Table 3.4).

Fault rupture models
A fault rupture model is a weighted combinations of the rupture scenarios for a fault, each combination representing one possibility for the long-term behavior of the fault. The weights are determined by expert opinion. The fault rupture models serve the same function as the “earthquake-cascade” models employed in WG95 (SCEC, 1995). For most faults, multiple fault rupture models are considered.

Regional model
A viable regional model is an aggregate of seven rupture models (one for each fault) and a background earthquake model (described below) that satisfies a plate-motion slip rate constraint across the entire SFBR defined by geodetic observations. A regional model provides a complete description of the long-term earthquake activity in the SFBR.
Background Earthquakes

Earthquakes that have occurred (and will occur) within the SFBR on structures other than the seven characterized faults are termed background earthquakes. Numerous known faults and structures in the SFBR not characterized here are considered capable of producing \( M \geq 6.7 \) earthquakes, as are, presumably, some yet-unrecognized faults and structures at depth in the SFBR (for example, prior to 1989, the source of the Loma Prieta earthquake).

Like the characterized earthquakes, background earthquakes have their origins in the elastic strain accumulation driven by the relative motions of the North American and Pacific plates. As described more fully in Chapter 4, the SFBR accommodates about 40 mm/yr of strike-slip plate motion (De Mets and Dixon, 1999; Prescott et al., 2001) and about 4 mm/yr of convergent plate motion (Prescott et al., 2001). Almost all of the strike-slip plate motion occurs on the characterized faults (excluding the Mt. Diablo thrust) but some also occurs in background earthquakes. The accommodation of plate tectonic motion by earthquakes of various types is schematically illustrated in Figure 2.6.

WG02 characterizes only one geologic structure that can accommodate appreciable convergent plate motion—the Mt. Diablo Thrust. Given the small dimension of this structure compared to the 220-km along-strike length of the SFBR, the Mt. Diablo Thrust can account for only a small fraction of the convergent plate motion. Convergent background earthquakes also accommodate convergent plate motion. These may occur in other regions of local uplift associated with thrust faults, along the eastern edge of the Great Valley, for example, or the west side of the Santa Clara Valley (Figure 2.7).

Background earthquakes of both the strike-slip and convergent types are considered here in terms of a Gutenberg-Richter distribution with \( b = 0.9, \ M_{\text{max}} = 7.25 \pm 0.25 \), and a constant rate of occurrence defined by the rates in the historical and instrumental records. WG02 does not apply a strain accumulation/release (moment-balance) constraint to the background earthquakes, as we do for earthquakes on characterized faults.

Probability Models

An earthquake probability model describes the time-dependence of earthquake occurrence. After the mean rupture rates and magnitudes are calculated for rupture sources in the SFBR, they become input for the several probability models used in this study and described more fully in Chapter 5. Different probability models incorporate different physical attributes of the earthquake process.

In calculating earthquake probabilities in the SFBR, WG02 recognizes two essential, time-dependent aspects of the causes and effects of earthquakes, the first relating to the earthquake cycle and the second to fault interactions. The concept of the earthquake cycle has its origins in the elastic-rebound hypothesis, first formulated for the 1906 earthquake and its likely successor on the San Andreas Fault (Reid, 1908). It holds that after a major earthquake and its immediate aftershocks, another major earthquake on the same reach of fault is not possible until elastic strain has re-accumulated in an amount comparable to that released in the previous major
earthquake. As time goes on and more and more elastic strain accumulates, the next large earthquake becomes increasingly likely. If the SFBR had only the San Andreas Fault and 1906-type earthquakes to account for, quantifying these effects would be far simpler (although not necessarily accurate with available data). But this is not the case. Smaller-magnitude but still large earthquakes, perhaps with their own “earthquake cycles,” have occurred on or near the reach of the San Andreas Fault that ruptured during the 1906 earthquake, both before (in 1838) and after (in 1989) this event.

With respect to fault interactions, it is necessary to estimate the effects of the 1906 earthquake on the other SFBR faults, as well as similar (but smaller and more localized) effects of the Loma Prieta earthquake (Oct. 17, 1989; $M = 6.9$). Both model calculations and known seismicity rates since 1836 (Figure 2.2) suggest that the 1906 earthquake cast a deep and long-lasting “stress shadow” across the entire SFBR (see, for example, Harris and Simpson, 1998). As noted previously, however, there is no consensus as to whether the SFBR remains within the 1906 stress shadow, is now emerging from it, or is well removed from 1906-related effects.

All of this lends considerable uncertainty to the probability estimates reported here—uncertainty in addition to that contained in the SFBR earthquake model. This uncertainty is expressed both in the range of probability models described below and in the expert opinion applied to them in the form of relative weights.

The first of the five probability models used to determine earthquake probabilities in the SFBR is the *Poisson* model. Poisson probabilities do not vary with time and are fully determined by the mean rates of earthquakes in the SFBR regional model.

The *Empirical* model is a variation of the *Poisson* model. It incorporates time-dependence by modulating the average rates of rupture sources with the current regional rate of seismicity, which is currently lower than its long-term average. The *Empirical* model thus uses modern seismicity rates as a proxy for stress shadow calculations that rely on poorly known rheological/mechanical properties of the crust and uppermost mantle under the SFBR. Inclusion of the *Empirical* model is a significant departure from the approaches toward probability modeling taken by WG90 and WG99.

The *Brownian Passage Time* (BPT) and *Time-Predictable* (TP) models used in this study are both time-dependent probability models. In BPT model, the failure condition of a fault or fault segment is specified by a state variable, which rises from a ground state to the failure state in the course of the earthquake cycle. Evolution of this model toward failure is governed by a deterministic parameter reflecting the reloading rate of the fault or fault segment and a stochastic parameter $\alpha$, or “aperiodicity”, that allows for random variations in the process. The “stress shadow” effects of nearby earthquakes are admitted in the BPT model through steps in the state variable calculated with elastic interaction models. The TP model requires that both the date and the amount of slip of the most recent earthquake be known. In this model, the expected time of the next characterized earthquake is equal to the time required for the strain accumulation process to provide for the same amount of faulting displacement as occurred in the previous event. The TP model is applied here only to segments of the San Andreas Fault that ruptured in
the 1906 earthquake; this is the only SFBR earthquake for which detailed slip measurements are available.

How the inherent randomness of the earthquake process is modeled affects the probability calculations for all of the rupture sources. We estimated $\alpha$ from 37 sequences of repeating earthquakes to be in the range 0.3–0.7, similar to the the cov of 0.5±0.2 used by WG95. This is in contrast to smaller values used by WG88 and WG90 based on the work of Buland and Nishenko (1987), and it is fair to say that the estimation of $\alpha$ remains a significant scientific challenge and a significant source of uncertainty in time-dependent earthquake forecasting. The effect of $\alpha$ on WG02's probability calculations depends on the time since the most recent rupture. For the 30-year period 2002-2031, assuming greater randomness decreases the probability on most of the faults, but increases the probability of earthquakes on the San Andreas Fault.

**Expert Opinion**

Expert opinion has been used in seismic hazard and risk analyses for more than two decades. For most earth scientists, the theory and practice of expert opinion will come as new developments, but WG02 believes that the basic principles are consonant with the philosophy of multiple working hypotheses (multiple working models, in the case of this report). Earth scientists have long embraced the use of multiple working hypotheses when knowledge is insufficient to eliminate any of them (Gilbert, 1886; Chamberlin, 1890). In this approach, experts are convened to define and portray the body and range of informed opinion on the matter at hand (SSHAC, 1997; Hanks, 1997). The process should be inclusive: that is, any other group of experts should express the same range of knowledge and models. The “truth” or “right answer” is assumed to lie somewhere among or between the various opinions. In this context it is not useful to try to decide which experts are “right” and which experts are “wrong” because there is no way of knowing. If there were, there would be no need for all the experts in the first place. Finally, all should recognize that experts are not convened to reduce uncertainty; indeed, in their differing opinions, they are the source of much of it.

This report is not a consensus report, at least not in the sense that previous reports on California earthquake probabilities (1988, 1990, 1995) were consensus reports. In particular, WG02 does not arrive at final probability numbers by agreeing in advance on a single model or method for calculating them. Rather, this report proceeds on the basis of a consensus process, which admits a variety of models that are significantly different from one another, for one reason or another. The final result is determined by the aggregated expert opinion expressed individually by the 13 members of the Overview Group of WG02, which had responsibility for contents and conclusions of this report. The members of that group are listed at the beginning of this report.

The SFBR earthquake model is a consensus feature of this study. WG02 uses only this model to estimate earthquake rates as a function of size on a fault-by-fault and segment-by-segment basis, even though other models, such as the cascade model of WG95 or the models of Ward (2000) and Andrews and Schwerer (2001), do similar things. Surely, therefore, there is some uncertainty associated with the adoption of this single model that is left unquantified here. Perhaps the segmentation basis of the analysis here is incorrect, or perhaps the choices of segments are
incorrect, or perhaps the proscription against ruptures of only a part of a segment (apart from floating earthquakes) is incorrect. If so, WG02 has no way of knowing by how much. What we can do is compare the SFBR model predictions of average earthquake occurrence rates to what is known to us through the historical and prehistoric records of earthquakes. The SFBR earthquake model passes these tests, but so do other models.

The Strain Accumulation/Release Constraint

Earthquakes in the San Francisco Bay Region have their origins in the elastic strain energy accumulating in the region due to the steady motion of the Pacific plate relative to the North American plate. Most of this relative motion is in the form of horizontal shear of 36-43 mm/yr across the SFBR and is released on faults in strike-slip earthquakes.

Both the accumulation and release of strain energy are measurable quantities for the San Francisco Bay Region (Bakun, 1999; Prescott and others, 2001). There are long-term and short-term estimates for each (Figure 2.8). In terms of slip velocity across the region, the long-term accumulation inferred from global plate motion models is 41±1 mm/yr (De Mets and Dixon, 1999). This value is an average over the past five million years, and has been corrected for the San Francisco Bay by subtracting contributions of Great Basin extension and motion of the Sierra Nevada-Great Valley block from the full relative motion of the Pacific and North American plates. The short-term accumulation rate measured using GPS data for the past seven years is in good agreement at 39.8±1.2 mm/yr (Prescott and others, 2001).

Long-term release of strain energy on individual faults is measured by the faults’ geologic slip rates averaged over thousands—often many thousands—of years. Sums of the slip velocity measured on strike-slip faults in the SFBR can be compared to the plate-motion rate (Figure 2.9). Finally, the short-term release of strain energy can be estimated from the historical record of earthquakes in the SFBR. The seismic moment sum for the period 1850 to present corresponds to a mean slip velocity of roughly 31 mm/yr. A large uncertainty—approximately 50% of this value—arises primarily from uncertainty in the seismic moment of the 1906 earthquake, which alone has contributed about two thirds of SFBR seismic moment sum since 1850 (Bakun, 1999).

The coincidence of these four very different measures of slip velocity reveals that what goes into the SFBR in the way of plate motion strain energy accumulation comes out as strain energy release, whether this is measured by geologic fault slip rates or by the seismic moment sum of the historical record of earthquakes. These estimates of strain energy accumulation and release are in remarkably good agreement on both the long term and, even more surprisingly, on the short term.

From Segments to Earthquakes

WG02’s method for estimating the size of earthquakes on the characterized faults (including both single-segment and multiple-segment ruptures) uses the fault area A to estimate moment magnitude M. Seismic moment M0 for each event is then determined from the inverse of the moment magnitude relation (Hanks and Kanamori, 1979).
To put the strain accumulation/release constraint of the last section into play, the seismic moment sum for each characterized fault is computed. These sums are balanced against the total moment rate defined by areas and geologic slip velocities determined for segments involved.

We use three sets of $M-\log A$ relations in this analysis: that of Wells and Coppersmith (1994); those developed originally by W.L. Ellsworth for WG99 and reproduced here in Appendix D; and those of Hanks and Bakun (2002) invoking L-model scaling of fault slip at $M \geq 7$. The differences between these relations make for the principal source of uncertainty in the SFBR earthquake model. Even modest differences (or uncertainties) among these relations (say 0.2 units in $M$) provide for a factor of 2 difference (or uncertainty) in $M_0$ and therefore in the rates of such earthquakes, given the moment-balanced format of our calculations.

In addition to the $M-\log A$ relations, several other considerations play key roles in determining the long-term average rate of earthquakes and their size distribution. Aseismic slip, or fault creep, comes into play through the seismogenic factor $R$, the ratio of seismogenic fault slip to total fault slip, by reducing the effective area of the rupture sources in the model (Appendix B). Generally, where the $R$ factor reduces the rupture area, it reduces the earthquake magnitude. For some of the shorter fault segments having significant amounts of aseismic slip, such as those on the Hayward, Calaveras, and Concord-Green Valley Faults, magnitudes associated with single-segment ruptures can be and often are $M < 6.7$. Thus, it is important to distinguish between the rates of $M \geq 6.7$ earthquakes, which is our principal concern in this analysis, and segment-rupture rates, which include all of the rupture sources involving a given segment, including those with $M < 6.7$. Segment-rupture rates may be more useful than $M \geq 6.7$ earthquake rates for interpreting geologic, site-rupture data for paleo-earthquakes with $M \sim 6.7$.

A third factor controlling the rates of earthquakes in the SFBR model are the various rupture scenarios and rupture models. These are important features in moment-balanced calculations such as these, because the seismic moments of just a few large earthquakes will typically dominate the total moment for a segment, for a fault, or for the SFBR as a whole. Finally, the choice of $M$ for the floating earthquakes may or may not be an important contributor to the total moment for that segment, depending on the floating earthquake’s size relative to the size of the segment-rupturing earthquakes on that fault.

The Calculation Sequence

The Calculation Sequence (CS), described more fully in Chapter 4, is the computational apparatus that embodies the SFBR earthquake model, the background earthquake model, and the probability models, and calculates the earthquake probabilities. The CS first calculates average rates of rupture sources on the characterized faults. These rates, in turn, are the input to each of the five probability models. The rates of background earthquakes are calculated with a Gutenberg-Richter model for the SFBR as a whole; probabilities for the background earthquakes are calculated only for the Poisson probability model.
The CS is illustrated schematically in Figures 2.10 and 2.11. Calculation of the rates of rupture sources is shown in Figure 2.10, beginning with the segment geometry and creep rates on the left and concluding with rupture rates on the right. Along the way, we calculate $M$ and $M_0$ for each rupture source in the bottom path of Figure 2.10. In the top path we calculate seismic moment rates for each segment and each rupture model through their $\Sigma M_0$’s, constraining them both locally and regionally according to individual fault slip rates and the plate-motion rate, respectively. The resulting rupture source rates are then input to the probability models (Figure 2.11).

Implicit in these schematic diagrams are the multiple choices of numerous parameters and models involved in these calculations and their assigned weights. For example, as illustrated in Figure 2.3, the seismogenic area $A$ of a fault segment is calculated from the product of its length $L$, width $W$, and seismogenic scaling factor $R$. Its length, in turn, is calculated from the geographic coordinates of the segment’s endpoints. The uncertainty in each of these parameters (each $L$ endpoint location, $W$, and $R$) is represented by three branches. Thus, there are 81 ($3^4$) paths through this part of the CS, yielding 81 measures of the seismogenic area. The most likely measure is that found for the highest-weighted branch choices, but the less likely paths are also followed in the Monte Carlo sampling of the CS. Put another way, each choice of these parameters, together with the weight assigned to it by WG02, occupies a branch of the logic tree. WG02 often assumes that the uncertainty in a parameter is normally distributed, and represents the mean and width of the distribution with three branches (or occasionally five) and their respective weights (corresponding to either the 90% and 95% uncertainty bounds), as given in Table 2.2.

Table 2.2: Branch weights corresponding to mean and 90% and 95% bounds for parameter estimates.

<table>
<thead>
<tr>
<th>Uncertainty bound</th>
<th>Branch weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% (±1.64 sigma)</td>
<td>0.185 0.63 0.185</td>
</tr>
<tr>
<td></td>
<td>0.13 0.74 0.13</td>
</tr>
<tr>
<td>95% (±1.96 sigma)</td>
<td>0.09 0.16 0.50 0.16 0.09</td>
</tr>
</tbody>
</table>

Similarly, alternate models for a calculation—for example, the several $M$–log $A$ models—are also represented by multiple branches in the logic tree, but with weights assigned by expert opinion. The number of possible paths through the whole CS is huge. WG02 explores the range of possible behaviors with a random sampling or Monte Carlo technique. The results of the CS—the calculated probabilities of earthquakes—are described in Chapter 6. For each result we report the mean and 95% confidence range for a suite of 10,000 model realizations. Through repeated testing of the code we have determined this number to be more than sufficient to ensure that mean and uncertainty bounds are well determined. The CS is carried out in a Fortran 77 program that is described in Appendix G.
Figure 2.1. Major faults of the San Francisco Bay Region. Arrows show the mostly strike-slip sense of tectonic plate motion accommodated by earthquakes and aseismic creep on SFBR faults. Yellow lines indicate extent of rupture in the 1868 M~6.8 earthquake on the southern Hayward faults and that in the 1989 M6.9 Loma Prieta earthquake near the San Andreas fault northeast of Monterey Bay.
Figure 2.2. Time sequence of earthquakes $M \geq 5.5$ in the SFBR since the early 19th century, from the catalog of Bakun (1999). The catalog is believed to be complete for such magnitude earthquakes since 1850. A high rate of earthquake activity in the late 1800’s was followed by relatively little activity after 1906. Asterisk indicates more than one earthquake occurred that year.
Figure 2.3. Illustration of WG02’s approach to model calculations. Blue histograms show values and frequencies of fault segment length L, width W, seismogenic scaling factor R, and slip rate v. Red histograms show resulting calculations of seismogenic area A and segment moment rate. This example is for the northern Hayward (HN) segment and the results are from 10,000 realizations of the calculation sequence.
Figure 2.4, Dashed rectangle (Working Group 2002 box) shows the region included for calculation of earthquake probability and seismic moment. Bold solid lines indicate major faults for which probabilities were calculated. MTD, Mount Diablo Thrust; Con, Concord Fault. San Andreas Fault segments: SAN, North Coast; SAO, Offshore; SAP, Peninsula; SAS, Santa Cruz Mountains. San Gregorio Fault segments: SGN, North; SGS, South.
Figure 2.5. Conceptual illustration of a segmented vertical fault. Also shown are measures of length $L$, down-dip width $W$ and reduction of seismogenic area due to near-surface creep. Dashed lines illustrate uncertainties in segment endpoint position and other quantities.
Figure 2.6. Schematic of the SFBR Earthquake Machine. The input (green) plate rate is output (red) as characteristic earthquakes, aftershocks, smaller earthquakes in the exponential tail, background earthquakes, and as creep. The approximate part of the total relative plate motion across the SFBR (about $2 \times 10^{18}$ N.m/yr of potential seismic moment) are expressed as percents. For example, the earthquake sources characterized in this report account for about 62% of the total plate motion across the SFBR.
Figure 2.7. Earthquakes from the Northern California Seismic Network catalog in the SFBR. Color and symbol show the dominant probability of association with the WG02 fault segments. (Figure 9 of Wesson, et al., 2003.)
Figure 2.8. Input and output rates of slip for the SFBR earthquake machine. Error bars represent ± 2σ. The long-term and short-term accumulation rates (input to the machine) are obtained from plate-motion rates and geodetic measurements over the past few years respectively. The long-term and short-term release rates (output to the machine) are obtained from geologic slip rates and historical seismicity respectively.
Figure 2.9, WG02 segments and slip rate. Solid gray lines tranverse to the major faults are the three transects used to sum slip rates across the region.
Seismogenic scaling factor, $R$

Seismogenic width, $W$ (base of seismogenic zone)

Calculate seismogenic areas, $A = LWR$

Calculate segment lengths, $L$

Calculate segment moment rates, $\mu Av$

Calculate rupture source moment rates

Calculate rupture source recurrence rates

To probability calculations

Relative rupture source rates (from fault rupture models)

Regional slip-rate constraint

Long-term slip rates, $v$

% moment in characteristic earthquakes $F_{char}$

$\lambda = F_{char} \frac{\dot{M}_0}{\bar{M}_0}$

Calculate mean magnitudes of rupture sources $\bar{M} = f(A)$

Calculate mean earthquake moments

Magnitude variability
Figure 2.11. WG02 uses five alternative models for calculating probability of earthquakes in a given time interval (e.g., 2002-2031), given the long-term rate of occurrence of rupture sources. Each model requires a different set of additional information, as described in the text. Branch weights $w_1$–$w_5$ were determined by expert opinion.