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Preliminary Assessment of Long-Term Probabilities for Large Earthquakes Along Selected Fault Segments of the San Andreas Fault System in California

by

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Introduction

Over the past 20 years, growing concern has been expressed within the earth-science community concerning the possibility of a great earthquake occurring within the near future on the San Andreas fault in southern California (Raleigh and others, 1982). This concern was heightened by an analysis of precise leveling surveys in the region which indicated that a broad region stretching almost 300 km along the San Andreas had uplifted about 30 cm during the period between 1961 and 1971 (Castle and others, 1975). Stimulated by this concern, a great deal of additional work has been conducted in the region since that time, and subsequent observations include a partial collapse of the uplift starting in about 1974 (Castle and others, in prep.), a dilatational anomaly in geodetic measurements in the Palmdale region since 1979 (Savage and others, 1981a & b), and an accompanying regional seismicity increase (Hutton and Johnson, 1981). In addition detailed geologic work has provided a much clearer picture of the history of great earthquakes along the San Andreas in the last 2000 years (Sieh, 1981).

In response to a national need for a broad overview of seismic hazard along the Pacific Coast of California, for strategic and emergency planning purposes, the U. S. Geological Survey recently undertook a study of the long-term probabilities of large earthquakes along the San Andreas system (FEMA, 1981; USGS, 1981). This resulted in, amongst other things, an estimated annual long-term probability of about 2% for a great earthquake on the San Andreas fault between Parkfield (in central California) and San Bernadino. This short report summarizes the result of applying a similar methodology to the entire San Andreas system between the Imperial Valley and Cape Mendocino.

One difference between this work and most other studies of long-term seismic hazard should be emphasized; this work attempts to identify where we currently stand in the cycle of earthquake recurrence on a given fault segment, and to use this information to increase the probability as the time approaches at which the next event is expected (Gilbert, 1884). Thus it might more appropriately be called medium-term hazard assessment, attempting as it does an instantaneous estimate of the probability of earthquake occurrence. The time span for which the estimates are appropriate is measured in decades, not centuries.

The important consequence of this difference in approach lies in the manner in which historical seismicity is included in the probability estimates. In the usual approach seismic hazard is treated as a stationary process, and a record of high levels of recent historical activity act to increase the calculated probabilities (see for instance, Thenhaus and others, 1980); in the approach outlined here the recent occurrence of large historical events will, in some cases, act to decrease the estimate of the current hazard. Thus this could be viewed as an attempt to incorporate the first-order consequences of plate tectonics and seismic gap theory (Fedotov, 1965; Mogi, 1968) in seismic hazard estimation.

Analysis

The data used in these calculations are estimates of repeat times of large earthquakes along specific segments of active faults, based on geologic and/or geodetic estimates of slip rates or recurrence intervals, combined with information from the historic record concerning when a large earthquake last occurred on a given segment. The segments were chosen by a variety of criteria, usually an historic earthquake on that segment, but also including geologic information in a few cases. The crucial assumptions are that faults can meaningfully be divided into segments in this way, and that each segment will have a characteristic earthquake which represents its most probable mode of future failure.

In the simplest cases, on the San Andreas fault, the choice of the characteristic earthquake is obvious; on the Olema and Carrizo segments, for instance, it is a repeat of the 1906 and 1857 earthquakes, respectively. On other segments, such as the San Francisco Peninsula, San Juan Bautista, and Mojave segments, I have followed Sieh (1981) in assuming that portions of the 1857 and 1906 breaks can be identified which are likely to fail next in events of lessor magnitude, based on the length of the segment, and in the case of the San Juan and San Francisco Penninsula segments, the occurrence in the 19th Century of M 6-7 events. In the case of the San Jacinto and Hayward faults, the division into segments is almost arbitrary, and the characteristic earthquakes represent an analgam of historic seismicity and geologic intuition.

The statistical model used is the simplest possible, and assumes that earthquake recurrence on a given segment can be characterized by a Gaussian distribution with a mean recurrence time ($\overline{\Delta t}$) and a standard deviation (δt). Because so little information exists with which to estimate δt, it is assumed equal to 30% of $\overline{\Delta t}$; that is, that the scatter in interevent times is about 1/3 of the mean recurrence time. Starting with the time of the last event (T_0) and $\overline{\Delta t}$, a probability can be calculated for any future time period. The results of these calculations for those fault segments for which I could obtain sufficient data are listed in Table 1 and displayed in Figure 1.

The probabilities shown in the columns at the right of the table are the conditional probabilities (CP) of an event, given that one has not yet occurred, for various time intervals between time T and T + ΔT.

$$CP(T, \Delta T) = P(T, \Delta T)/P(T,\infty)$$

$$\text{where } P(T, \Delta T) = (1/2\pi) \int_{u_1}^{u_2} \text{EXP } (-X^2/_2) \; dx$$

$$\text{where } U_1 = (T - T_0 - \overline{\Delta} t)/\delta t$$

$$\text{and } U_2 = (T + \Delta T - T_0 - \overline{\Delta t})/\delta t$$

T is the time for which the calculation is being made (1982 in this case). ΔT is the time interval following T to which the probability applies (1, 10, 20 and 30 years for the four columns in Table 1). In a few cases two or more values of $\overline{\Delta t}$ and δt are shown for a given segment, in cases for which significantly different estimates are obtained by geologic or geodetic data; the preferred (more conservative) value is listed first.

Also shown in Figure 1 are probabilistic estimates for future large earthquakes along a number of other major late Quaternary faults in central and southern California for which approximate slip rates are known (Ziony and Yerkes, in prep.) but on which, in most cases, no historic earthquake has occurred. The algorithm used for computing current annual probabilities for these faults is that a slip rate of 1 mm or more per year implies a recurrence time of 1000 years or less ($P \geq .1\%$), and .1 mm or more of slip per year implies a recurrence time of 10000 years or less ($P < .1\%$). This assumes that characteristic earthquakes for these faults are M 6-7 events with about 1 m of slip.

Discussion

The long-term probability estimates presented here represent a quantitative attempt to assess relative seismic hazard throughout most of the San Andreas system in California. While they are doubtless incomplete in some areas, and reflect little more than educated guesses in others, they are a reasonable first approximation to the "true" distribution of the hazard. However, estimates for individual fault segments should not be interpreted more literally than the data warrant. Before use is made of a specific listed probability for a given fault segment, the recurrence data and assumptions on which it is based must be carefully appraised. Given the current state of our knowledge, these calculations are meaningful only as gross estimates at the order of magnitude level. Substantial changes in these estimates for many fault segments are to be expected as additional information on the repeat times of large earthquakes become available from detailed geologic studies, and as the various model assumptions are subjected to quantitative test. A more detailed discussion of these estimates and the methodology is in preparation (Lindh and Ellsworth, in prep.).

Despite these limitations, the estimates reported here are of value for several reasons:

1) They constitute a first attempt at a quantitative assessment of the relative seismic hazard of the major active faults of California.
2) They help identify those major faults where additional research on recurrence might most profitably be focused,
3) They provide guidance concerning where studies of earthquake mechanisms and precursors, and monitoring for recordings of strong ground motion, are most likely to be fruitful.

The dominant feature of the probabilities listed in Table 1 is the significantly higher average probability in southern California (Figure 1); overall the probabilities for the five segments south of the Carrizo segment aveage 2 1/2 times those for the five segments north of the creeping section. This reflects the fact that the last great earthquake in northern California (1906) occurred almost 50 years after the last great event on the southern San Andreas (1857), and that an even longer time has passed since the last great event on the Indio segment. A growing body of evidence suggests that because of these differences in time to the last great event, all of southern California is farther along in the "seismic cycle" than northern California (Ellsworth et al., 1981; Moth and Ellsworth, in prep.). It is believed that the regional stress levels are nearer failure levels, and that moderate to large earthquakes are more likely to occur in the southern part of the state. Thus the higher average probability in southern California is not strongly dependent on the statistical model, but likely reflects the actual distribution of relative seismic hazard.

A note of caution should be added concerning use of the individual probabilities listed here to estimate overall probability of a large earthquake within a given area; Table 1 lists probabilities only for those faults for which we have a fairly high level of understanding. It is likely that a significant fraction of the damaging earthquakes that will occur in the coming decades will occur on faults whose potential is poorly understood today. Thus an attempt to use data in Table 1 to sum probabilities for an area, e.g., the Los Angeles region, will substantially underestimate the total hazard. Some additional factor must be added to account for future earthquakes on faults about which too little is known for them to be included here.

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Table 1 Legend

Characteristic Earthquake - The event that is assumed to account for most of the slip on a given segment, averaged over many cycles. In most cases this is the last large event on a given segment. In a few cases, such as the 1906 and 1857 rupture zones, a more complicated model has been used, and the characteristic event assumes that part of the rupture zone may fail before the next great event. For the Indio segment, 1857 is listed as the characteristic event, even though it actually occurred on the Carrizo and Mojave segments. [See Lindh and Ellsworth, (in prep.), for a full discussion of these thorny questions.]

T_0 - Date of last major slip event. (Assumed in some cases.)

$\overline{\Delta t}$ - Average recurrence interval, based on geologic, geodetic and seismic data.

δt - Standard Deviations of the assumed inter-event time distribution, taken as 30% of $\overline{\Delta t}$ for all of the cases considered here.

Table 1

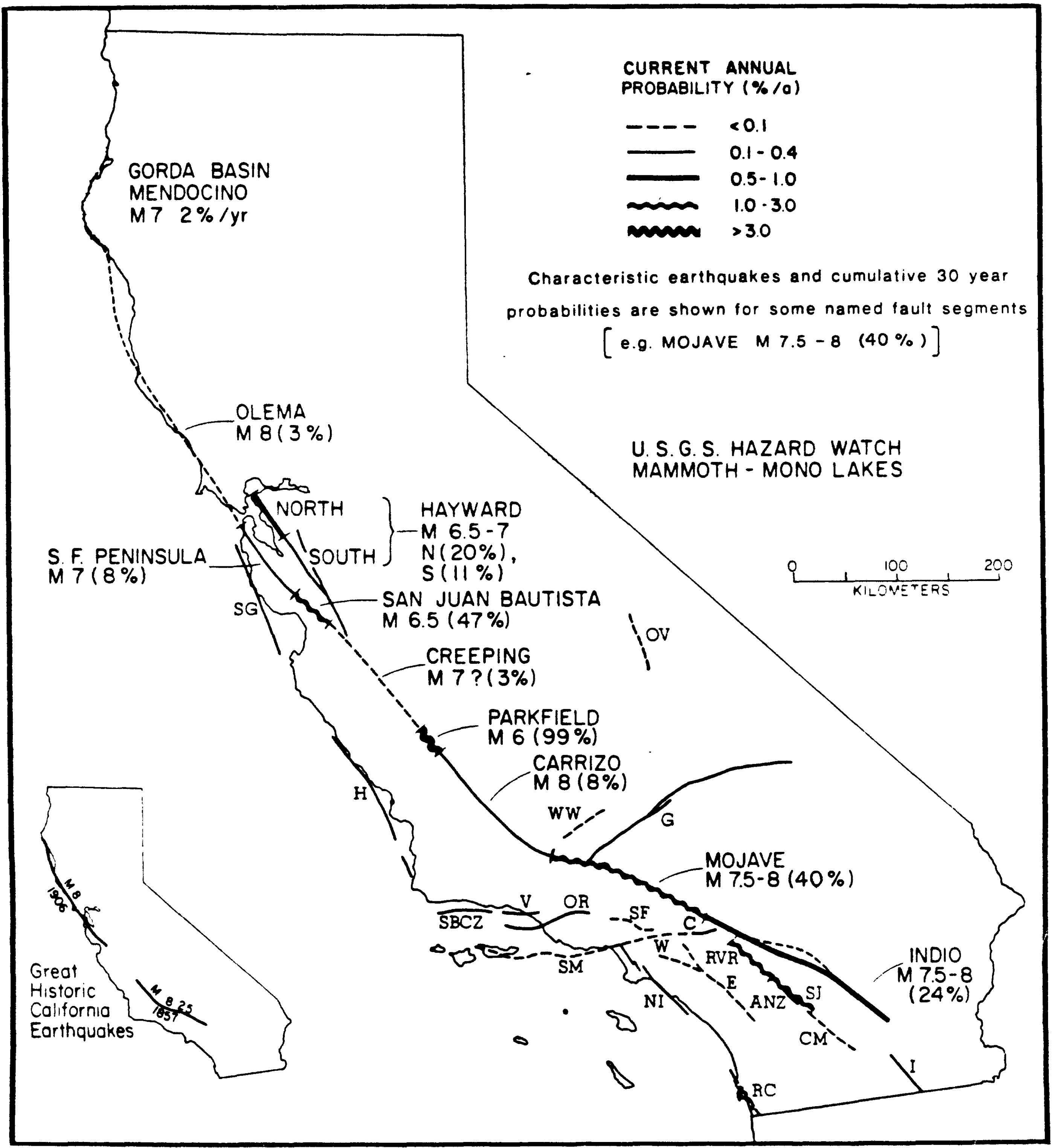
	Fault	Segment	Characteristic Earthquakes Date	MAG	Date T	Recurrence Interval Ave.	S.D.	Probabilities % Annual 1982	Cummulative(years) 10	20	30
A	San Jacinto	Coyote Mtn.	1968	6 3/4	~1955	100	30	0.07	1	3	7
B	San Jacinto	Anza	1890	6 3/4	1890	100	30	2.1	22	43	62
C	San Jacinto	Riverside	1899	6 3/4	~1908	100	30	1.1	13	28	45
D	San Andreas	Indio	(1857)	7 1/2-8	(1382)	500	150	0.8	8.2	16	24
E	San Andreas	Mojave	1857	7 1/2-8	1857	145	44	1.2	13	26	40
F	San Andreas	Carrizo	1857	8	1857	228	68	0.2	2	5	8
G	San Andreas	Parkfield	1966	6	1966	22	6.6	5.2	67	98	99.9
H	San Andreas	Creeping		(7)	(1792)	(400)	(120)	(0.08)	(1)	(2)	(3)
I	San Andreas	San Juan	1865	6 1/2	1906	100	30	1.2	14	30	47
		Bautista				75	22.5	3.7	35	64	83
J	San Andreas	San Francisco	1838	7	1906	167	50	0.16	2	5	8
		Peninsula				125	38	0.5	6	14	23
K	San Andreas	Olema	1906	8	1906	225	68	0.05	1	2	3
						150	45	0.24	3	7	12
L	Hayward	South	1868	6 1/2-7	1868	200	60	0.26	3	7	11
M	Hayward	North	(1836)	6 1/2-7	1836	200	60	0.55	6	12	20

Warning: These estimates are preliminary, and while they are intended to provide a broad overview of the relative earthquake likelihood in California, specific probability estimates on individual fault segments should not be interpreted too literally.

Figure 1. Map showing annual probabilities for selected fault segments of the San Andreas fault system. These are conditional probabilties of an event of the magnitude indicated, within the next 12 months, given that one has not yet occurred. Also shown in parenthesis for some segments are cummulative probabilities for an event in the next 30 years, given that one has not yet occurred.

ANNUAL EARTHQUAKE PROBABILITIES

for selected fault segments of the San Andreas Fault System



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