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**≥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 20^{th} 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 $\mathbf{M}\geq5.5$ 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.