The Loma Prieta, California, Earthquake of October 17, 1989—Forecasts

By RUTH A. HARRIS

EARTHQUAKE OCCURRENCE
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PREFACE

There was a time when the weather belonged to the gods. Storms and drought were inflicted on man in punishment or for vengeance, man strove to avert them by sacrifice or prayer, and the priest was his intercessor. Now the weather belongs to nature, and the priestly robe has fallen on the Weather Bureau. Man's new agent, however, is not an intercessor; he does nothing to placate; he makes no attempt to control the source of nature; but inspired by science he foretells the coming changes so that his lay client may take warning and be prepared. The crops are harvested before the rain, the herds escape from the lowland before the flood, the ships reach harbor before the gale; and man chants a hymn of praise to science.

There was a time when the earthquake was equally enveloped in mystery, and was forecast in the enigmatic phrases of the astrologer and oracle; and now that it too has passed from the shadow of the occult to the light of knowledge, the people of the civilized earth—the lay clients of the seismologist—would be glad to know whether the time has yet come for a scientific forecast of the impending tremor. The outlook for earthquake-forecasting is my theme to-day.

—From G.K. Gilbert, "Earthquake Forecasts," Science, new series, v. 29, no. 734 (Jan. 22, 1909), p. 121

THE LOMA PRIETA, CALIFORNIA, EARTHQUAKE OF OCTOBER 17, 1989: EARTHQUAKE OCCURRENCE

FORECASTS

By Ruth A. Harris

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ABSTRACT

The magnitude (M_w) 6.9 Loma Prieta earthquake struck the San Francisco Bay region of central California at 5:04 p.m. P.d.t. on October 17, 1989, killing 62 people and generating billions of dollars in property damage. Scientists were not surprised by the occurrence of a destructive earthquake in this region and had, in fact, been attempting to forecast the location of the next large earthquake in the San Francisco Bay region for decades. This paper summarizes more than 20 scientifically based forecasts made before the 1989 Loma Prieta earthquake for a large earthquake that might occur in the Loma Prieta area. The forecasts geographically closest to the actual earthquake primarily consisted of right-lateral strike-slip motion on the San Andreas fault northwest of San Juan Bautista. Several of the forecasts did encompass the magnitude of the actual earthquake, and at least one approximately encompassed the along-strike rupture length. The 1989 Loma Prieta earthquake differed from most of the forecasted events in two ways: (1) it occurred with considerable dip-slip in addition to strike-slip motion, and (2) it was much deeper than expected.

INTRODUCTION

Was the 1989 Loma Prieta earthquake (fig. 1) a predicted event? Was it an expected or anticipated event? Was it formally forecasted, and, if so, how well, in what sense, and by whom? The answers to these question, as detailed below, show that this earthquake had been forecasted by many groups, in varying ways and with varying degrees of success and accuracy, during the eight decades that preceded it. Over this period, our understanding of earthquakes has evolved tremendously and, along with it, our ability to model and forecast some aspects of future earthquake activity. As our understanding of earthquakes has evolved, so have our ideas about how to define an earthquake forecast. A review of the published forecasts of the 1989 Loma Prieta earthquake makes this evolutionary path clear. Thus, this earthquake is an important milestone along this path whereby we can assess the progress, note the successes and failures, and speculate on the future of earthquake forecasting.

An earthquake forecast is defined as a statement that an earthquake is expected to occur within a period of a few years to a few decades (Wallace and others, 1984). Scientifically based earthquake forecasting is not new to our lifetimes; instead, evidence points to earlier roots. In the late 19th century, the great earth scientist Grove Karl Gilbert (1843–1918) forecast where the next large earthquake would strike the Wasatch Front (Utah) and the east side of the Sierra Nevada (California) (Gilbert, 1884). In 1909, he delivered a lecture entitled "Earthquake Forecasts" as his presidential address to the American Association of Geographers (Gilbert, 1909). His lecture, published in the journal *Science*, encompassed the specific details required for a successful forecast, the importance of local ground conditions (site effects) for assessing damage potential, and the insurance rates for an earthquake-prone region. Gilbert (1909, p. 133) declared that it was not difficult to predict the locations of future damaging earthquakes but that the timing of these events was still an enigma:

In a word the determination of danger districts and danger spots belongs to the past, the present and the near future; the determination of times of danger belongs to the indefinite future. The one lies largely within the domain of accomplishment; the other still lingers in that of endeavor and hope...

We may congratulate ourselves that it is not the place factor which lags behind, for knowledge of place has far more practical value than knowledge of time. In fact I see little practical value in any quality of time precision attainable along lines of achievement now seen to be open...Or suppose that prelude phenomena should be found to afford real warning; the forecaster on duty would still have to deal in probabilities, and when in doubt would often sound vain warnings, in the conscientious effort to escape the greater error of omission at the critical time—

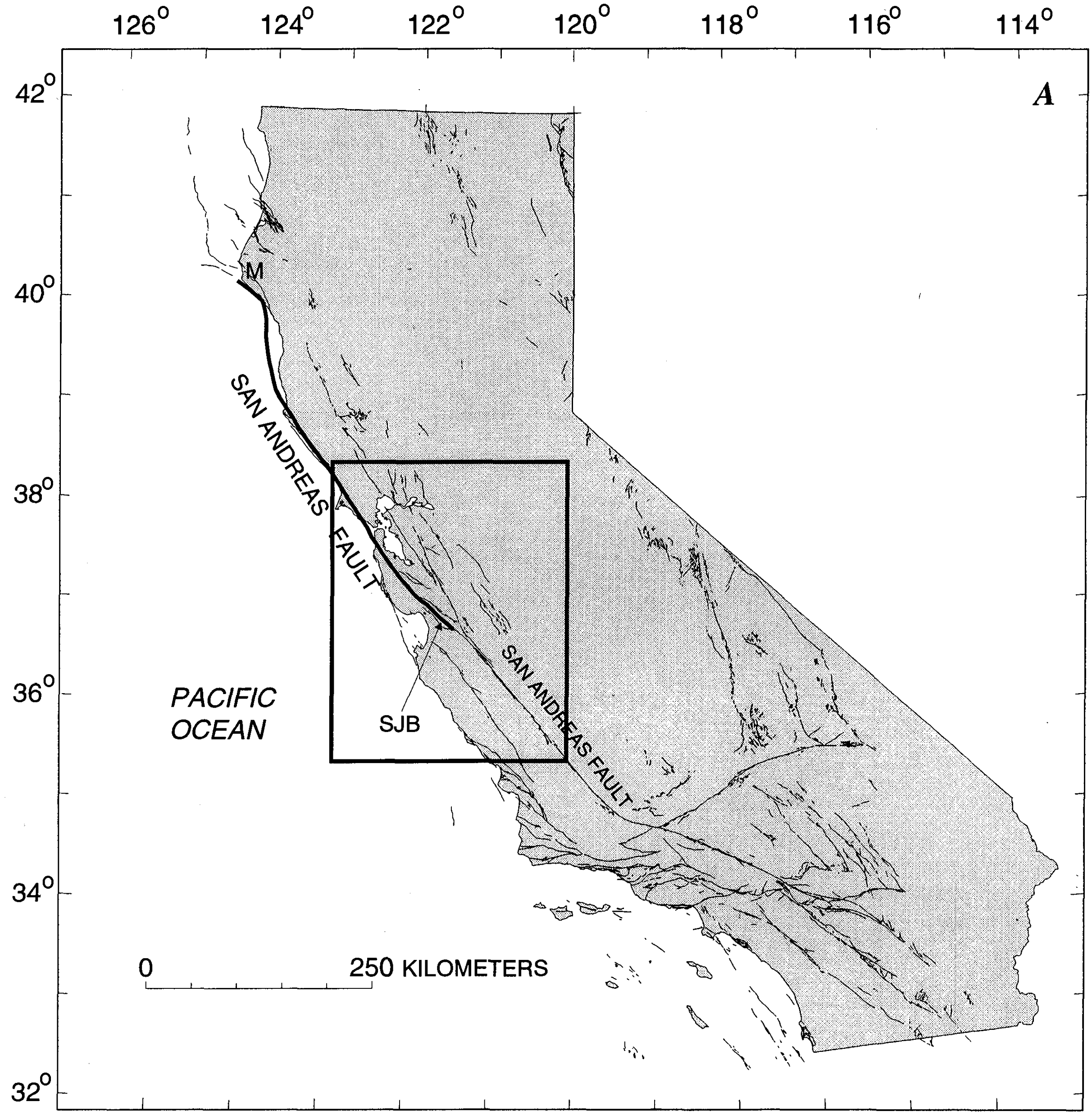
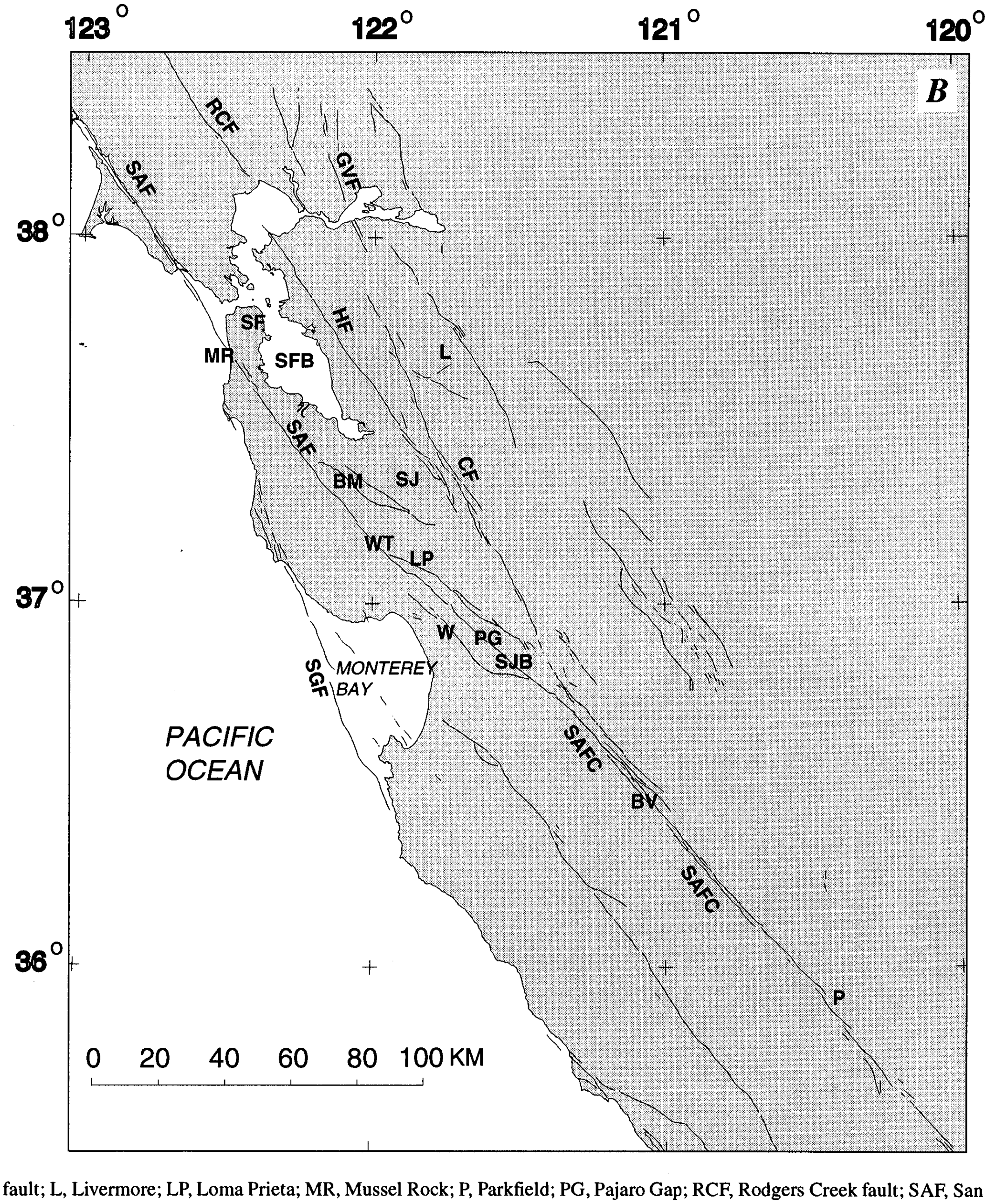


Figure 1.—Active faults in California and the San Francisco Bay region. *A*, Active faults in California (from Jennings, 1992). Box outlines area of figure 1*B*. North half of the San Andreas fault (heavy line; from Thatcher and others, 1997) broke in the great 1906 San Francisco earthquake from Cape Mendocino (M) to Juan Bautista (SJB) (Ellsworth and others, 1981). *B*, Active faults in the San Francisco Bay region and southeast (from Jennings, 1992). BM, Black Mountain; BV, Bear Valley; CF, Calaveras fault; GVF, Green Valley fault; HF, Hayward

and again nervous strain would be wasted. And even if warning were definite, timely and infallible, so that peril of life could be altogether avoided, property peril would still remain unless construction had been earthquake-proof. If, on the other hand, the places of peril are definitely known, even though the dates are indefinite, wise construction will take all necessary precautions, and the earthquake-proof house not only will insure itself but will practically insure its inmates.

During the 88 years since Gilbert's (1909) paper, numerous earthquake forecasts have been made for earthquake-prone regions around the world. These forecasts commonly are hotly debated. Earthquake prediction remains a topic of intense discussion (for example, Sykes, 1996; Geller, 1997; Geller and others, 1997; Scholz, 1997) as we enter the closing years of the 20th century.

In the following sections, I review 18 studies published between 1910 and 1989 that variously offer or relate to scientific forecasts of the 1989 Loma Prieta earthquake. I attempt to reconstruct what some scientists were writing and saying before the earthquake, to review what data they relied upon and what assumptions they made, and to compare the various forecasts with what actually occurred during the earth-



fault; L, Livermore; LP, Loma Prieta; MR, Mussel Rock; P, Parkfield; PG, Pajaro Gap; RCF, Rodgers Creek fault; SAF, San Andreas fault; SAFC, creeping section of the San Andreas fault; SFB, San Francisco Bay; SGF, San Gregorio fault; SJ, San Jose; SJB, San Juan Bautista; W, Watsonville; WT, Wrights Tunnel. The Maacama fault is north of the RCF.

Table 1.—*Summary of pre-1989 forecasts for large earthquakes in the Loma Prieta area*
[SAF, San Andreas fault; SJB, San Juan Bautista]

Reference	Location	Magnitude ($\underline{M}$)	Probability (percent)	Time period	Notes
Reid (1910)	SAF	Important event	---	---	--
Willis (1923b, 1924)	San Francisco Bay region, Monterey County and southern part of Santa Clara County	Severe earthquake	3.3	Annual	1
			---	---	2
Tocher (1959)	San Francisco Bay area	Large event	---	0-100 years	--
Thenhaus and others (1980)	SAF	$6.4 \leq \underline{M}_S \leq 7.0$	4	Annual	--
		$7.0 \leq \underline{M}_S \leq 7.6$	1.5	Annual	3
		$7.6 \leq \underline{M}_S \leq 8.2$	0.57	Annual	--
Ellsworth and others (1981)	SAF: Peninsula segment	Large event	---	---	--
U.S. Geological Survey (1981)	SAF: Entire 1906 rupture	8.3	1	Annual	--
Moths and others (1981)	SAF: Pajaro Gap and NW. (fig. 2)	6+	---	---	4
Lindh and others (1982a, b)	SAF: Pajaro Gap and 40 km NW. (40 km long)	6+	---	---	4
Lindh (1983)	SAF: Peninsula segment	7	5-14 (5)	1982-2002	3,5
	SAF: San Juan Bautista segment (~ 40-45 km long) (fig. 2)	6.5	30-64 (30)	1982-2002	4,5
Sykes and Nishenko (1984)	SAF: San Francisco to San Jose	---	0.6-8 (2)	1983-2003	6
	SAF: San Jose to SJB (75 km) (fig. 3)	$\underline{M}_W$=7.0	19-95 (71)	1983-2003	3,6
Scholz (1985)	SAF: Black Mountain to SJB (75 km) (fig. 3)	$\underline{M}_S$=6.9	---	---	3,7
Keilis-Borok and others (1986b)	7 x9 degree rectangle centered at 37.5 deg. N., -119.5 deg. E. (fig. 4)	≥7.5	---	Jan. 84-Dec. 88	--
Thatcher and Lisowski (1987)	SAF: SJB and NW. (90 km long)	7	6	1986-2006	3
	SAF: SJB and NW. (45 km long)	6.5	---	---	4
	SAF: SJB and NW. (30 km long) (fig. 6)	---	---	---	--
Wesson and Nicholson (1988)	SAF: Northwest of creeping section, near SJB, Watsonville, and Corralitos (NW. of SJB) (fig. 7)	≥5.7	33	1987-1996	3,8

Table 1.—*Summary of pre-1989 forecasts for large earthquakes in the Loma Prieta area*—Continued

Reference	Location	Magnitude (M)	Probability (percent)	Time period	Notes
Keilis-Borok (in Updike, 1989)	3.8°-radius circle centered at lat 37.5° N., long 119.5°W.	≥7.5	---	until Dec. 91	--
	2.5°-radius circle centered at lat 38° N., long 122° W.	≥7	---	Jul. 84-Jul. 89	--
	2.5°-radius circle centered at lat 36° N., long 120° W. (fig. 5)	≥7	---	Jan. 85-Jan. 90	3
Lindh (1988)	SAF: San Francisco Peninsula segment	7	7.7	1987-2007	3
	SAF: Loma Prieta segment (~ 40-45 km long)	≤6.5	32	1987-2007	4
Working Group on California Earthquake Probabilities (1988)	SAF: Southern Santa Cruz Mountains segment (35 km long)	6.5	30	1988-2018	4
	SAF - SJB and NW. (90 km long) (fig. 8)	7	20	1988-2018	3
James Davis (unpub. data, 1988); California Office of Emergency Services (1988; 1989)	SAF: Santa Cruz Mountains segment (fig. 9)	6-6.5	6	5 days after each M5 event	--

1. Business-insurance risk given as an average of one severe shock in 30 years.
2. Business-insurance risk given as 30 years between groups of severe shocks, with the last "group" ending in 1906.
3. Magnitude of forecast approximately correct.
4. Rupture length of forecast approximately correct.
5. Value in parentheses is the preferred value.
6. Value in parentheses is based on repeat times derived from the historical/prehistoric record.
7. Stated that the probability was the same as that of Lindh (1983) and Sykes and Nishenko (1984).
8. Defined region where an M≥5.7 earthquake might initiate (nucleate).

quake. These forecasts vary widely, ranging from vague to specific, and many of them address only one or a few aspects of an anticipated event while saying nothing about other aspects. Because of these disparities, it is neither possible nor desirable to try to "rate" their comparative success on the basis of the occurrence of the 1989 Loma Prieta earthquake. Instead, I present these reviews to document the early evolution of earthquake forecasting in central California, to highlight what worked and what didn't in these early forecasting attempts, and to infer insights about possible future directions for predictive studies.

THE FORECASTS

Certain ideas that prevailed in the decades before the 1989 Loma Prieta earthquake led some scientists to make detailed forecasts for earthquakes on specific faults, and others to speculate more generally about the possible time frames and fault regions of future earthquakes. One study could even be considered an "anti-forecast," in that it stated where a large earthquake would be highly unlikely to occur during a specific time period. The studies reviewed in this section are listed in order of their publication date. My main purpose here is to present as objectively as possible what was thought and recorded *before* the 1989 Loma Prieta earthquake. Therefore, I include only documented information predating October 17, 1989. Relevant parameters of the various forecasts are summarized in table 1.

REID

The great 1906 San Francisco earthquake ruptured more than 400 km of the San Andreas fault in central and northern California, from San Juan Bautista to Cape Mendocino (fig. 1; Ellsworth and others, 1981; Thatcher and others, 1997). Earthquake forecasting in the San Francisco Bay region came of scientific age shortly thereafter with Gilbert's (1909) paper and Harry Fielding Reid's (1859–1944) short section entitled "The Prediction of Earthquakes" in Lawson's (1908) comprehensive report on the 1906 earthquake (Reid, 1910). Reid, a scientist at the Johns Hopkins University, was quite optimistic that future earthquakes could be predicted; he had just witnessed the clean signature of the 1906 earthquake on geodetic markers at the Earth's surface and used the data to develop his theory of elastic rebound. This pioneering theory, which assumes a simple mechanical model of accumulating elastic strain and sudden slip on faults, still forms a basis for our mechanical understanding of earthquakes today. Reid's observations led him to propose one of the first forecasts of future earthquakes on the San Andreas fault (Reid, 1910, p. 32):

> It seems probable that a very long period will elapse before another important earthquake occurs along that part of the San Andreas rift which broke in 1906; for we have seen that the strains causing the slip were probably accumulating for 100 years. There have been no serious earthquakes reported along this part of the rift, except at its southern extremity, since the country has been occupied by white men, altho strong earthquakes have occurred in neighboring regions. It seems probable that more consistent results might be obtained regarding the periodicity of earthquakes if only the earthquakes occurring at exactly the same place were considered in the series....
>
> It is quite possible, however, for strong earthquakes to occur on neighboring faults after short intervals. The ruptures of the Haywards [sic] fault in 1868 and of the San Andreas fault in 1906 are a fair example, tho the interval is rather long....

WILLIS

In 1923 and 1924, Bailey Willis, president of the Seismological Society of America, wrote several papers outlining his thoughts on earthquake risk in California (for example, Willis, 1923b, 1924). Among these papers, Willis (1924), calculated the likelihood of earthquakes in different parts of the State. He divided California into five earthquake provinces, then further subdivided three of these provinces, which he thought to be seismically active, into districts (see Wood, 1916). The districts closest to Loma Prieta included the Bay district, which encompassed San Francisco Bay, and the Monterey-Santa Clara district, which encompassed parts of Monterey and southern Santa Clara Counties and included the towns of Gilroy, Hollister, San Juan Bautista, Salinas, Monterey, and Santa Cruz.

Willis (1924) examined the historical record of earthquakes in these two districts from 1850 to 1906. He counted seven earthquakes exceeding intensity VIII for the Bay district (1858, 1865, 1868, 1889, 1892, 1898, 1906) and six earthquakes for the Monterey-Santa Clara district (1865, 1868, 1890, 1897, 1903, 1906). He argued that liability (or damage) is confined to the area immediately surrounding a fault. Therefore, because the aforementioned earthquakes occurred on different faults—for example, in the Bay district, the 1858, 1865, and 1906 earthquakes were on the San Andreas fault or nearby minor faults, the 1868 and 1898 earthquakes were on the Hayward fault, and the 1889 and 1892 earthquakes were on another fault—the calculated risk should not simply be seven shocks in 56 years. Instead, he proposed that the local risk should be one shock in 30 years, at least for business-insurance purposes. He added the suggestion that the 1906 earthquake had lengthened the interval of time to more than 30 years.

Willis (1924) also calculated the insurance risk of an earthquake in the Monterey-Santa Clara district. For this district, he assigned a 30-year interval between (groups of) severe earthquakes. He obtained this number from two observations. First, there had been 18 years (1906–24) of relative quiescence since the 1906 earthquake. Second, excluding the 1890 earthquake, which he stated was just a local event, widely felt earthquakes had occurred in 1865, 1868, and 1897. He used this collection of late-19th-century earthquakes to arrive at 29 years between 1868 and 1897. He then proposed that more damaging earthquakes would occur 10 years in the future (from the time of his writing in 1924).

TOCHER

Three decades after Willis' 1923 and 1924 papers, Don Tocher, then a seismologist at the University of California, Berkeley, studied the moderate (M=5.3) 1957 San Francisco earthquake, which damaged buildings in the San Francisco Bay region, and commented on its relation to the pattern of seismicity on regional faults (Tocher, 1959). The two earthquakes of greatest energy release since 1850 (the beginning of the reliable historical record) were the 1868 earthquake on the Hayward fault and the 1906 earthquake on the San Andreas fault (Tocher, 1959). He noted the following pattern: In the 18 years up to and including 1868, 12 "strong" earthquakes had occurred, whereas in the 13 years after 1868 (1869–81), no "strong" earthquakes had occurred. Then, in the 25 years up to and including 1906, 26 "strong" earthquakes had occurred, whereas in the 47 years after 1906 (1907–53), only 10 "strong" earthquakes had occurred. Given this catalog of strong earthquakes in the San Francisco Bay region, Tocher suggested that it would be wise to prepare for an upcoming big event anytime the rate of "moderately strong" earthquakes approached one event per year. In the period 1954–57, the rate did approach one event per year, with one strong earthquake in 1954 (M=5.3), two in 1955 (M=5.5, 5.4), and one in 1957 (M=5.3). After the series of events in those 4 years, Tocher (1959, p. 48) wrote: "Whether or not these are the first of a series which will continue for a number of years and culminate in a major shock remains to be seen. The historic record is too short and too uncertain in its details for such a definitive statement; a major earthquake could hit San Francisco before these lines reach the printer, or there might not be such a shock in the next hundred years."

THENHAUS AND OTHERS

By the end of the 1970's, earthquake scientists and engineers were following Gilbert's (1909) advice and were collaborating to produce estimates of the expected damaging ground motion from future large earthquakes. Paul Thenhaus and his colleagues at the U.S. Geological Survey (Thenhaus and others, 1980) produced maps of maximum expected seismic horizontal ground motion for rock sites in coastal and offshore California. To calculate the ground motion, they needed, first, to estimate the potential sources of ground motion, that is, the distribution of moderate to large earthquakes on nearby active faults. They estimated annual occurrence rates of earthquakes for several seismogenic zones, including the San Andreas fault. Potential earthquake sources in the San Francisco Bay region were located in a zone encompassing much of the San Andreas fault, including segments in southern California (their zone 24) and another wider and more easterly zone (their zone 38) that encompassed many known active faults, including the Hayward fault. Thenhaus and others estimated annual earthquake-occurrence rates for various magnitude intervals within each seismogenic zone. Thus, in zone 24, the San Andreas fault, an earthquake of $6.4 \leq M_S \leq 7.0$ was assigned an annual occurrence rate of 0.040 (event/year), an earthquake of $7.0 \leq M_S \leq 7.6$ was assigned an annual occurrence rate of 0.015, and an earthquake of $7.6 \leq M_S \leq 8.2$ was assigned an annual occurrence rate of 0.0057 (table 1). In comparison, in zone 38, an earthquake of $6.4 \leq M_S \leq 7.0$ was assigned an annual occurrence rate of 0.0057, an earthquake of $7.0 \leq M_S \leq 7.6$ was assigned an annual occurrence rate of 0.00165, and an earthquake of $7.6 \leq M_S \leq 8.2$ was assigned an annual occurrence rate of 0.000475.

ELLSWORTH AND OTHERS

By the 1980's, the theory of plate tectonics had become widely accepted by the scientific community. In 1981, William Ellsworth and his coworkers at the U.S. Geological Survey (Ellsworth and others, 1981) reevaluated the temporal pattern of earthquake activity surrounding the great 1906 San Francisco earthquake in light of the accepted scientific theory. In the half-century before the 1906 earthquake, many more strong earthquakes were felt and recorded than in the half-century after this earthquake, leading to an apparent quiescence after 1906. Then, starting in 1955, the rate of $M \geq 5$ earthquakes appeared once again to have increased (Tocher, 1959). Ellsworth and others (1981) commented that this pattern was consistent with the idea of a seismic cycle (Fedotov, 1965; Mogi, 1981), consisting of a great earthquake, followed by a quiet period, followed by an increase in moderate to large events leading up to another great earthquake.

Ellsworth and others (1981) observed that the rate of $M \geq 5$ earthquakes was not yet comparable to the rate just before the 1906 earthquake and concluded that another great (M=8) earthquake was not imminent. They proposed that although the largest (great) event was unlikely to occur soon, slightly smaller, but still large (M=6–7) earthquakes similar to those that preceded the 1906 earthquake were likely to occur in the next 70 years, and they made an approximate forecast about the possible locations of these large events. They proposed as potential sites for these earthquakes the most rapidly slipping faults in the region, including the San Francisco Peninsula segment of the San Andreas fault, and the San Gregorio, Hayward, Calaveras, Rodgers Creek, Maacama, and Green Valley faults (fig. 1*B*).

U.S. GEOLOGICAL SURVEY

After the spectacular and devastating 1980 eruption of Mount St. Helens in Washington State, President Carter called for an immediate assessment of the possible consequences of and preparedness for a major California earthquake. As a result of this directive, earthquake scientists at the U.S. Geological Survey (1981) prepared a report on the potential losses from some scenario earthquakes in populated regions of California. These scenario earthquakes were used to estimate the probable intensities and strong ground motions that could occur. Their report also presented probability estimates for the scenario earthquakes. The postulated events involving the San Francisco Bay region included an M=8.3 event on the northern section of the San Andreas fault (a repeat of the great 1906 San Francisco earthquake) and an M=7.4 earthquake on the Hayward fault. These two scenario earthquakes were each assigned an annual probability of occurrence of 0.01, with a "moderate" probability in the next 20 years (from 1981), according to their report. In comparison, an M=8+ event on the southern section of the San Andreas fault was assigned an annual probability of occurrence of 0.05, with a "high" probability for the next 20 years, and an M=7.0 event on the Rose Canyon fault near San Diego, Calif., was assigned an annual probability of occurrence of 0.0001, with a "very low" probability in the next 20 years.

MOTHS AND OTHERS

In a talk presented at the annual meeting of the American Geophysical Union in San Francisco, Barbara Moths and her colleagues at the U.S. Geological Survey (Moths and others, 1981) estimated the seismogenic potential of the San Andreas fault just north of San Juan Bautista near the southernmost reach of the 1906 San Francisco earthquake (fig. 2). Inferred long-term fault-loading rates were straining the shallow part of the San Andreas fault that was believed to have been locked (was not slipping) since 1906. Recurrence calculations based on slip during the 1906 earthquake appeared to allow for an M=6–6.5 earthquake on the San Andreas fault north of San Juan Bautista. Moths and others compared the seismicity pattern near San Juan Bautista with that of another seismically section of the San Andreas fault near Parkfield, Calif., some 150 km to the south. Parkfield had been the site of five M=5.5–6.0 earthquakes since 1881, most recently in 1966, whereas San Juan Bautista experienced three or four M=6–7 earthquakes during the 19th century. Between these two sections, the San Andreas fault slips freely, producing earthquakes no larger than $M\approx5$. Moths and others noted that both "locked" sections were next to the creeping section of the San Andreas fault and that shallow diffuse microseismicity appeared in the adjacent creeping section, whereas deeper earthquake clusters occurred in the locked sections. On the basis of slip calculations and similarities in the two seismicity patterns, Moths and others made a long-term forecast of an M=6+ event north of San Juan Bautista. They suggested that this event would initiate near Pajaro Gap and rupture into the locked section of the San Andreas fault (fig. 2).

LINDH AND OTHERS

Allan Lindh of the U.S. Geological Survey composed a series of publications on earthquake forecasts for the San Francisco Bay region, starting with simple back-of-the-envelope calculations relating 1906 slip to the cumulative strain on the shallow part of the San Andreas fault since 1906 (Lindh and others, 1982a, b), and combining this information with seismicity pattern recognition. The conclusions were then expanded into probability estimates for some of California's active faults (Lindh, 1983, 1988).

Lindh and others (1982a, b) discussed the seismic potential of the southernmost section of the San Andreas fault that had last ruptured in the great 1906 San Francisco earthquake. This section, which extends just northwestward of San Juan Bautista, was believed to be the site of three or four $M\geq6$ earthquakes in the 110 years before 1906, but it had been quiet since 1906. They proposed that the 19th-century earthquakes could have been accounted for by repeated slip on the 50-km-long section of the fault just northwest of San Juan Bautista. Geodetic triangulation data provided evidence that the strain was accumulating across that zone at a rate equiva-

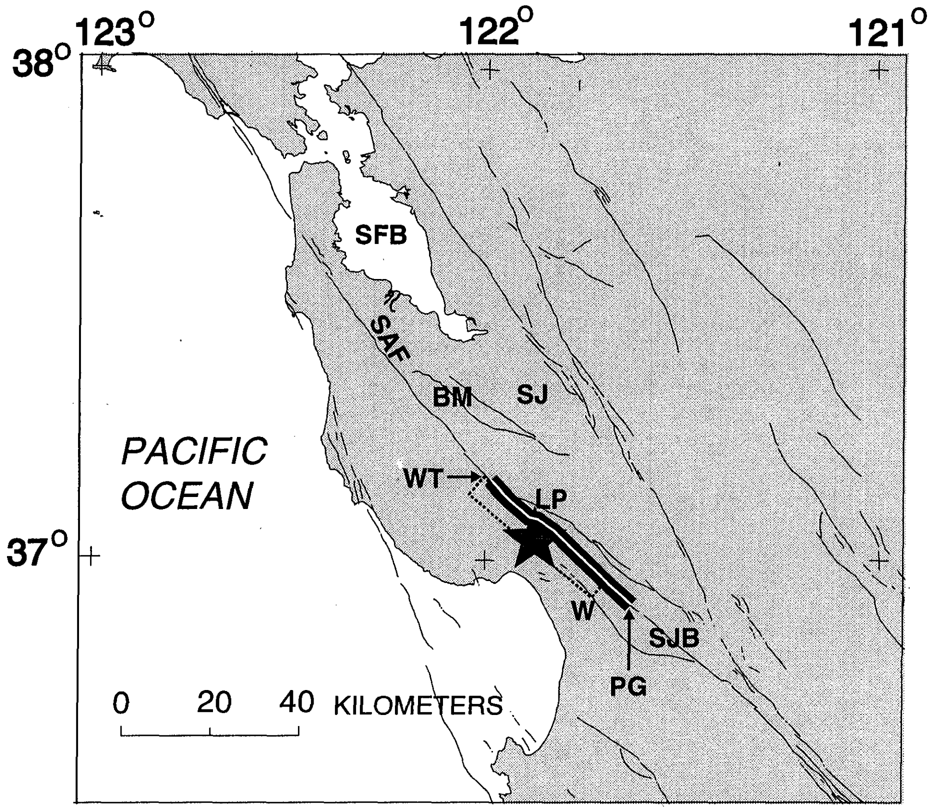


Figure 2.—San Francisco Bay (SFB) region, showing extent of best forecast (heavy double line) by Lindh (1983). Moths and others (1981) also predicted an earthquake starting at Pajaro Gap (PG) and extending northwestward. Northwest limit of rupture was not specified but would have been similar to Lindh's, given Moths and others' forecast that earthquake would be of M=6+. Dotted rectangle shows actual extent of Loma Prieta rupture (horizontal and projected vertical), as inferred by Steidl and Archuleta (1996) and Wald and others (1996). BM, Black Mountain; LP, Loma Prieta; PG, Pajaro Gap; SAF, San Andreas fault; SJ, San Jose; SJB, San Juan Bautista; W, Watsonville; WT, Wrights Tunnel. Star, epicenter of 1989 Loma Prieta earthquake.

lent to 2 cm/yr, given a fault that was also locked interseismically down to 10-km depth (Prescott, 1980). They reasoned that sufficient strain was accumulating to produce an M=6.5 earthquake approximately every 30 years. This interevent timing approximately agreed with what appeared to have occurred during the 19th century.

Lindh and others (1982a, b) estimated that (by 1981) the section of the San Andreas fault northwest of San Juan Bautista had accumulated sufficient strain to reproduce the 1.5 m of slip released there in the great 1906 earthquake. Given this model, they proposed that a large ($M \geq 6$) earthquake could occur in this region at any time.

In addition to these slip-based calculations, Lindh and others (1982a, b) also commented on the seismicity pattern for smaller earthquakes. A sequence of M=4 earthquakes had been occurring since 1979 on the San Andreas fault northwest of San Juan Bautista, after a 40-year-long drought of such events. Microearthquakes associated with these M=4 events highlighted two sections of the San Andreas fault where they postulated future large earthquakes might occur. Like Moths and others' (1981) study, Lindh and others (1982a, b) noted a similarity between the section of the fault northwest of San Juan Bautista and the active, moderate-earthquake-producing section 150 km to the southeast, near Parkfield. Lindh and others (1982a, b) identified two San Andreas fault zones with high seismogenic potential: a 10- to 15-km-long zone between San Juan Bautista and Pajaro Gap, and a 40-km-long zone northwest of Pajaro Gap that they suggested (fig. 2) appeared most likely to produce a large earthquake. They presented a fault cross section with the proposed rupture area outlined (Lindh and others, 1982a, b).

Lindh (1983) estimated the probability of large earthquakes along the San Andreas fault system between the Imperial Valley and Cape Mendocino. His evaluation differed from most other studies of the time in that it attempted to identify where (temporally) a fault segment was in its recurrence cycle and used that information to modify the earthquake probabilities. According to his calculations, recent historical occurrences of large earthquakes could actually decrease the probability estimate.

For his estimates, Lindh (1983) used geologically or geodetically derived estimates of the repeat times of large earthquakes along specific segments of active faults and combined this information with the historical record of when the latest large earthquake occurred on those fault segments. The fault segmentation was assigned on the basis of several criteria, generally the locations of historical earthquakes. All of the results assumed that each fault segment would be most likely to fail in a "characteristic" earthquake. Lindh (1983) assumed that the San Juan Bautista and San Francisco Peninsula segments of the San Andreas fault failed in M=6–7 events, similar to those that occurred during the 19th century.

The statistical model used by Lindh (1983) assumed that earthquake occurrence along a given fault segment could be characterized by a Gaussian distribution with a mean recurrence time and standard deviation, the latter of which he took to be 30 percent of the mean recurrence time. He assigned a probability for future time periods, starting with the date of the latest event. For fault segments where the geologic and geodetic estimates gave much different recurrence intervals, the more conservative value was used, although both values were presented.

Lindh's (1983) results for some San Francisco Bay region faults are as follows. The San Juan Bautista segment of the San Andreas fault was assigned an annual probability (in 1982) of 1.2 to 3.7 percent (1.2 percent was the more conservative value), with a cumulative 10-year probability of 14 to 35 percent (14 percent was the more conservative value) and a cumulative 20-year probability of 30 to 64 percent (30 percent was the more conservative value). The San Francisco Peninsula segment of the San Andreas fault was assigned annual, cumulative 10-year, and cumulative 20-year probabilities of 0.16 to 0.5 percent, 2 to 6 percent, and 5 to 14 percent, respectively (where the more conservative, preferred value was the first one in the range). In summary, Lindh's (1983) evaluation showed the San Juan Bautista segment (fig. 2) of the San Andreas fault with the highest likelihood of an upcoming large earthquake among San Francisco Bay region fault segments.

Although Lindh's (1988) was mostly an update of Lindh's (1983) report, it did assign Lindh's (1983) San Juan Bautista segment a new name, calling it the Loma Prieta segment, after Willis' (1923a) California fault study. Lindh (1988) also stated that probabilities as high as 1.6 percent in 1 year were now applicable to an $M \leq 6.5$ event, an increase over the 1.2 percent quoted in his earlier work, simply because 5.5 years had elapsed (and was therefore added to the interevent period) since the previous calculation.

SYKES AND NISHENKO

Lynn Sykes and Stuart Nishenko of the Lamont-Doherty Geological Observatory (Sykes and Nishenko, 1984) estimated the probabilities of large earthquakes on the San Andreas, San Jacinto, and Imperial faults between 1983 and 2003. They used as inputs to their calculations the time since the latest large earthquake (where known), model estimates for the average recurrence interval, and the standard deviation of the time between earthquakes. They calculated conditional probabilities by using two methods, one based on the estimated repeat times and the other based on the displacement during the latest large earthquake divided by the rate of fault motion. The faults were segmented mostly on the basis of the locations of historical earthquake ruptures but also on the basis of changes in fault strike, changes in the amounts of slip in the previous earthquake (where known), and tectonic complexity.

Looking at the San Andreas fault in the San Francisco Bay region, Sykes and Nishenko (1984) defined a San Francisco Peninsula segment of the San Andreas fault (their zone 3) that extended from San Francisco to San Jose. Estimated repeat times derived from historical or prehistoric earthquakes gave a probability of 2 percent for the period 1983–2003. When they divided the 1906 earthquake slip in this region, 2.5 to 4 m (depending on location along strike of the fault), by the fault-slip rates obtained from geologic and geodetic measurements, they obtained a conditional probability of 0.6 to 8.0 percent for a large earthquake on this segment in the period 1983–2003.

Sykes and Nishenko (1984) defined another segment (fig. 3) of the San Andreas fault that extended from San Jose to San Juan Bautista (their zone 4) and was differentiated from their zone 3 on the basis of a change in the amount of slip during the 1906 earthquake. They used a 1906 coseismic displacement of 0.6 to 1.4 m and the same fault-slip rates as for zone 3 to obtain a recurrence interval of 50 to 115 years. The wide range in this recurrence interval also led to a wide range in conditional probability of 19 to 95 percent for an M_w=7.0 earthquake on this segment in the period 1983–2003. Sykes and Nishenko (1984) determined this conditional probability on the basis of the historical earthquake sequence by noting that this segment may have broken before 1906, in an $M \geq 7$ earthquake in 1838 and in two M=6.0 earthquakes in 1865 and 1890. They suggested that, owing to their size, the 1865 and 1890 earthquakes probably ruptured only part of zone 4. By assuming that the 1838 earthquake ruptured zone 4, they calculated a 68-year repeat time (from 1838 to 1906), which gave a 71-percent probability of an M_w=7.0 earthquake. They mentioned that part of zone 4 could rupture in a moderate earthquake like that in 1865.

Farther south, the segment of the San Andreas fault from San Juan Bautista to Bear Valley (zone 5 of Sykes and Nishenko (1984)) also bears mentioning. Sykes and Nishenko postulated that the aseismic slip in zone 5 is similar to that at Parkfield, which breaks regularly in M=5.5–6 events, and that zone 5 might rupture in conjunction with zone 4 mentioned above, as may have occurred in 1838 (Sykes and Nishenko, 1984).

SCHOLZ

Chris Scholz of the Lamont Doherty Geological Observatory (Scholz, 1985) suggested that changes in fault geometry can control earthquake rupture propagation and discussed how slip during the great 1906 San Francisco earthquake may have been affected in this manner. He observed that the 1906 coseismic slip was greater to the northwest than to the southeast of a 9° bend in the San Andreas fault (on the San Francisco peninsula) near Black Mountain. The 75-km-long section of the fault between Black Mountain and San Juan Bautista (fig. 3) slipped only 1 to 1.4 m, whereas farther northwest on the San Francisco Peninsula the slip was 2.5 to 4 m. By assuming a long-term slip rate of 15±2 mm/yr, Scholz calculated that a rupture of this 75-km-long slip-deficient segment could occur in 60 to 110 years. Using one of his scaling laws (Scholz, 1982), which related slip to rupture length, Scholz (1985) estimated a slip of 0.9 m, which would result in an M_S=6.9 earthquake. The rupture length of Scholz's (1985) forecasted earthquake was 30 km longer than that of Lindh's (1983) and the same as that of Sykes and Nishenko's (1984) forecasted events. Scholz (1985) stated that the 20-year probability estimates were the same as the former studies' because only the rupture length was changed from one of the previous calculations.

KEILIS-BOROK AND OTHERS

Of all of the proposed scientific prediction methods used for forecasting earthquakes in California, the Russian algorithm M8 has perhaps engendered the most protracted dialog. Algorithm M8 (Keilis-Borok and others, 1986b; Keilis-Borok and Kossobokov, 1988) received much attention after its authors, scientists at the Academy of Sciences of the USSR's Institute of Physics of the Earth in Moscow, used it to make forecasts for large to great earthquakes in California during the 1980's. At the Geneva Summit Meeting in 1985, Chairman Gorbachev passed information to President Reagan about forecasts for $M \geq 8.0$ and $M \geq 7.5$ earthquakes in California (Vladimir Kossobokov, written commun., August 1997) within the next 3 years (see app. 3).

Keilis-Borok and others' (1986b) algorithms were designed to diagnose a "time of increased probability" (TIP), using a set of traits described as (1) level of seismic activity, (2) temporal variation of clustering, (3) space-time clustering, (4) concentration in space, and (5) long-range interaction. The two algorithms for the diagnosis of TIP's were an older algorithm called CN, which was designed to predict, and was based on, earthquakes of $M \geq 6.4$ in California and Nevada, and a newer algorithm called M8, which was designed to predict worldwide $M \geq 8$ earthquakes. Keilis-Borok and others (1986a) applied algorithm M8 (and CN) to earthquake catalogs for several regions and claimed success in some of these retrospective tests. Using algorithm M8, Keilis-Borok and others (1986a, table 14) also made a forward-looking earthquake forecast for a part of California and Nevada for an $M \geq 7.5$ earthquake in a 7°-latitude by 9°-longitude rectangle centered at lat 37.5° N., long 119.5° W. (fig. 4). The time interval for the TIP was January 1, 1984, to December 31, 1988. (Keilis-Borok and others, 1986a, lists January 1, 1988, as the end of the TIP, but numerous published correspondences soon after the manuscript's release corrected this date to December 1988, in accordance with their 5-year TIP's for other regions.)

On December 16, 1986, Leon Knopoff of the University of California, Los Angeles, having recently returned from a meeting in Moscow, sent a letter to Lynn Sykes, the chairman of the National Earthquake Prediction Evaluation Council (NEPEC). In his letter (Updike, 1989), Knopoff noted that Keilis-Borok wanted his forecast entered into the lists of earthquake predictions considered by NEPEC. In June 1988, Keilis-Borok had an opportunity to present his research to NEPEC (Updike, 1989, app. A). Keilis-Borok's handouts showed the $M \geq 7.5$ TIP for California extended to July 1, 1992. The geographic area of the TIP was also changed from that shown by Keilis-Borok and others (1986a): Instead of the previous rectangle, it was now a circle, still centered at lat 37.5° N., long 119.5° W., and encompassing much of California and western Nevada.

Keilis-Borok's NEPEC presentation included a figure describing $M \geq 7.0$ forecasts for the Western United States (Keilis-Borok and Kossobokov, 1988; Updike, 1989, app. A) in which two plotted TIP's encompassed the Loma Prieta area. The more northern TIP was a circular region of radius 2.5° centered at lat 38° N., long 122° W. The TIP started in July 1984 and extended through July 1989, and so it did not include the time of the 1989 Loma Prieta earthquake. The more southern TIP was a circle of the same radius centered at lat 36° N., long 120° W. This documented (Updike, 1989, app. A) TIP started in 1985 and ended in 1990, encompassing both the location and date of the 1989 Loma Prieta earthquake (fig. 5).

THATCHER AND LISOWSKI

Wayne Thatcher and Michael Lisowski of the U.S. Geological Survey (Thatcher and Lisowski, 1987) investigated the long-term (≥10 yr) earthquake potential of the San Francisco Peninsula segment of the San Andreas fault (which they defined as the 125-km-long segment southeast of San Francisco, from Mussel Rock to San Juan Bautista; see fig. 1*B*). They addressed the seismic potential of parts of this segment, including the 90-km-long section of the San Andreas fault northwest of San Juan Bautista, in addition to smaller subsections of 30 and 45 km (fig. 6). Much of the 90-km-long fault reach is correlated with the segment discussed by Sykes and Nishenko (1984).

Using geodetic observations made before and after 1906, Thatcher and Lisowski (1987) evaluated the slip that occurred during the great 1906 San Francisco earthquake and compared it with the slip that had not occurred since 1906.

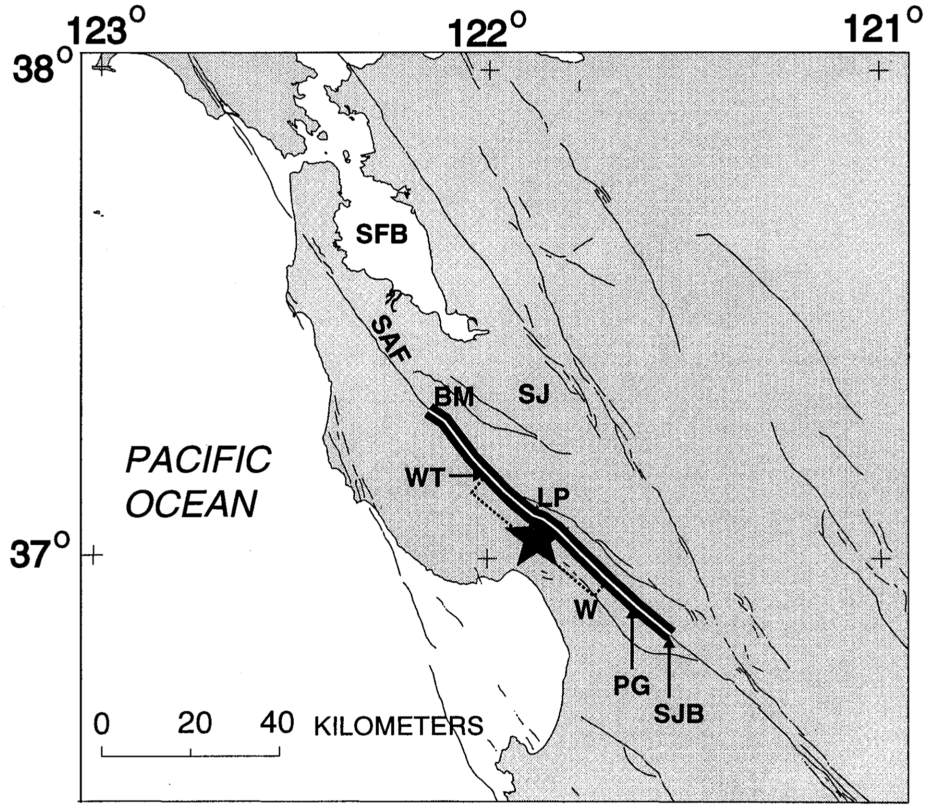


Figure 3.—San Francisco Bay (SFB) region, showing extent of closest forecasts (heavy double line) by Sykes and Nishenko (1984) and Scholz (1985). Dotted rectangle shows actual extent of Loma Prieta rupture (horizontal and projected vertical), as inferred by Steidl and Archuleta (1996) and Wald and others (1996). BM, Black Mountain; LP, Loma Prieta; PG, Pajaro Gap; SAF, San Andreas fault; SJ, San Jose; SJB, San Juan Bautista; W, Watsonville; WT, Wrights Tunnel. Star, epicenter of 1989 Loma Prieta earthquake.

Thatcher and Lisowski's modeled 1906 slip (2.6±0.2 m) differed by a factor of 2 from the 1906 slip (<1.5 m) observed at the Earth's surface. They argued that this discrepancy was due to distributed surface slip, which was not easily observed, and that their geodetically determined value was correct. Assuming 2.6 m for the 1906 coseismic slip and taking the long-term fault-slip rate for this segment of the San Andreas fault to be 15 mm/yr, Thatcher and Lisowski used a time-predictable model of earthquake recurrence (Shimazaki and Nakata, 1980). They concluded that the probability of an $M\approx7$ earthquake on the southern 90 km of the San Francisco Peninsula segment of the San Andreas fault (the 90-km-long section of the San Andreas fault northwest of San Juan Bautista, fig. 6) during the upcoming several decades was quite low. Using the probability methods of Sykes and Nishenko (1984), they estimated a 20-year conditional probability of 6 percent for the period 1986–2006.

Thatcher and Lisowski (1987) also considered two other scenarios: an M=6.5 earthquake on the southernmost 45 km of the 1906 rupture and an event of unspecified magnitude on the southernmost 30 km of the 1906 rupture (fig. 6). They concluded that the geodetic data were insufficient to resolve

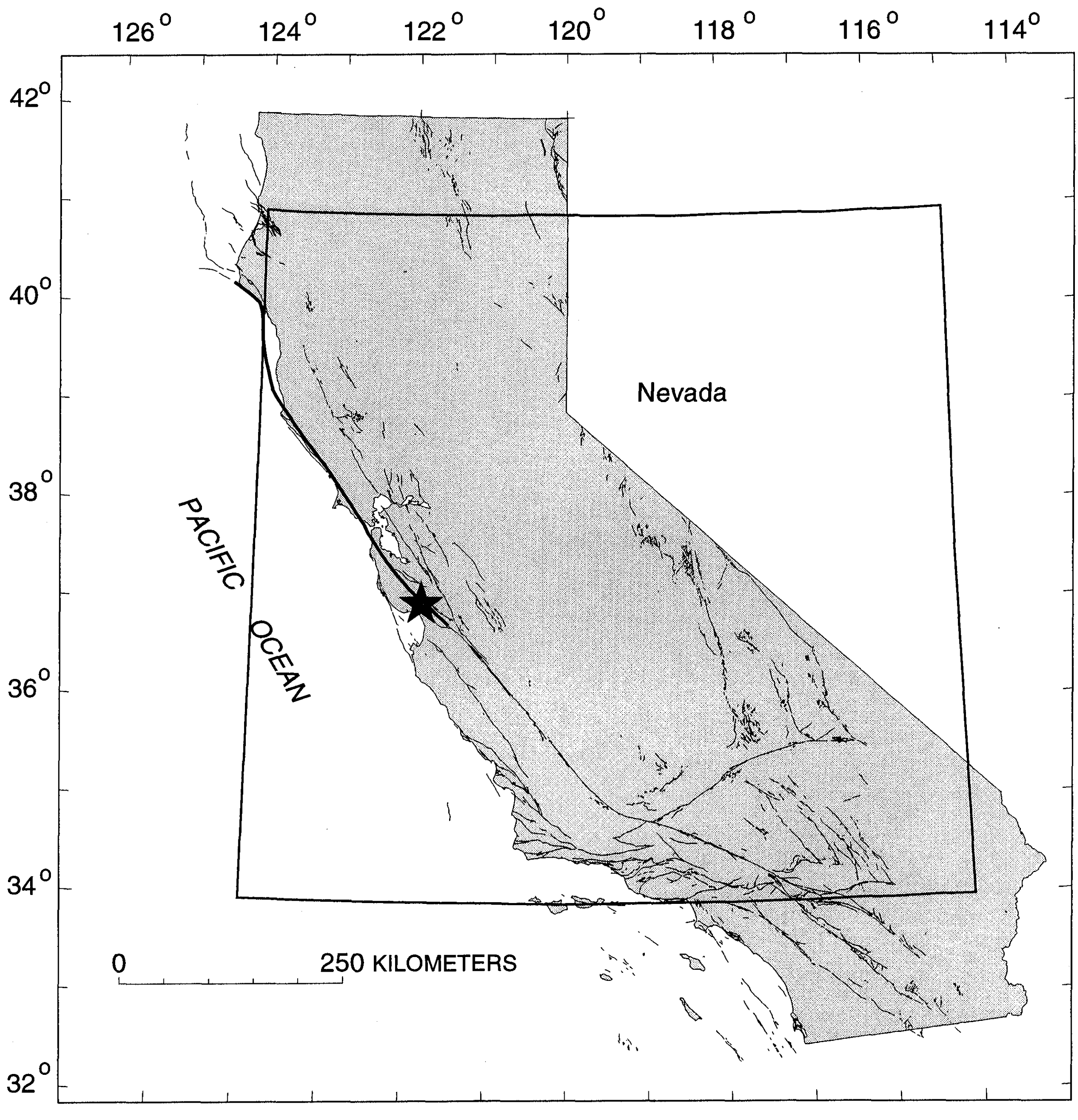


Figure 4.—California, showing 7°-by-9° rectangular area centered at lat 37.5° N., long 119.5° W., in which Keilis-Borok and others (1986a) used algorithm M8 to predict an $M\geq7.5$ earthquake. Star, epicenter of 1989 Loma Prieta earthquake; heavy line, part of the San Andreas fault that ruptured in great 1906 San Francisco earthquake.

the deep 1906 slip for the northern part of the 45-km-long rupture. They also examined the possibility of a 30-km-long rupture just northwest of San Juan Bautista. Their calculations, which assumed 1.2 m of slip in 1906, in combination with a 15-mm/yr long-term fault-slip rate, did permit an upcoming $M\approx6.5$ event, but they declared that Lindh's (1983) 20-year conditional probability of 30 percent was unmerited. Their conclusion was based on 0.5 m of fault offset inferred from an 1890 coseismic measurement of the Pajaro River bridge, 11 km northwest of San Juan Bautista. They believed that the 1890 earthquake already slipped that segment of the San Andreas fault and therefore an imminent event was unlikely.

WESSON AND NICHOLSON

Robert Wesson and Craig Nicholson of the U.S. Geological Survey presented their work at an international conference on intermediate-term earthquake prediction held in California in November 1986. In summarizing their conference presentation, Wesson and Nicholson (1988) combined

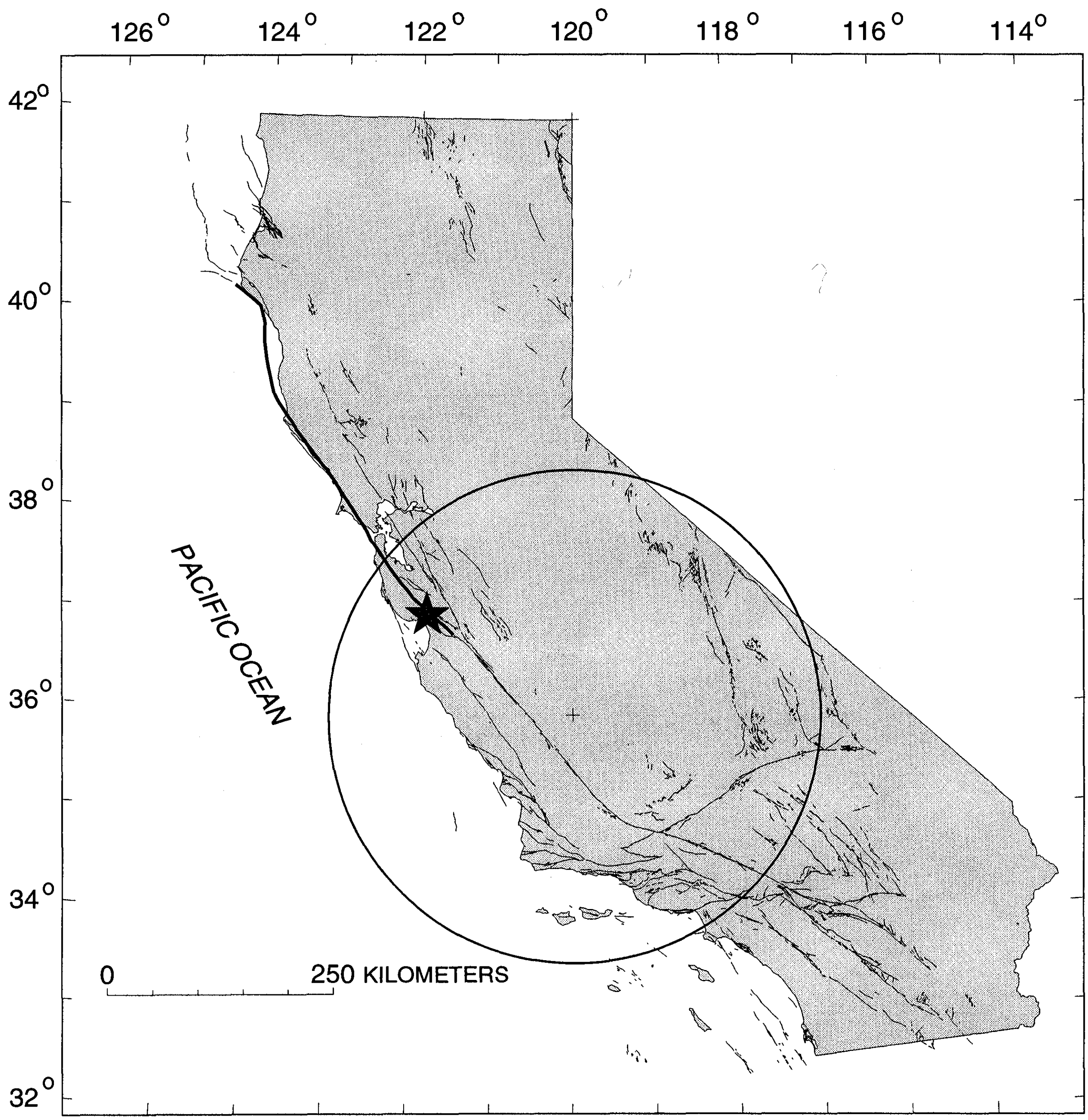


Figure 5.—California, showing 2.5° circular area centered at lat 36° N., long 120° W., in which V.I. Keilis-Borok (in Updike, 1989, app. A) used algorithm M8 to predict an $M\geq7.0$ earthquake. Star, epicenter of 1989 Loma Prieta earthquake; heavy line, part of the San Andreas fault that ruptured in great 1906 San Francisco earthquake.

observations from a decade of California earthquakes with physical arguments about fault behavior and postulated a set of forecast rules that they used to highlight 16 sites in California which they thought had a likelihood of nucleating an $M \geq 5.7$ earthquake during the decade 1987–96:

- A sudden increase in seismic activity in a previously quiet area must be taken seriously as an intermediate-term precursor and should be reflected as a probability gain in assessing the intermediate-term seismic potential of the surrounding area.
- Larger earthquakes in California along faults exhibiting fault creep tend to occur at the ends of creeping sections, or where the creep rate is markedly reduced.
- Large earthquakes tend to occur adjacent to previous large earthquakes, representing either an extension of the rupture, a migration, or perhaps a response (commonly delayed by creep) to static-stress change. Therefore, the occurrence of any significant earthquake increases the intermediate-term probability of future earthquakes on adjacent fault segments and in the surrounding area.
- There is marginal evidence for periods of high regional deformation. Therefore, any evidence for a period of similar high regional deformation (a regional strain event or the occurrence of an earthquake of $M \geq 5.7$) increases the intermediate-term probability of future earthquakes throughout the region.

Using these forecast rules, Wesson and Nicholson (1988) identified 16 sites in California for their earthquake potential. On the basis of their previous experience with the 1975–86 earthquakes, they concluded that about a fourth of the "independent" (excluding aftershocks, and counting only one earthquake in an earthquake sequence) earthquakes in the decade 1987–96 would occur without recognizable intermediate-term precursory phenomena, and that about a third would occur at the ends of creeping fault segments and about a third of their identified sites would be the locations of significant earthquakes in the decade 1987–96. They thus estimated that the probability of occurrence for any one of their forecast sites was about 1/3. Of their 16 sites, 4 were located in the San Francisco Bay region: at the north and south ends of the Hayward fault, on the central Calaveras fault and east of the Calaveras fault south of Livermore Valley, and at the north end of the creeping section of the San Andreas fault near San Juan Bautista (fig. 7).

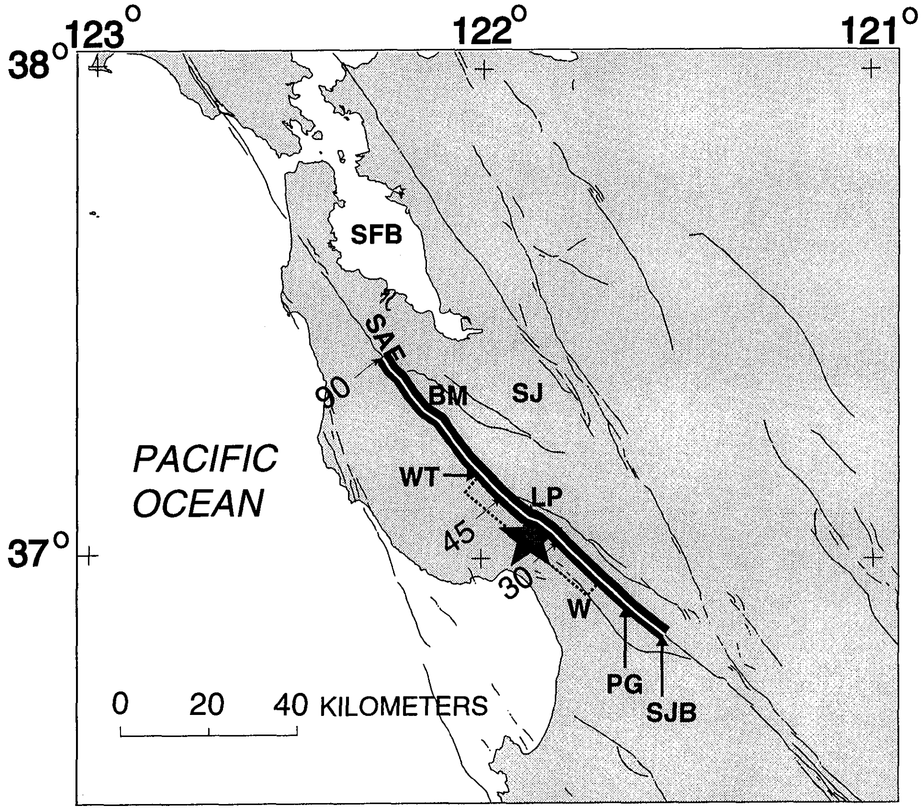


Figure 6.—San Francisco Bay (SFB) region, showing locations of closest forecasts (heavy double line) by Thatcher and Lisowski (1987) for ruptures starting at San Juan Bautista (SJB) and extending 30, 45, and 90 km northwestward. Dotted rectangle shows actual extent of Loma Prieta rupture (horizontal and projected vertical), as inferred by Steidl and Archuleta (1996) and Wald and others (1996). BM, Black Mountain; LP, Loma Prieta; PG, Pajaro Gap; SAF, San Andreas fault; SJ, San Jose; SJB, San Juan Bautista; W, Watsonville; WT, Wrights Tunnel. Star, epicenter of 1989 Loma Prieta earthquake.

WORKING GROUP ON CALIFORNIA EARTHQUAKE PROBABILITIES

In early 1988, the Working Group on California Earthquake Probabilities, consisting of Duncan Agnew (University of California, San Diego); Clarence Allen and Kerry Sieh (California Institute of Technology); Lloyd Cluff (Pacific Gas & Electric Co.); James Dieterich, William Ellsworth, Allan Lindh, David Schwartz, Wayne Thatcher, and Robert Wesson (U.S. Geological Survey); Stuart Nishenko (now U.S. Geological Survey); and R. Keeney (University of Southern California) published a consensus report for NEPEC on the probabilities of large earthquakes on the San Andreas fault system (Working Group on California Earthquake Probabilities, 1988). Their probability estimates were based on a time-dependent model in which the probability increases as a function of time after the latest large earthquake. They estimated the 30-year probability for one or more large earthquakes on any of the fault segments that they evaluated in the San Francisco Bay region at 0.5, the 20-year (1988–2008) probability at 0.3, and the 10-year (1988–98) probability at 0.2. These probability estimates were for an M=7 earthquake, and the faults included in their study were the entire Hayward fault (including a northern and southern segment), the San Francisco Peninsula segment of the San Andreas fault that extends 90 km from Menlo Park to San Juan Bautista (fig. 8), a 30- to 35-km-long section of the San Francisco Peninsula segment called the Southern Santa Cruz Mountains segment just northwest of San Juan Bautista (fig. 8), and the 360-km-long North Coast segment of the San Andreas fault that extends northward from the San Francisco Peninsula segment. The Hayward fault segments were the presumed sites of large earthquakes in 1836 and 1868; the San Andreas fault segments were defined on the basis of the slip believed to have occurred in 1906.

The North Coast segment of the San Andreas fault was assigned the lowest probability of all the San Francisco Bay region fault segments studied. The Working Group on California Earthquake Probabilities (1988) assumed 4.5±1.0 m of slip on this segment in 1906 and estimated its long-term slip rate at 16±2.5 mm/yr. They calculated a probability of less than 0.1 for a large earthquake on this segment in the 30-year period 1988–2018.

The San Francisco Peninsula segment of the San Andreas fault produced much debate among the scientists in the Working Group on California Earthquake Probabilities (1988), cen-

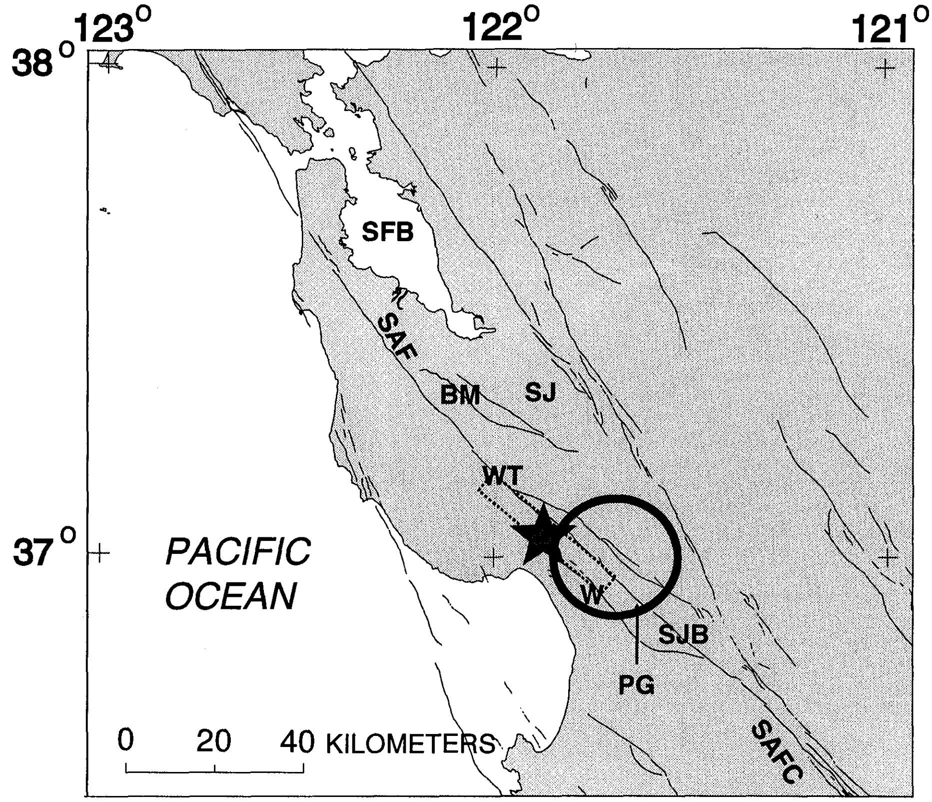


Figure 7.—San Francisco Bay (SFB) region, showing locations of closest forecast (circle) by Wesson and Nicholson (1988) for the initiation point of an $M\geq5.7$ earthquake between 1987 and 1996. Dotted rectangle shows actual extent of Loma Prieta rupture (horizontal and projected vertical), as inferred by Steidl and Archuleta (1996) and Wald and others (1996). BM, Black Mountain; LP, Loma Prieta; PG, Pajaro Gap; SAF, San Andreas fault; SAFC, creeping section of the San Andreas fault; SJ, San Jose; SJB, San Juan Bautista; W, Watsonville; WT, Wrights Tunnel. Star, epicenter of 1989 Loma Prieta earthquake.

tering on the amount of slip during the 1906 earthquake. The amount of slip in the southernmost part of the 1906 rupture was discussed by Lindh (1983), Sykes and Nishenko (1984), Scholz (1985), and Thatcher and Lisowski (1987). The geodetic (Thatcher and Lisowski, 1987) and geologic (Lindh, 1983; Sykes and Nishenko, 1984; Scholz, 1985) 1906 slip estimates for the southernmost part of the San Francisco Peninsula segment differed by a factor of 2. Because the probability estimates depended heavily on this value, the Working Group on California Earthquake Probabilities discussed the ramifications and ultimately assumed a value of 2.6±0.6 m for the 1906 slip, arguing that this value was within two standard deviations of the maximum fault offset (geologic) measurements of less than 1.5 m. A long-term fault-slip rate of 16±2.5 mm/yr was also selected. Geologic and geodetic data gave rates of 8 to 15 mm/yr, but they chose a slightly higher rate to allow for the possibility that the long-term fault-slip rate of 33 mm/yr recorded across the San Andreas fault system 100 km farther south was distributed in the north only along the Hayward, Calaveras, and San Andreas faults. This distribution would have determined a long-term fault-slip rate of 20 mm/yr for the San Andreas fault north of San Juan Bautista.

Assigning a 16±2.5 mm/yr long-term fault-slip rate and 2.6±0.6 m of 1906 slip produced a 30-year probability of 0.2 for the San Francisco Peninsula segment of the San Andreas fault. This was the probability finally adopted by the Working Group on California Earthquake Probabilities (1988). They also noted that reducing the 1906 slip estimate to 1.5±0.5 m raised this probability to 0.4; however, this calculation was not formally adopted for the official publication.

The Working Group on California Earthquake Probabilities (1988) discussed the possibility of a somewhat smaller (M=6.5–7) earthquake rupturing the Southern Santa Cruz Mountains segment of the San Andreas fault (fig. 8). Although they did not want to project high probabilities for this segment on the basis of what they considered to be incomplete information, they did suggest that 1906 slip must decrease southward along this segment, with a value of at least 1.2 m 5 km northwest of San Juan Bautista. They used an average

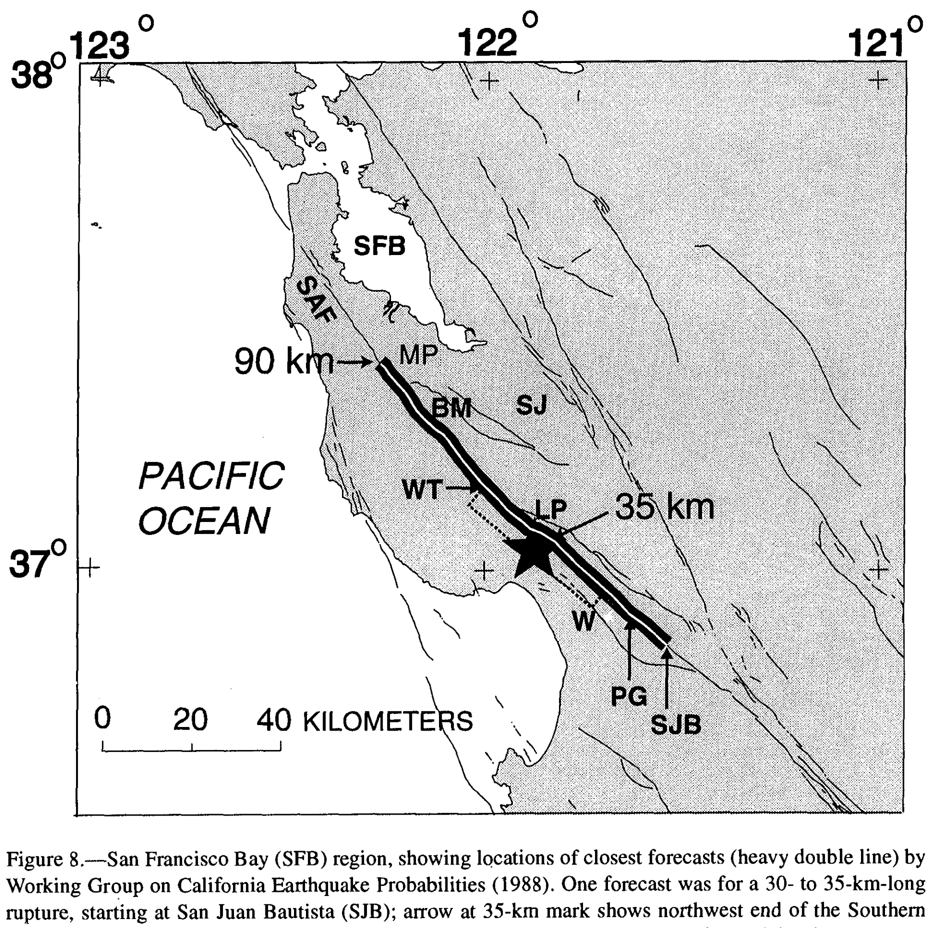


Figure 8.—San Francisco Bay (SFB) region, showing locations of closest forecasts (heavy double line) by Working Group on California Earthquake Probabilities (1988). One forecast was for a 30- to 35-km-long rupture, starting at San Juan Bautista (SJB); arrow at 35-km mark shows northwest end of the Southern Santa Cruz Mountains segment of the San Andreas fault. Another forecast was for a 90-km-long rupture, also starting at SJB, of the entire San Francisco Peninsula segment of the San Andreas fault. Dotted rectangle shows actual extent of Loma Prieta rupture (horizontal and projected vertical), as inferred by Steidl and Archuleta (1996) and Wald and others (1996). BM, Black Mountain; LP, Loma Prieta; MP, Menlo Park, PG, Pajaro Gap; SAF, San Andreas fault; SJ, San Jose; SJB, San Juan Bautista; W, Watsonville; WT, Wrights Tunnel. Star, epicenter of 1989 Loma Prieta earthquake.

value of 2.0±0.5 m for 1906 slip on the Southern Santa Cruz Mountains segment and a long-term fault-slip rate of 16±2.5 mm/yr. They calculated a 30-year probability (1988–2018) of 0.3 for an earthquake on this segment, but they assigned it the lowest level of reliability.

DAVIS (LAKE ELSMAN EARTHQUAKES)

In 1988 and 1989, two M=5 earthquakes occurred in a region proposed by several forecasters to have the potential of producing a large earthquake on the San Andreas fault (fig. 9). These earthquakes were named the "Lake Elsman earthquakes" by the U.S. Geological Survey, and the "Lake Elsman and Lexington Reservoir earthquakes" by the State of California. Given the recent forecast by the Working Group on California Earthquake Probabilities (1988), the State of California decided to take seriously the potential implications of the Lake Elsman earthquakes. For the first time in San Francisco Bay region history, the California Office of Emergency Services issued an official short-term advisory regarding a potential upcoming large earthquake. This advisory assigned a slightly increased likelihood of an M=6.5 event on the Santa Cruz Mountains segment of the San Andreas fault in the next 5 days. Appendix 2 describes the incidents that followed the first M=5 earthquake, as transcribed in a draft report by the California State Geologist James Davis (unpub. data, 1988).

On August 8, 1989, another M=5 Lake Elsman earthquake occurred (fig. 9). The Office of Emergency Services issued another 5-day (short term) advisory similar to that issued in June 1988. Five days later, this advisory also expired.

KERR

In August 1989, Richard Kerr, a writer for *Science* magazine, reported on the relation of the two Lake Elsman earthquakes to the forecasts made by Lindh and others (1982a, b) and Lindh (1983, 1988) for the 45-km-long segment of the San Andreas fault south of Lake Elsman (Kerr, 1989a). He

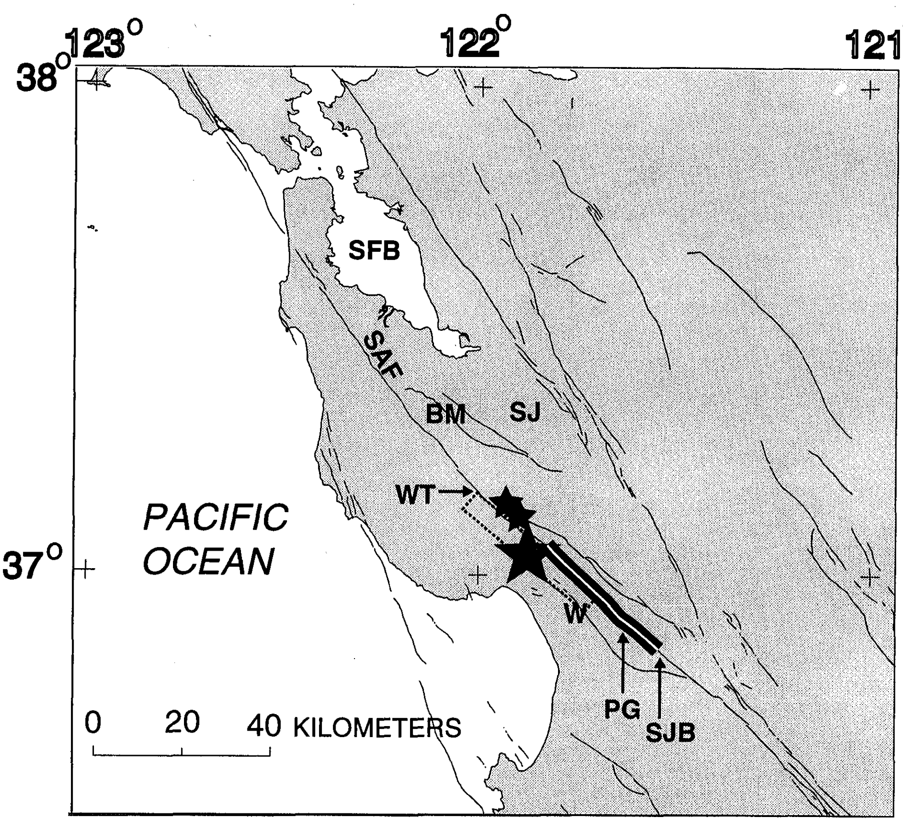


Figure 9.—San Francisco Bay (SFB) region, showing locations of epicenters of 1988 and 1989 Lake Elsman earthquakes (small stars) north of the Southern Santa Cruz Mountains segment of the San Andreas fault (heavy double line; Working Group on California Earthquake Probabilities (1988).). 1988 Lake Elsman earthquake was located at lat 37.13° N., long 121.90° W., at 13.4-km depth; 1989 Lake Elsman earthquake was located at lat 37.14° N., long 121.93° W., at 13.9-km depth (data from Northern California Earthquake Data Center, March 1997). Dotted rectangle shows actual extent of Loma Prieta rupture (horizontal and projected vertical), as inferred by Steidl and Archuleta (1996) and Wald and others (1996). BM, Black Mountain; LP, Loma Prieta; PG, Pajaro Gap; SAF, San Andreas fault; SJ, San Jose; SJB, San Juan Bautista; W, Watsonville; WT, Wrights Tunnel. Large star, epicenter of 1989 Loma Prieta earthquake.

remarked that the Lake Elsman earthquakes were two of the three largest earthquakes since 1914 on the more than 400 km of the San Andreas fault that last broke in 1906. Each Lake Elsman earthquake ruptured an estimated 1-km patch of fault at 14-km depth. The location was right at the end of Lindh's forecasted rupture segment, and he was quoted as saying: "Now we've had two of these magnitude 5's where we didn't have anything. I thought it was a dangerous segment before anything happened; I can only be reinforced in that feeling now" (A.G. Lindh, in Kerr, 1989a). Kerr (1989a) also noted that the 30-percent probability assigned (pre-Lake Elsman) to the Santa Cruz Mountains segment of the San Andreas fault by the Working Group on California Earthquake Probabilities (1988) was, after the Lake Elsman earthquakes, looking a bit low.

THE 1989 LOMA PRIETA EARTHQUAKE

The Loma Prieta earthquake occurred at 5:04 P.d.t. on October 17, 1989, killing 62 people and generating billions of dollars in property damage (Plafker and Galloway, 1989). Although no scientific agreement exists on the exact form of some details of the main shock, many of its features have been generally agreed upon by those who have studied the earthquake. Spudich (1996) summarized the main shock as an M_S=7.1 (M_w=6.9) earthquake that occurred on a fault dipping steeply northwest which was approximately 35 km long (fig. 10). The hypocenter was located at lat 37.036° N., long 121.883° W., at 19-km depth. The slip was mostly confined to depths between 7 and 20 km and was oblique right lateral, with a considerable vertical component. Large amounts of slip concentrated in two regions, located northwest and southeast of the hypocenter. This distribution of slip caused seismic energy to radiate both southeastward and northwestward, thereby lessening the ground-shaking intensity in each direction from that of a unilateral rupture. The northwestern slip region had a considerable reverse component, whereas the southeastern slip region was predominantly strike slip.

Dietz and Ellsworth (1997) analyzed both pre- and post-Loma Prieta seismicity for the 20 years before and a few years after the earthquake. They found that the aftershocks and the main-shock rupture plane were not highlighted by the preceding 20 years of seismicity. Using aftershock patterns, they

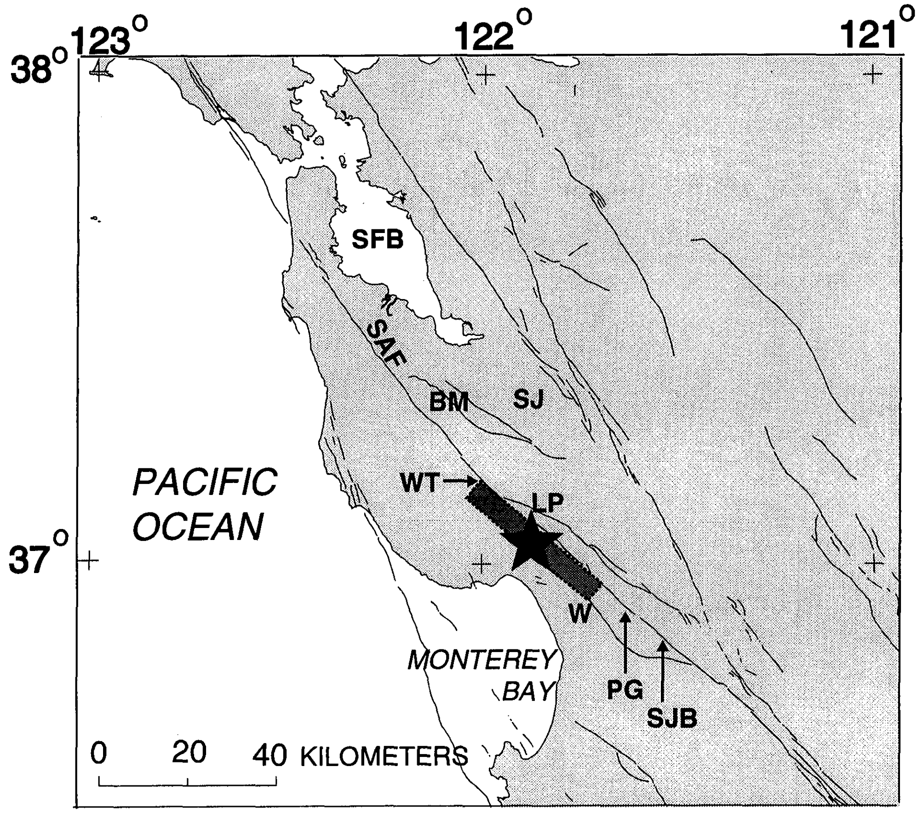


Figure 10.—San Francisco Bay (SFB) region, showing location of epicenter of 1989 Loma Prieta M_w=6.9 (M_S=7.1) earthquake (star). Rupture was approximately 35 km long on a steeply dipping fault and generated both strike-slip and dip-slip motions. Shaded rectangle shows extent of rupture (horizontal and projected vertical), as inferred by Steidl and Archuleta (1996) and Wald and others (1996). BM, Black Mountain; LP, Loma Prieta; PG, Pajaro Gap; SAF, San Andreas fault; SJ, San Jose; SJB, San Juan Bautista; W, Watsonville; WT, Wrights Tunnel.

also showed that the Loma Prieta main-shock rupture plane was distinct from a San Andreas fault which extended vertically from the Earth's surface, at least in the northwestern part of the rupture zone. Southeast of the hypocenter, Dietz and Ellsworth's aftershock locations show the main-shock fault plane merging with the San Andreas fault near Pajaro Gap. These results led them to propose that the Loma Prieta main shock occurred on an ancestral, formerly strike slip section of the San Andreas fault that is now acting as a right-lateral reverse fault.

COMPARISON OF THE FORECASTS WITH THE 1989 LOMA PRIETA EARTHQUAKE

Most pre-1989 forecasts for large earthquakes in the Loma Prieta area and for the entire San Francisco Bay region were for events on the major strike-slip faults. It was assumed (for example, Ellsworth and others, 1981) that these large earthquakes would occur as events which were (apparently) similar to most of the large earthquakes that had already occurred in the late 19th and 20th centuries. Discussions surrounding large earthquakes that might rupture the San Andreas fault had primarily focused on the horizontal strain budget (for example, Reid, 1910; Moths and others, 1981; Lindh and others, 1982a, b; Lindh, 1983, 1988; Sykes and Nishenko, 1984; Scholz, 1985; Thatcher and Lisowski, 1987; Working Group on California Earthquake Probabilities, 1988) and its relation to the slip that occurred during the 1906 earthquake. Many of the forecasts for "large" earthquakes in the San Francisco Bay region also assumed that such an earthquake would rupture the entire plate boundary (Sykes and Nishenko, 1984). Thus, in these two respects, the 1989 Loma Prieta earthquake differed from the forecasts: It was an oblique-slip event on a dipping fault, with both strike-slip and reverse-slip components; and it occurred much deeper than any of the forecasted events, with little, if any, slip on shallow parts of the fault.

The rupture length and magnitude of the 1989 Loma Prieta earthquake differed from those in many of the forecasts. Most of the forecasted events closest geographically to the earthquake involved rupture scenarios for a nearby segment of the San Andreas fault (Reid, 1910; Thenhaus and others, 1980; Ellsworth and others, 1981; U.S. Geological Survey, 1981; Moths and others, 1981; Lindh and others, 1982a, b; Lindh, 1983, 1988; Sykes and Nishenko, 1984; Scholz, 1985; Thatcher and Lisowski, 1987; California Office of Emergency Services, 1988, 1989; James Davis, unpub. data, 1988; Wesson and Nicholson, 1988; Working Group on California Earthquake Probabilities, 1988). The rupture lengths ranged from hundreds of kilometers (U.S. Geological Survey, 1981) to 30–35 km (Working Group on California Earthquake Probabilities, 1988). Of all the forecasted rupture lengths, Lindh's (1983) most closely matched that of the actual earthquake (Sykes, 1996), with the forecasted earthquake extending approximately 40 to 45 km, starting near Pajaro Gap. The magnitude of the earthquake was, however, greatly underestimated by Lindh (1983) and more accurately captured by workers who overestimated the rupture length (Sykes and Nishenko; 1984; Scholz, 1985; Working Group on California Earthquake Probabilities; 1988) and thereby forecasted an M=7 earthquake (Sykes, 1996).

Time-dependent probabilities for the forecasted rupture scenarios were assigned by Thenhaus and others (1980), U.S. Geological Survey (1981), Lindh (1983, updated in 1988), Sykes and Nishenko (1984), Thatcher and Lisowski (1987), California Office of Emergency Services (1988, 1989), James Davis (unpub. data, 1988), Wesson and Nicholson (1988), and Working Group on California Earthquake Probabilities (1988); these probabilities were for times ranging from 5 days and upward (table 1). A few of the forecasts that did encompass the correct geographic region did not include the date of the earthquake; these forecasts included the two 5-day advisories by the State of California (California Office of Emergency Services, 1988, 1989; James Davis, unpub. data, 1988) and at least one of the forecasts using algorithm M8 (V.I. Keilis-Borok, in Updike, 1989).

Some of the forecasts that did encompass the earthquake's date and magnitude were for very large geographic regions. Thenhaus and others (1980) calculated a probability estimate for a range of earthquake magnitudes, including that of the 1989 earthquake, but the source nucleation region was highly uncertain, encompassing hundreds of kilometers of the San Andreas fault. V.I. Keilis-Borok's (in Updike, 1989) $M \geq 7$ forecast, which did not present any probability estimates, was for an even-larger area, encompassing more than 200,000 km^2 (fig. 5).

POST-LOMA PRIETA INFORMATION THAT MIGHT HAVE LED TO DIFFERENT FORECASTS

Some of the debates surrounding the characteristics of the 1989 Loma Prieta earthquake regard its relation to the 1906 earthquake rupture and the San Andreas fault. Several workers have worried that accepting the 1989 earthquake as a forecasted event could lead to an incorrect downweighting of the likelihood of future events on the San Andreas fault (for example, Segall and Lisowski, 1990; Beroza, 1991; Thatcher and others, 1997). Their arguments have primarily been based on the depth of the Loma Prieta slip and on its rake. Other workers have proposed that the 1906 surface slip measurements used to make the forecasts were just plain incorrect and that the adoption of "correct" values would have led to much lower probability assignments for the Loma Prieta area (Thatcher and others, 1997). In an attempt to resolve these controversies, geologists and geophysicists have studied the 1989 Loma Prieta earthquake intensively. Some have compared their results with the data that are still available from the 1906 rupture. The information about 1906 slip in the Loma Prieta area is summarized in table 2.

1906 SLIP MODELS—GEOLOGIC INFORMATION

After the 1989 Loma Prieta earthquake, geologists investigated sites where the effects of both the 1906 and 1989 earthquakes might be accessible (Prentice and Schwartz, 1991; Prentice and Ponti, 1997). One study site was Wrights Tunnel (figs. 1, 2), an abandoned railroad tunnel approximately 50 km northwest of San Juan Bautista that crosses the San Andreas fault in the southern Santa Cruz Mountains. Deformation of Wrights Tunnel during the 1906 earthquake was recorded soon after the great earthquake, and some of this information was used as a basis for constructing several of the forecasts for future events on the San Andreas fault. In preparing their forecasts, Lindh and others (1982a, b), Lindh (1983, 1988), Sykes and Nishenko (1984), and Scholz (1985) all adopted values for the 1906 slip in Wrights Tunnel from the report by Lawson (1908).

After the 1989 Loma Prieta earthquake, Prentice and Schwartz (1991) and Prentice and Ponti (1997) searched the literature for information about Wrights Tunnel and also performed field investigations in the tunnel. In contrast to some previous assumptions about distributed slip across a broad shear zone during the 1906 earthquake (for example, Sarna-Wojcicki and others, 1975; Thatcher and Lisowski, 1987), Prentice and Ponti's study of Wrights Tunnel concluded that 1906 faulting was confined to a zone less than 400 m wide and that 60 to 85 percent of the coseismic slip occurred across a single line. They inferred that at least 1.7 to 1.8 m of 1906 coseismic slip took place across the San Andreas fault in Wrights Tunnel, a value that differs from the 1.4 m assumed by Sykes and Nishenko (1984) and Scholz (1985) and from the 1.5 m assumed by Lindh and others (1982a, b). (Lindh, 1988, assumed 1.5±0.5 m.) Higher 1906 slip values might, conceivably, have decreased the probabilities assigned by those workers.

In another study, Schwartz and others (in press) investigated a site in the Santa Cruz Mountains for evidence of large earthquakes on the San Andreas fault. They found indications of the 1906 surface rupture, as well as a previous surface-rupturing earthquake that they estimated occurred in the mid-1600's. The date (range) on this penultimate earthquake approximately matched the timing of surface-rupturing events inferred at several sites farther north along the

Table 2.—*Published estimates of 1906 coseismic slip on the San Andreas fault in the Loma Prieta area*

Reference	Description	Horizontal slip
Lawson (1908)	Displacement in Wright's Tunnel, as described by G.A. Waring.	5 feet
Lawson (1908)	Displacement in Wright's Tunnel measured by E.P. Carey.	4.5 feet
Lindh and others (1982a, b)	Assumed from Lawson (1908)	1.5 m
Lindh (1983, 1988)	Assumed from Lawson (1908) and Thatcher and Lisowski (1987).	1.5±0.5 m
Sykes and Nishenko (1984)	Assumed from Lawson (1908).	0.6-1.4 m
Scholz (1985)	Assumed from Lawson (1908).	1.4 m
Thatcher and Lisowski (1987)	Inferred from geodetic data	2.6 m
Working Group on California Earthquake Probabilities (1988)	None: assumed value is intermediate between those of Lawson (1908) and Thatcher and Lisowski (1987).	2.0±0.5 m
Segall and Lisowski (1990)	Inferred from geodetic data	2.5±0.4 m
Prentice and Ponti (1997)	Modeling and reevaluation of Wright's Tunnel-data provided by historical documents.	≥1.7-1.8 m
Thatcher and others (1997)	Inferred from geodetic data	2.73±0.35 m

San Andreas fault. Schwartz and others did not find evidence for large surface-rupturing earthquakes between the mid-1600's and 1906.

Sykes and Nishenko (1984) used an earthquake that occurred in 1838 as a "prototype" for their Loma Prieta forecast, and Lindh and others (1982a, b) used an earthquake that occurred in 1865 as a "prototype" for their Loma Prieta forecast. Schwartz and others (in press) did not see evidence in their geologic trenches for either 1838 or 1865 surface rupture, but it is unclear how and whether this new information might have changed either Lindh and others' or Sykes and Nishenko's forecasts, especially that of Lindh and others (1982a, b), who depicted the 1865 earthquake as an event that did not rupture to the Earth's surface.

1906 SLIP MODELS—GEODETIC INFORMATION

After the 1989 Loma Prieta earthquake, Segall and Lisowski (1990) and Thatcher and others (1997) analyzed geodetic data comparing the 1989 and 1906 earthquakes and examined the relation between these two earthquakes. Thatcher and Lisowski (1987) had originally proposed, on the basis of detailed modeling of triangulation data, that the 1906 earthquake in the vicinity of Loma Prieta peak (figs. 1, 2) slipped approximately 2.6 m down to a depth of approximately 10 km. After the 1989 Loma Prieta earthquake, Segall and Lisowski (1990) analyzed the triangulation data available for the 1906 coseismic period and determined that the geodetic station at Loma Prieta peak was displaced slightly more than 1 m parallel to the trace of the San Andreas fault, indicating more than 2 m of strike-slip motion on that part of the fault in 1906. Assuming that fault slip extended from the Earth's surface down to 10-km depth, Segall and Lisowski (1990) calculated a 1906 fault slip of 2.5±0.4 m of strike-slip motion. They observed that in 1989 the Loma Prieta station moved 0.15 m parallel to the San Andreas fault and 0.11 m perpendicular to the fault, markedly different from the 1 m of fault-parallel motion observed for the 1906 earthquake. On the basis of their analysis of the 1989 data, Segall and Lisowski concluded that the 1989 earthquake slipped much differently from the 1906 earthquake, in that it produced both dip-slip and strike-slip motion and occurred on a different fault plane.

Thatcher and others (1997) reevaluated the triangulation data set used to calculate the deep-fault-slip values for the 1906 earthquake; they especially scrutinized resolution problems that might affect their slip results. Most of their analyses resulted in calculations producing a minimum value of slip. For 1906 slip in the vicinity of Loma Prieta, their triangulation data inversion resulted in a slip of 2.73±0.35 m (again assuming that the fault slipped down to 10-km depth), close to the value previously obtained (Thatcher and Lisowski, 1987) and still higher than all values of 1906 surface slip reported for the Loma Prieta area.

Thatcher and others (1997) also examined several variations from a vertical San Andreas fault rupturing in 1906. Included among the test cases were a uniformly dipping fault near Loma Prieta and a fault that dips at depth but becomes vertical near the Earth's surface. These test cases produced 1906 strike-slip motion on the San Andreas fault ranging from 2.3 to 3.1 m in the vicinity of Loma Prieta. In all of the cases, there still appeared to be substantial differences between the 1906 geodetically modeled slip and the modeled slip that occurred during the 1989 earthquake. In light of this modeling effort, and because the geodetically derived 1906 slip was still, after careful consideration, much greater than the surface slip used in the forecasts (Lindh, 1983, 1988; Sykes and Nishenko, 1984; Scholz, 1985; Working Group on California Earthquake Probabilities, 1988), Thatcher and others (1997) concluded that the 1989 earthquake was not correctly forecasted by those who used the smaller slip values.

SAN ANDREAS FAULT-SLIP-RATE MEASUREMENTS

Unlike the 1906 slip measurements, which have been refined in the wake of the 1989 Loma Prieta earthquake, estimates of the slip rate on the San Andreas fault have not changed significantly. Williams (1995) inverted geodetic data and, assuming a 12-km locking depth, calculated a slip rate of 15.6±1.2 mm/yr for segments of the San Andreas fault near Loma Prieta. His value is similar to the values of 15±2 to 16±2.8 mm/yr used by the forecasters and most likely would not have resulted in any significant changes to the forecast probabilities.

WAS THE 1989 LOMA PRIETA EARTHQUAKE AN ANTICIPATED EVENT?

Debate continues about whether or not the 1989 Loma Prieta earthquake was actually predicted (for example, Kerr, 1989b; Segall and Lisowski, 1990; U.S. Geological Survey, 1990; Beroza, 1991; Prentice and Schwartz, 1991; Kanamori and Satake, 1996; Sykes, 1996; Thatcher and others, 1997; Geller, 1997; Schwartz and others, in press). Both protagonists and antagonists have presented data and concepts that were developed before the earthquake, data and concepts that were developed after the earthquake, and various ideas about the position and timing of large earthquakes in central California tectonics. Some geologists and geophysicists who studied the big-picture history and mechanics of the San Andreas fault system have presented testimony that the 1989 Loma Prieta earthquake was predicted. It was an event that occurred on the San Andreas fault zone (Wallace,

1990) in the Santa Cruz mountains, and it released much of the horizontal strain accumulated since the 1906 earthquake (Ellsworth, 1990; Working Group on California Earthquake Probabilities, 1990; Hanks and Krawinkler, 1991; Sykes, 1996; R.E. Wallace, written commun., 1997). For this conception, several of the forecasts were successful.

Alternatively, other geologists and geophysicists have looked at a different definition of forecasts for large earthquakes in the San Francisco Bay region. They have depicted the San Andreas fault as a single vertical planar feature that broke with fairly shallow right-lateral slip in 1906, and have required the forecasts to be events that would produce similar action at the same depth (Segall and Lisowski, 1990; Beroza, 1991; Prentice and Schwartz, 1991; Thatcher and others, 1997; Schwartz and others, in press). According to this perspective, none of the forecasts were successful, with the authors not delivering judgment on two of the forecasts, M8 (Keilis-Borok and Kossobokov, 1988; Updike, 1989) and Wesson and Nicholson (1988). From this discussion, it can be seen how different views of earthquake faulting and fault-zone mechanics heavily influenced previous assessments of the Loma Prieta forecasts. At the same time, this debate would not have occurred if none of the forecasts had encompassed the 1989 Loma Prieta earthquake's time, rupture extent, and magnitude.

SUMMARY

Before the 1989 Loma Prieta earthquake, more than a century of earthquake history and geomorphic evidence from long-term geologic fault slip in the San Francisco Bay region had already provided evidence that earthquakes do and will occur on regional faults. In the decades before the 1989 Loma Prieta earthquake, scientists were therefore well aware of the potential for large, destructive earthquakes. Some attempted to take the next step, to forecast where the next large earthquake might occur.

Reid (1910) presented the first known scientifically based forecast for a large San Francisco Bay region earthquake. His forecast was followed in the next 79 years by at least 20 more forecasts. Although Reid's forecast was not particularly specific as far as a time was concerned, some subsequent forecasters came closer to the mark, including Moths and others (1981), Lindh (1983), Sykes and Nishenko (1984), and Scholz (1985), all of whom used estimates of the slip during the 1906 earthquake to calculate when the next large earthquake might occur on the San Andreas fault northwest of San Juan Bautista. Using a slightly different tactic, Wesson and Nicholson (1988) presented a forecast that geographically and temporally encompassed the 1989 Loma Prieta earthquake, looking at patterns of previous seismicity and fault activity to determine where future earthquakes might occur. On a much bigger scale and over a much larger forecast area, Keilis-Borok and Kossobokov (1988) used seismicity patterns to forecast $M \geq 7$ and $M \geq 7.5$ earthquakes in the Loma Prieta area.

Although none of the forecasts of the 1989 Loma Prieta earthquake can be rigorously tested, because most of them are incomplete, the forecasts can be qualitatively judged on those aspects that came closest to the actual event, including the rupture length, which was most closely estimated by Lindh (1983), and the magnitude, which was accounted for by many of the forecasters, including Thenhaus and others (1980), Sykes and Nishenko (1984), Scholz (1985), Keilis-Borok and Kossobokov (1988), and Wesson and Nicholson (1988). In contrast to those who presented scenarios of probable large earthquakes, Thatcher and Lisowski (1987) showed that an earthquake on the San Andreas fault near Loma Prieta was unlikely.

Thus, the 1989 Loma Prieta earthquake did not follow all of the specifications set out for it by the forecasters. Instead, it occurred much deeper than expected, and with a significant reverse-slip component. There is still discussion about whether or not the 1989 earthquake occurred on the same fault that ruptured in the great 1906 earthquake. Segall and Lisowski (1990), Dietz and Ellsworth (1997), Thatcher and others (1997), and Schwartz and others (in press) present evidence that the 1989 and 1906 earthquakes could not have occurred on the same fault plane. This evidence has not, however, dissuaded other workers (for example, Hanks and Krawinkler, 1991; Sykes, 1996) who have viewed the forecasts more favorably, noting that the 1989 earthquake released the horizontal strain accumulated since 1906 and thus that it was an expected (and forecasted) event.

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REFERENCES CITED

Beroza, G.C., 1991, Near-source modeling of the Loma Prieta earthquake; evidence for heterogeneous slip and implications for earthquake hazard: Seismological Society of America Bulletin, no. 5, v. 81, p. 1603–1621.

California Office of Emergency Services, 1988, Additional quakes possible following Bay Area earthquake: news release, June 28, 1988.

———1989, Additional quakes possible following Bay Area earthquake: news release, August 8, 1989.

Dietz, L.D., and Ellsworth, W.L., 1997, Aftershocks of the 1989 Loma Prieta earthquake and their tectonic implications, *in* Reasenberg, P.A., ed., The Loma Prieta, California, earthquake of October 17, 1989—aftershocks and postseismic effects: U.S. Geological Survey Professional Paper 1550–D, p. D5–D47.

Ellsworth, W.L., 1990, Earthquake history, *in* Wallace, R.E., ed., The San Andreas fault system, California: U.S. Geological Survey Professional Paper 1515, p. 153–181.

Ellsworth, W.L., Lindh, A.G., Prescott, W.H., and Herd, D.G., 1981, The 1906 San Francisco earthquake and the seismic cycle, *in* Simpson, D.W., and Richards, P.G., eds., Earthquake prediction, an international review (Maurice Ewing series, no. 4): Washington, D.C., American Geophysical Union, p. 126–140.

Fedotov, S.A., 1965, Regularities in the distribution of strong earthquakes in Kamchatka, the Kuriles, and northeastern Japan: Akademiya Nauk SSSR, Institut Fiziki Zemli Trudy, v. 36, p. 66–93 [in Russian].

Geller, R.J., 1997, Earthquakes; thinking about the unpredictable: Eos (American Geophysical Union Transactions), v. 78, no. 6, p. 63, 66–67.

———in press, Earthquake prediction; are further efforts warranted?: Geophysical Journal International.

Geller, R.J., Jackson, D.D., Kagan, Y.Y., and Mulargia, Francesco, 1997, Earthquakes cannot be predicted: Science, v. 275, no. 5306, p. 1616–1617.

Gilbert, G.K., 1884, A theory of the earthquakes of the Great Basin, with a practical application: American Journal of Science, ser. 3, v. 27, no. 157, p. 49–53.

———1909, Earthquake forecasts: Science, n. ser., no. 734, v. 29, p. 121–138.

Hanks, T.C., and Krawinkler, Helmut, 1991, The 1989 Loma Prieta earthquake and its effects; introduction to the special issue: Seismological Society of America Bulletin, v. 81, no. 5, p. 1415–1423.

Jennings, C.W., compiler, 1992, Preliminary fault activity map of California: California Division of Mines and Geology Open-File Report 92–03, scale 1:750,000.

Jones, L.M., 1985, Foreshocks and time-dependent earthquake hazard assessment in southern California: Seismological Society of America Bulletin, v. 75, no. 6, p. 1669–1679.

Kanamori, Hiroo, and Satake, Kenji, 1996, Broadband study of the source characteristics of the earthquake, *in* Spudich, Paul, ed., The Loma Prieta, California, earthquake of October 17, 1989—main-shock characteristics: U.S. Geological Survey Professional Paper 1550–A, p. A75–A80.

Keilis-Borok, V.I., and Kossobokov, V.G., 1988, Premonitory activation of seismic flow; algorithm M8: paper presented at the International Centre for Theoretical Physics Workshop on Global Geophysical Informatics with Applications to Research in Earthquake Predictions and Reduction of Seismic Risk, Trieste, Italy, 1988, 25 p.

Keilis-Borok, V.I., Kossobokov, V.G., and Rinehart, Wilbur, 1986a, The test of algorithm M8, Western US, chap. 3 *of* Gabrielov, A.M., Dmitrieva, O.E., Keilis-Borok, V.I., Kossobokov, V.G., Kuznetsov, I.V., Levshina, T.A., Mirzdev, K.M., Molchan, G.M., Negmatullaev, S.Kh., Pisarenko, V.F., Prozoroff, A.G., Rinehart, Wilbur, Rotvain, I.M., Shebalin, P.N., Shnirman, M.G., and Shreider, S.Yu., Algorithm of long-term earthquakes' prediction, *in* International School on Research Oriented to Earthquakes' Prediction—Algorithms, Software and Data Handling: Lima, Peru, Centro Regional de Sismologia para America del Sur, p. 42–51.

Keilis-Borok, V.I., Kossobokov, V.G., and Rotvain, I.M., 1986b, Diagnosis of the time of increased probability of a strong earthquake, chap. 1 *of* Gabrielov, A.M., Dmitrieva, O.E., Keilis-Borok, V.I., Kossobokov, V.G., Kuznetsov, I.V., Levshina, T.A., Mirzdev, K.M., Molchan, G.M., Negmatullaev, S.Kh., Pisarenko, V.F., Prozoroff, A.G., Rinehart, Wilbur, Rotvain, I.M., Shebalin, P.N., Shnirman, M.G., and Shreider, S.Yu., Algorithm of long-term earthquakes' prediction, *in* International School on Research Oriented to Earthquakes' Prediction—Algorithms, Software and Data Handling: Lima, Peru, Centro Regional de Sismologia para America del Sur, p. 8–22.

Kerr, R.A., 1989a, Another California seismic hot spot: Science, v. 245, no. 4919, p. 704.

———1989b, Reading the future in Loma Prieta: Science, v. 246, no. 4929, p. 436–439.

Lawson, A.C., chairman, 1908, The California earthquake of April 18, 1906; report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, 2 v.

Lindh, A.G., Estrem, J.E., Olson, J.A., Reneau, Dave, and Dollar, R.S., 1982a, Parkfield prediction experiment, *in* Charonnat, B.B., Rodriguez, T.R., and Seiders, W.H., compilers, Summaries of technical reports, volume XIII, prepared by participants in National Earthquake Hazards Reduction Program: U.S. Geological Survey Open-File Report 82–65, p. 280–285.

Lindh, A.G., Moths, B.L., Ellsworth, W.L., and Olson, J.A., 1982b, Historic seismicity of the San Juan Bautista, California region, *in* Joint Meeting of the U.S.-Japan Conference on Natural Resources (UJNR) Panel on Earthquake Prediction Technology, 2d, Proceedings: U.S. Geological Survey Open-File Report 82–180, p. 45–50.

Lindh, A.G. 1983, Preliminary assessment of long-term probabilities for large earthquakes along selected fault segments of the San Andreas fault system in California: U.S. Geological Survey Open-File Report 83–63, 14 p.

———1988, Estimates of long-term probabilities for large earthquakes along selected fault segments of the San Andreas fault system in California, *in* Guha, S.K., and Patwardhan, A.M., eds., Earthquake prediction—present status: University of

Poona, India, Department of Geology Symposium Proceedings, p. 189–200.

Mogi, Kiyoo, 1981, Seismicity in western Japan and long term earthquake forecasting, *in* Simpson, D.W., and Richards, P.G., eds., Earthquake prediction, an international review (Maurice Ewing Series, no. 4): Washington, D.C., American Geophysical Union, p. 43–51.

Moths, B.L., Lindh, A.G., Ellsworth, W.L., and Fluty, L., 1981, Comparison between the seismicity of the San Juan Bautista and Parkfield regions, California (abs.): Eos (American Geophysical Union Transactions), v. 62, no. 45, p. 958.

Plafker, George, and Galloway, J.P., 1989, Lessons learned from the Loma Prieta, California, earthquake of October 17, 1989: U.S. Geological Survey Circular 1045, 48 p.

Prentice, C.S., and Ponti, D.J., 1997, Coseismic deformation of the Wrights tunnel during the 1906 San Francisco earthquake; a key to understanding 1906 fault slip and 1989 surface ruptures in the southern Santa Cruz Mountains, California: Journal of Geophysical Research, v. 102, no. B1, p. 635–648.

Prentice, C.S., and Schwartz, D.P., 1991, Re-evaluation of 1906 surface faulting, geomorphic expression, and seismic hazard along the San Andreas fault in the southern Santa Cruz mountains: Seismological Society of America Bulletin, v. 81, no. 5, p. 1424–1479.

Prescott, W.H., 1980, The accommodation of relative motion along the San Andreas fault system in California: Stanford, Calif., Stanford University, Ph.D. thesis, 195 p.

Reid, H.F., 1910, The mechanics of the earthquake, v. 2 *of* Lawson, A.C., chairman, The California earthquake of April 18, 1906; report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, 192 p.

Sarna-Wojcicki, A.M., Pampeyan, E.H., and Hall, N.T., 1975, Map showing recently active breaks along the San Andreas fault between the central Santa Cruz Mountains and the northern Gabilan Range, California: U.S. Geological Survey Miscellaneous Field Studies Map MF–650, scale 1:24,000.

Scholz, C.H., 1982, Scaling laws for large earthquakes; consequences for physical models: Seismological Society of America Bulletin, v. 72, no. 1, p. 1–14.

———1985, The Black Mountain asperity; seismic hazard of the southern San Francisco Peninsula, California: Geophysical Research Letters, v. 12, no. 10, p. 717–719.

———1997, Whatever happened to earthquake prediction?: Geotimes, v. 42, no. 1, p. 16–19.

Schwartz, D.P., Pantosti, Daniela, Okumura, Kei, Powers, T.J., and Hamilton, J.C., in press, Recurrence of large magnitude earthquakes in the Santa Cruz Mountains, California; implications for behavior of the San Andreas fault: Journal of Geophysical Research.

Segall, Paul, and Lisowski, Michael, 1990, Surface displacements in the 1906 San Francisco and 1989 Loma Prieta earthquakes: Science, v. 250, no. 4985, p. 1241–1244.

Shimazaki, Kunihiko, and Nakata, Takashi, 1980, Time-predictable recurrence model for large earthquakes: Geophysical Research Letters, v. 7, no. 4, p. 279–282.

Spudich, Paul, 1996, Synopsis, *in* Spudich, Paul, ed., The Loma Prieta, California, earthquake of October 17, 1989—main-shock characteristics: U.S. Geological Survey Professional Paper 1550–A, p. A1–A7.

Steidl, J.H., and Archuleta, R.J., 1996, Are rupture models consistent with geodetic measurements?, *in* Spudich, Paul, ed., The Loma Prieta, California, earthquake of October 17, 1989—main-shock characteristics: U.S. Geological Survey Professional Paper 1550–A, p. A195–A207.

Sykes, L.R., 1996, Intermediate- and long-term earthquake prediction: National Academy of Sciences Proceedings, v. 93, p. 3732–3739.

Sykes, L.R., and Nishenko, S.P., 1984, Probabilities of occurrence of large plate rupturing earthquakes for the San Andreas, San Jacinto, and Imperial faults, California, 1983–2003: Journal of Geophysical Research, v. 89, no. B6, p. 5905–5927.

Thatcher, Wayne, and Lisowski, Michael, 1987, Long-term seismic potential of the San Andreas fault southeast of San Francisco, California: Journal of Geophysical Research, v. 92, no. B7, p. 4771–4784.

Thatcher, Wayne, Marshall, G.A., and Lisowski, Michael, 1997, Resolution of fault slip along the 470-km-long rupture of the great 1906 San Francisco earthquake and its implications: Journal of Geophysical Research, v. 102, no. B3, p. 5353–5367.

Thenhaus, P.C., Perkins, D.M., Ziony, J.I., and Algermissen, S.T., 1980, Probabilistic estimates of maximum seismic horizontal ground motion on rock in coastal California and the adjacent outer continental shelf: U.S. Geological Survey Open-File Report 80–924, 69 p.

Tocher, Don, 1959, Seismic history of the San Francisco region, *in* Oakeshott, G.B., ed., San Francisco earthquakes of March 1957: California Division of Mines and Geology Special Report 57, p. 39–48.

Updike, R.G., compiler, 1989, Proceedings of the National Earthquake Prediction Evaluation Council June 6–7, 1988, Reston, Virginia: U.S. Geological Survey Open-File Report 89–144.

U.S. Geological Survey, 1981, Scenarios of possible earthquakes affecting major California population centers, with estimates of intensity and ground shaking: Open-File Report 81–115, 44 p.

U.S. Geological Survey staff, 1990, The Loma Prieta, California, earthquake; an anticipated event: Science, v. 247, no. 4940, p. 286–293.

Wald, D.J., Heaton, T.H., and Helmberger, D.V., 1996, Strong-motion and broadband teleseismic analysis of the earthquake for rupture process and hazards assessment, *in* Spudich, Paul, ed., The Loma Prieta, California, earthquake of October 17, 1989—main-shock characteristics: U.S. Geological Survey Professional Paper 1550–A, p. A235–A262.

Wallace, R.E., Davis, J.F., and McNally, K.C., 1984, Terms for expressing earthquake potential, prediction, and probability: Seismological Society of America Bulletin, v. 74, no. 5, p. 1819–1825.

Wallace, R.E., 1990, General features, *in* Wallace, R.E., ed., The San Andreas fault system, California: U.S. Geological Survey Professional Paper 1515, p. 3–12.

Wesson, R.L., and Nicholson, Craig, 1988, Intermediate-term, pre-earthquake phenomena in California, 1975–1986, and preliminary forecast of seismicity for the next decade: Pure and Applied Geophysics, v. 126, no. 2–4, p. 407–446.

Williams, S.D.P., 1995, Current motion on faults of the San Andreas system in central California inferred from recent GPS and terrestrial survey measurements: Durham, U.K., University of Durham, Ph.D. thesis, 282 p.

Willis, Bailey, 1923a, A fault map of California: Seismological Society of America Bulletin, v. 13, no. 1, p. 1–12.

———1923b, Earthquake risk in California, 1. The point of view: Seismological Society of America Bulletin, v. 13, no. 3, p. 89–99.

———1924, Earthquake risk in California, 8. Earthquake districts: Seismological Society of America Bulletin, v. 14, no. 1, p. 9–25.

Wood, H.O., 1916, California earthquakes; a synthetic study of recorded shocks: Seismological Society of America Bulletin, v. 6, p. 55–180.

Working Group on California Earthquake Probabilities, 1988, Probabilities of large earthquakes occurring in California on the San Andreas fault: U.S. Geological Survey Open-File Report 88–398, 62 p.

———1990, Probabilities of large earthquakes in the San Francisco Bay region, California: U.S. Geological Survey Circular 1053, 51 p.

APPENDIX 1. DEFINITION OF AN EARTHQUAKE ADVISORY

In his July 12, 1988, draft after the first M=5 Lake Elsman earthquake, California State Geologist James Davis (unpub. data, 1988) defined the terms earthquake "advisory" and earthquake "warning or alert." He stated that an advisory is a commentary on earthquake potential which has less urgency in terms of public safety than an alert or warning. The advisory provides information about a scientific conclusion that has not developed consensus on the likelihood that the damaging earthquake will occur, so that a quantifiable probability cannot be agreed upon, although the time frame of concern may be short, as in a few days. An advisory can also be for a longer time period (for example, now to decades in the future), or for an event that may not cause extensive enough damage to merit full-scale response.

In the case of the Lake Elsman advisories (starting one, June 27; ending one, July 2), there was not a short-term prediction, just the potential for a moderate event in a relatively sparsely populated region. Similar advisories were issued in June 1985 for San Diego and in July 1986 for Chalfant Valley.

APPENDIX 2. THE LAKE ELSMAN ADVISORY

The first M=5 Lake Elsman earthquake occurred just before noon on June 27, 1988 (fig. 9). Preliminary locations requested by California State Geologist James Davis (unpub. data, 1988) soon after the earthquake placed the event at 35-km depth at lat 37°7.7′ N., long 121°54.2′ W., about 35 km northwest of San Juan Bautista. (Later estimates placed the event much shallower, at 14.4-km depth.) That afternoon, Al Lindh of the U.S. Geological Survey informed Davis that the earthquake was on the San Andreas fault at the northern margin of the Working Group on California Earthquake Probabilities' (1988) Southern Santa Cruz Mountain segment. The (first) Lake Elsman earthquake also appeared to have been the largest earthquake on this part of the San Andreas fault since 1906. Lindh told Davis that this Lake Elsman earthquake could be a foreshock preceding an M=6–6.5 earthquake on the Santa Cruz Mountains segment of the San Andreas fault.

Brian Tucker of the California Division of Mines and Geology and Jim Davis decided to call the California Office of Emergency Services to discuss whether or not the release of an earthquake advisory (which is a commentary on earthquake potential (see app. 1; Wallace and others, 1984; James Davis, unpub. data, 1988) to local governments was the appropriate next step. Meanwhile, several conference calls were coordinated to discuss whether or not the M=5 earthquake might set off any of the forecasted earthquake scenarios. In the scientific discussions, it was decided that it would be difficult to assign a meaningful probability gain that everyone could agree on and that they were not dealing with earthquake prediction as such. The scientists did agree, however, that the likelihood of a larger subsequent earthquake was probably higher than usual, owing to the location of the earthquake on a segment of the San Andreas fault that had built up considerable strain since 1906. The final consensus by the scientists was that the Office of Emergency Services should decide what type of message would be used best by local agencies and that this message should be low key, without a news release. As a result, an advisory was edited by the State and the Office of Emergency Services and sent by the Office of Emergency Services over the telephone to the local governments of Santa Clara, Santa Cruz, San Benito, and Monterey Counties. This was the first time in San Francisco Bay region history that the State Office of Emergency Services had ever sent an official short-term advisory regarding a potential upcoming large earthquake.

The advisory stated that there was a slightly increased likelihood of an M=6.5 event on the Santa Cruz Mountains segment of the San Andreas fault in the next 5 days. The 5-day time period was based on a southern California-based study by Jones (1985) stating that there exists a 6-percent chance of a larger earthquake within 5 days after an $M \geq 3$ earthquake. The advisory mentioned that agencies in the specified areas should maintain preparedness and awareness measures.

On June 28, after the advisory had been received by local governments, several State officials decided that a news release would be desirable, and so one was drafted and sent out. The public was now also aware of the advisory.

On June 30, State officials started preparing a notice for July 2 stating that the 5-day advisory had expired. Meanwhile, extremely low aftershock activity occurred near the Lake Elsman main shock. On July 2, the State issued the official expiration advisory.

On August 8, 1989, another M=5 earthquake occurred (fig. 9). The Office of Emergency Services issued another 5-day (short term) advisory similar to that issued in June 1988. Five days later, this advisory also expired.

APPENDIX 3.
PECK AND PEARLMAN CORRESPONDENCES

United States Department of the Interior

OFFICE OF THE SECRETARY
WASHINGTON, D.C. 20240

DEC 3 1985

Memorandum

To: Executive Secretary--National Security Council

From: Executive Assistant to the Secretary Don Pearlman /s/

Subject: Recent reference to California earthquakes by a Soviet official

At a recent meeting a Soviet official indicated that their studies showed that during the next 3 years there is a 60 percent probability of a magnitude 8-8.5 earthquake and a 70 - 75 percent chance of a magnitude 7-7.5 earthquake in southern California.

Under the aegis of the National Earthquake Hazards Reduction Program, the Geological Survey carries out research and other activities on earthquake hazards assessment and earthquake prediction. Within this program and through an agreement on "Cooperation in Environmental Protection" between the United States and the Soviet Union signed in 1972, the Geological Survey has cooperated in earthquake prediction studies with the Academy of Sciences of the Soviet Union. For the past several years this cooperation has been in the exchange of scientists to carry out joint studies and to discuss recent results. During these exchanges, Soviet scientists have worked with colleagues at California universities on earthquake prediction problems.

Based on detailed geological study of active faults and seismicity patterns in California, the Geological Survey has made earthquake hazards assessments of various regions. The salient features of these assessments are that there is about a 50 percent chance of a major (magnitude 8+) on the southern San Andreas fault northeast of Los Angeles within the next 30 years and a 90 percent chance of a moderate earthquake (magnitude 6) along the same fault east of Paso Robles within the next 7 years. This latter area is the site of an intensive earthquake prediction experiment in an attempt to give warning within a few days or hours of the anticipated event. A successful outcome of this experiment would have wider application. There are many other active faults in California capable of producing damaging earthquakes in the near future, but the two regions mentioned above are the most well understood.

It is believed that the recent reference to earthquakes in California has resulted from a Soviet approach to earthquake prediction based on statistical analyses to the historical record of earthquakes in a given region. This technique has had some success in retrospectively identifying "times of increased probability," periods of a few years, when earthquakes of magnitude 6 or greater have occurred in California. United States scientists have not acclaimed this work because of its lack of geological basis and geographical specificity. The recent reference appears to be cast with much greater precision than previous results.

It is recommended that follow-up contact be made with Soviet scientists through the existing agreement to determine and evaluate the basis for the recent statement.

United States Department of the Interior

GEOLOGICAL SURVEY
RESTON, VA. 22092

In Reply Refer To:
Mail Stop 905

DEC 9 1985

Memorandum

To: Executive Assistant to the Secretary

From: Director, Geological Survey

Subject: Summary of a meeting at the White House, December 5, 1985, on Soviet prediction of southern California earthquake

Attendees:
Billy Martin, NSC
Rod McDaniel, NSC
Ty Cobb, NSC
Max Robinson, State/Soviet Desk
Jack Blanchard, State/OES
Gary Waxmonsky, EPA
Dallas Peck, USGS
John Filson, USGS

Background: Chairman Gorbachev passed to President Reagan at the Geneva Summit Meeting a prediction by Soviet scientists that there was a 60 percent probability of a magnitude 8-8.5 earthquake and a 70 - 75 percent probability of a magnitude 7-7.5 earthquake occurring in southern California in the next 3 years. Admiral Poindexter requested that there be some follow-up.

The subject meeting focused on our reaction to the Soviet prediction, the state of US/Soviet cooperation in earthquake prediction research, and possible ways to pursue the matter.

Waxmonsky, Executive Secretary of the US/Soviet cooperative in Environmental Protection summarized the history of that program since it was established in 1972. At the time of the recent Geneva Summit, Lee Thomas of EPA was heading a delegation to Moscow to meet with the Soviets to review that agreement and discuss future activities. This agreement contains a section on earthquake studies that includes a project on earthquake prediction.

Filson, who is a cochairman of the earthquake project, then summarized some of the joint work under the project, which has included exchange visits of a Soviet mathematician named Keilis-Borok. Keilis-Borok recently worked with Professor Leon Knopoff of UCLA to predict retrospectively times of heightened seismic activity in California through statistical analyses of past earthquake occurrence. Review of his approach by leading American scientists has yielded mixed but mostly mildly favorable reviews. Keilis-Borok may be the originator of the prediction that was passed to President Reagan.

Executive Assistant to the Secretary 2

Filson summarized the current USGS outlook on southern California earthquakes. Based on the recurrence intervals of past earthquakes in southern California and detailed geologic studies of the faults there, we have estimated the probabilities of future earthquakes along segments of the San Andreas and other faults. The probability of a magnitude 8 earthquake near Los Angeles is estimated to be 1-3 percent a year or about 50 percent in the next 30 years--an estimated probability far smaller than that advanced by the Soviets.

After discussing what the next steps should be, McDaniel and Martin requested that Peck and Filson draft a memo (attached) to Martin for your signature summarizing the above material and proposing scientist-to-scientist discussions on the subject under the US/Soviet agreement. After receipt of a copy of this memo, Robinson and Blanchard are to prepare a memo suggesting steps to take to carry the matter forward. We were requested to keep Judge Clark informed on the matter. After receipt of the memos, the NSC will advise us how to proceed.

Dallas L. Peck /s/

Dallas L. Peck

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