CHAPTER 8. REFLECTIONS AND FUTURE DIRECTIONS

Reflections on the Working Group process

This analysis of earthquake probabilities in California continues a legacy dating back to 1983, a legacy consisting primarily of time-predictable models for single-segment ruptures. At the same time, it departs from the previous work in three significant ways: 1) in the development of the average, regional SFBR earthquake model in which multi-segment ruptures evolve for the characterized faults; 2) in the use of a suite of probability models, not just one, to develop the time-dependent, 30-year earthquake probabilities; and 3) in the use of aggregated expert opinion to accommodate the range of differing scientific judgments, itself a source of significant uncertainty.

Developing new methods and models is the essential business of research science, but developing and using unvetted methods and models in a results-oriented, practical exercise such as this report will generally make for unanticipated problems that may take considerable time to resolve. Conversely, utilizing tried and true models, methods, and data will make for smoother and more efficient applications, but it may well lead to results that are out of date before they are out in print, given the present pace of earthquake science. In formulating research results for use in making public-policy decisions, it was incumbent upon WG99 and WG02 to strike a balance between these approaches.

While the SFBR earthquake model is straightforward in concept, with its origins in the decades-old ideas of characteristic earthquakes and fault-segmentation models, a number of difficult issues arose in implementing it. Such matters included the use of floating earthquakes of uncertain sizes in recognition of possible limitations of the fault-segmentation model; accommodating aseismic slip in the strain accumulation/strain release balances; developing new **M**–log *A* relations upon recognizing that the Wells and Coppersmith (1994) relation underestimated **M** at large *A*; and in allowing for multi-segment ruptures, which provided several challenges involving expert opinion, relative rupture rates, and a separate moment-balancing calculation.

WG02 also expanded the range of probability models put to use in studies such as these. The BPT Model was new and unpublished when it was first put to use in this analysis, and while its use permitted incorporation of fault-interaction effects, first through clock corrections (WG99) and later with state-steps (this report), these advances presented significant and time-consuming computational challenges.

Stress changes arising from elastic-plate fault interactions were found to be insufficient to explain the 1906 stress shadow. In brief, stress changes recover too rapidly after 1906 to explain low rates of moderate-**M** earthquakes several decades later. What appears to be needed are fully time-dependent stress interactions involving the poorly constrained rheology of the lower crust and upper mantle beneath SFBR. In the absence of agreed-upon models for this phenomena, WG02 developed the Empirical Model, which employs the observed SFBR seismicity rates since 1906 as a proxy for the 1906 stress shadow. None of this transpired quickly and in fact involved a considerable expenditure of time, effort and controversy. But it has also made for the central difference between this report and its predecessor and for the central conclusion of this analysis: the limits of our knowledge of the extent and duration of the 1906 stress shadow are the essential limitation on the 30-year earthquake probabilities reported here.

The general principles underlying the use of diverse expert opinion have been discussed in **Chapter 2**, and its actual use has been described in **Chapters 3**, **4**, and **5.** Expert opinion in principle and expert opinion in practice, however, can be very different things. Even in the best of circumstances, which include a well-structured prospectus of how, where, when, and why expert opinion will be used, the process of actually exercising it is time-consuming and cumbersome. This "well-structured process" should also include feedback loops to the experts, with sufficient time for the experts to digest the consequences of their decisions.

WG02 sought out the views of many experts of diverse experiences and points of view and arranged for extensive interaction among them. Their expert opinions, finally expressed through voting, were applied in many instances, at all levels of importance to the results reported here. Due to the complexities noted above, our "well-structured process" developed over the course of our deliberations, and feedback on the consequences of decisions was uneven.

Because diverse expert opinion is itself a significant source of uncertainty in this analysis, we doubt that any future, comprehensive study of earthquake probabilities will be credible in the absence of sampling and quantifying the body and range of scientific judgments. If this is indeed the case, future studies of the scope of this one are well advised to think through in advance the processes by which they will employ differing scientific opinion and to make ample allowance for unanticipated problems that arise in the course of completing such studies.

The computer code developed by WG02 is a major product that allows the SFBR earthquake model and earthquake probabilities to be recalculated as new input values and branch weights become available. The code can easily be modified to accommodate new models, and can serve as a useful tool for exploring the sensitivity of results to the underlying models and input parameters. Given this flexibility, when should serious consideration be given to updating and replacing the results presented here? Incremental improvements in inputs (e.g., a refined slip rate or segmentation point) could be handled by re-running the WG02 code with modified input parameters or branch weights. However, our experience suggests that certain events may make it worthwhile to convene a new Working Group. These include:

- A sizeable earthquake on one of the characterized faults, or a background earthquake that significantly changes the stress state of characterized faults.
- New or improved data that significantly changes the calculated rate or magnitude of earthquakes on the characterized faults, in particular changes in the inferred rate of earthquakes on the San Andreas fault because of its dominating effect on the seismic moment budget and earthquake occurrence throughout the region.
- New results that increase understanding of the 1906 stress shadow.
- The development of a new probability model, or an evolution of opinion in the scientific community that would significantly change probability model weights.

Key questions for future research

We have noted throughout this report that there is little about it that is not without uncertainty. The purpose of this chapter is to cast those things that most greatly influence the results in the form of questions to be addressed through research, noting those bodies of knowledge on which they depend and their attendant uncertainties. Critical goals of research in this field are to improve models for the occurrence, rate and probability of large earthquakes, and to better quantify the parameters needed to apply them to regions at risk.

The SFBR model balances strain energy accumulation against its release in all earthquakes and related phenomena, but not all earthquakes are equal in the accounting. The slip in one big earthquake equals that of many smaller ones, so a key aspect of the model is the manner in which big earthquakes are made. The *segmentation models*, the rupture models which specify the likelihood *of multi-segment ruptures*, the ***M**- log A relations*, and ***M** for the 1906 event* are all critical in defining the frequency of big earthquakes and their import in releasing the regional deformation available to make all of the earthquakes. *Creep or aseismic slip* is also crucial, particularly in the description of the Hayward fault.

The calculation of 30-year probabilities are based on the SFBR model, and also are critically dependent on our description of *fault interactions*, particularly the extent to which earthquake occurrence on faults in the SFBR in the next 30 years is controlled by the stress shadow of the 1906 event. The 30-year probabilities are also pivotally dependent on the variability of recurrence intervals of earthquakes on a fault segment, represented here by the *coefficient of variation* or *aperiodicity*, α.

Segmentation Models

WG02's segmentation model was designed by committees of earth scientists expert in the workings of faults in general and SFBR faults in particular. There was considerable discussion in these groups about the existence and locations of fault segment end points -the consistent end points of rupture in significant earthquakes, Which end points are particularly strong? Which end points in the SFBR are clearly supported by geologic and geophysical observation? Which are not? How would removing these segments affect the model and the 30-year probabilities? WG02 included floating earthquakes of a particular **M** to account for unknown segmentation. Should floating earthquakes be part of future models? Or, is a continuous distribution of earthquake sizes, perhaps a Gutenberg-Richter distribution, more appropriate? Should future working groups consider a range of possible fault characterization approaches beyond the segmentation model?

Multi-segment Ruptures

How frequently earthquakes rupture through segment endpoints and grow into multi-segment (big) earthquakes is a crucial aspect of fault characterization. WG02's fault characterization committees based their assessments of the frequency of multi-segment ruptures on a collective subjective judgment (expert opinion) rather than on a specific analysis of resistance to failure. Future working groups would benefit from clarification of how earthquakes stop and which fault characteristics are particularly diagnostic of resistance to failure in big earthquakes. Does the apparent offset of the Hayward and Rodgers Creek faults beneath San Pablo Bay provide a barrier that is rarely broken in multi-segment earthquakes? Or, like the 1995 Kobe, Japan earthquake, does the fault trace offset concentrate stress and act as a nucleation point for multi-segment ruptures? What is the best way to assess the frequency of multi-segment ruptures on SFBR faults?

M-logA Relations

WG02 used a suite of empirical M-log relations to determine the magnitude of earthquakes from their areal dimensions. How fast does the average slip increase with area? WG02 struggled with the discrepancy between the available examples of big San Andreas fault system events (the 1857 earthquake in southern California and 1906 in northern California) and observations from big strike-slip earthquakes worldwide. Are earthquakes on the San Andreas fault system fundamentally different from their cousins worldwide? Or, are the 1906 and 1857 events extreme examples of the aleatory variability in the slip or rupture length of great strike-slip events? More specifically, should future working groups consider the low slip in 1906 as anomalous or representative of future comparable-length multi-segment ruptures? There is considerable aleatory uncertainty in the observations worldwide and great continental strike-slip earthquakes like 1906 and 1857 happen infrequently, so timely answers to these questions will not come from a data set supplemented by future great strike-slip earthquakes. Is the aleatory uncertainty normally distributed in **M**? Or in M_0?

M for the 1906 Event

If 1906 earthquake is treated as representative of comparable-length multi-segment ruptures, what **M** should be used for 1906 in constructing the long-term model? WG02 assumed **M** 7.8, but recognized that the uncertainty in this estimate corresponds to the slip in several **smaller** events. Thus, the estimates of 30-year probability of **M** ≥ 6.7 events depend on the value of **M** assumed for the 1906 event. Is the slip in the 1906 earthquake a repeat of earlier 4-segment ruptures of the San Andreas fault? What is the paleoseismic evidence for the occurrence of 1-, 2-, or 3-segment ruptures on the San Andreas fault? What is the paleoseismic evidence for multi-segment events on the Hayward-Rodgers Creek fault? Or on the other characterized faults?

Creep or Aseismic Slip

Recent satellite geodetic measurements suggest that a large part of segment HN may be creeping aseismically throughout the seismogenic zone. If true, the absence of locked patches would imply a diminished accumulation of elastic strain energy on this segment and a smaller likelihood that large earthquakes could nucleate there. Even if HN were freely creeping, however, locked patches to north and south could significantly retard slip on HN over the geologic rate, leading to substantial unreleased moment on that segment. Thus, even if failure of segment HN by itself were unlikely, HN might well rupture coseismically when earthquakes occurred on the segments to north or south in order to erase its slip deficit. Paleoseismic trenching of the HN segment at El Cerrito suggests that there have been at least four (and maybe seven or more) surface rupturing events in the past 2200 years, the last occurring between 1640 and 1776. Waldhauser and Ellsworth (2002) have inferred a locked patch on the HN segment based on the distribution of carefully located repeating earthquakes. It seems clear that an accurate assessment of the probability of large earthquakes on the HN segment depends on a much better understanding than we presently have of its creep behavior at depth and its reaction to earthquakes on adjacent segments.

How extensive is aseismic slip on SFBR faults at seismogenic depths? In particular, we need more and better GPS and INSAR data to resolve the extent to which creep is occurring at depth and the partition of slip on the different, closely spaced faults in the region. Is HN creeping at all depths? Or, is there sufficient accumulation of strain at depth on HN to generate **M** ≥6.7 earthquakes?

Coefficient of Variation

The variation of recurrence intervals of earthquakes on a fault segment is accounted for in the SFBR through the coefficient of variation α. The uncertainty in α is an important source of uncertainty in our 30-year probabilities. Further evaluation of the appropriate range of α will be important to future working groups. What α should be used for segments like SAP that rupture alone and also as components of multi-segment ruptures? What data should be used to constrain α in these cases? How relevant are repeating sequences of small earthquakes on creeping segments to the behavior of large earthquakes on locked segments? Should α be estimated from SFBR data only, or should future working groups consider evidence from recurring earthquakes in other tectonic environments?

Fault Interactions

The stress shadow of the 1906 earthquake and uncertainty about its effects in the 2002-2031 period has been discussed at length in this report. We considered several probability models to represent the 1906 effects because no model available to us was completely satisfactory. In fact, WG02's recognition of the lack of any adequate model has stimulated the development of viscoelastic and rate-and-state models that promise to better represent the effects of the 1906 earthquake on future earthquake activity in the SFBR. A suite of such models needs to be developed, evaluated and made available for use by the next working group. In the following section we discuss the state—and promise—of modeling efforts already underway.

The available data on post-seismic quienscence are tantalizing, but questions on their proper interpretation abound. For example, analyses of SFBR seismicity reveal regional quiescence of shorter duration followed the **M**6.8 earthquake in 1868, the **M**6.9 earthquake in 1989, and perhaps the **M**6.8 earthquake in 1838. Are there good analogs of these observations in other regions of the world? What do these quiescences tell us about the nature of stress shadows in general? Did the seismic quiescence after 1906 extend to smaller **M**? What is the relationship between spatial extent and duration of the quiescence and magnitude? Are the developing viscoelastic and rate-and state models discussed below consistent with these observations? The answers to these questions will bear directly on the uncertainties in future assessments of SFBR earthquake sources.

Modeling fault interactions in a viscoelastic earth

Deep post-earthquake afterslip and viscoelastic relaxation of the lower crust and upper mantle may act to redistribute stress into the seismogenic crust over time. Stress transfer within the elastic crust is static and immediate, whereas stress transferred by a large earthquake into the higher-temperature lower crust and upper mantle is likely time dependent because strain occurs at depth by viscoelastic flow iresponse to a sudden stress change. Deep post-seismic stress readjustment may impact the seismogenic crust, and act to modify the coseismic static stress change. This process is known as stress diffusion, and appears to occur rapidly relative to the seismic cycle. For example, stress diffusion models were fit to geodetic measurements made after the 1999 **M**7.1 Hector Mine, California and 1999 **M**7.4 Izmit, Turkey earthquakes. Stress diffusion models have seen some success in explaining the Landers - Hector Mine earthquake pair, especially the 7-year delay between the two events.

Post-1906 stress diffusion in the SFBR has been calculated using various finite-element (e.g., Kenner and Segall, 1999; Parsons, 2002a) and semi-analytic techniques (Pollitz, 2001), with all three studies predicting the effect of viscoelastic relaxation on the erosion rate and length of the 1906 stress shadow. The viscoelastic models generally predict lengthening of the 1906 stress shadow on faults sufficiently distant from the SAF. A comparison of the calculated post-1906 effects on the Hayward fault shows similar stress-shadow durations of 30-130 years (Kenner and Segall, 1999), 30-90 years (Pollitz, written comm.), and 37-74 years (Parsons, 2002a), depending on parameter choices and assumed deep fault geometry. If longer stress shadow durations are incorporated in probability calculations, then slightly lower probability values result. However, models that allow for a weak and mobile mantle produce a shortening of the 1906 stress shadow on faults located between the Calaveras and San Andreas faults. In addition, the viscoelastic models generally predict relatively faster reloading of the San Andreas fault itself. In both these cases, again depending on model parameters, the impact of viscoelastic relaxation would be to increase probability values on these faults.

Tectonic stressing rates must be calculated to estimate the duration of a stress shadow and to make clock-change estimates. Fault-stressing rates calculated with a finite element model were evaluated against numbers calculated using deep dislocation slip by Parsons (2002a). In the viscoelastic finite element model, tectonic stressing is distributed throughout the crust and upper mantle. In contrast, tectonic loading calculated with dislocations focuses nearly all plate-boundary stress on faults, and comparably little in the surrounding crust. Thus calculation of tectonic stressing rates is model dependent, and higher rates are found on most Bay area faults with elastic dislocation models. Higher stressing rates cause shorter stress-shadow durations and slightly higher calculated earthquake probability.

So far, earthquake interactions have been viewed as 1) static stress changes that, when divided by the tectonic stressing rate, yield clock changes; 2) changes in state of the BPT model; or 3) coseismic static stress changes modified by time-dependent post-seismic stress changes. In addition to these possibilities, laboratory studies of rock friction show complex time- and rate-dependent elastic behavior known as rate-and-state friction (e.g., Dieterich, 1978). A prediction emerges from rate-and-state theory that, following a sudden stress change, earthquake rates on affected faults change suddenly, and then obey an Omori-law return to background rates (Dieterich, 1994). If rate-and-state-dependent friction occurs in the Earth, then earthquake interactions should cause predictable rate changes that can be folded into probability calculations.

Dieterich and Kilgore (1996) formulated a method for incorporating rate-and-state transient functions into earthquake probability calculations. Studies show that globally, earthquake interactions cause marked **M**≥4.5 earthquake rate increases followed by exponential decay with time. The technique has been used to calculate interaction earthquake probabilities in the Kobe, Japan region, in Turkey, and in the San Francisco Bay region.

Modeling and laboratory studies in combination with post-earthquake deformation and seismicity rate data should yield improvement in earthquake probability calculations where interactions from past large earthquakes are important. It will be necessary to gain confidence in model parameters, or at least to narrow the allowable range of values, to limit uncertainties in probability calculations introduced when more complex earthquake interaction calculations are made. In particular, advances in the rheologic character of the lithosphere, the deep configuration of faults, and rate/state parameters are needed.