EARTHQUAKE RECURRENCE IN THE SAN FRANCISCO BAY REGION, CALIFORNIA, FROM FAULT SLIP AND SEISMIC MOMENT

by

Kaye M. Shedlock, Robin K. McGuire, and Darrell G. Herd

U.S. Geological Survey
Open-File Report 80-999

1980

INTRODUCTION

An evaluation of the seismic hazard in the San Francisco Bay region requires estimation of the frequency of occurrence of damaging earthquakes in the surrounding central Coast Ranges of California. This estimate would ideally be based on a record that spans thousands of years of seismicity in central California. However, the historic record of seismicity in the San Francisco Bay area is short, comprising only several hundred years of data. To date, a geologic record of earthquake shaking in central California has not been found which might extend the historic record thousands of years.

The frequency of damaging earthquakes can be calculated from fault slip and seismic moment (Molnar, 1979). We have modified Molnar's theory to include a lower bound on event size. We report here the application of this theory in the San Francisco Bay region, to calculate the annual expected number of earthquakes on faults in the central Coast Ranges.

RECENTLY ACTIVE FAULTS IN THE SAN FRANCISCO BAY REGION

The central Coast Ranges surrounding San Francisco Bay (fig. 1) are cut by a number of faults that can be expected to produce future, damaging earthquakes. Several have ruptured historically during large earthquakes (table 1); a few are currently moving (fig. 2). All have been repeatedly active throughout the last 500,000 years (late Quaternary Period).

Most of the recently active faults in the San Francisco Bay region are northwest-trending, right-lateral, strike-slip faults. Principal among these is the San Andreas fault zone, which extends from southern California through the central Coast Ranges past San Francisco, then northward along the Pacific coastline. The San Andreas is paralleled to the east by several subsidiary, recently active right-slip faults which branch from the San Andreas southeast of Hollister. Offshore near San Francisco the San Andreas is joined by the San Gregorio fault zone which trends northward from Monterey.

Southeast of Oakland is the Las Positas fault. This is a small, historically active, northeast-trending left-slip fault which ends to the northeast at the Greenville fault zone. That fault, the Las Positas, ends to the southwest in an imbricate thrust fault zone, the Verona, one of three youthful thrust fault zones in the Bay area. The other two, the Monte Vista and the Evergreen, abut the foot of the hills flanking San Jose. Farther east of San Francisco Bay, the San Joaquin fault zone bounds the east side of the Coast Ranges. This recently active zone, which is predominantly normal in character (east side down), is composed of three separate en echelon parts (northern, middle, and southern). Just west of the southern San Joaquin fault zone, within the east flank of the Coast Ranges, are two large, recently active reverse faults--the O'Neill[1/] and Ortigalita, and several other minor reverse faults which are not shown in figure 1. These faults are characterized by east-side-up movement along east-dipping fault planes.

[1/] The O'Neill fault is considered here as a single break, although it is actually a zone of discontinuous, en echelon, or locally parallel fault strands (Herd, 1979a).

TABLE 1

HISTORIC SURFACE FAULT DISPLACEMENTS ASSOCIATED WITH EARTHQUAKES IN THE SAN FRANCISCO BAY REGION

Date	Fault	Rupture length	Magnitude M (Richter)	Magnitude M_S	Magnitude M
Late June 1838	San Andreas	Unknown	7.0		
July 4, 1861	Calaveras-Sunol	Unknown	5.3		
October 21, 1868	Hayward	30 km	6.7		
April 24, 1890	San Andreas	10 km?	5.9		
April 18, 1906	San Andreas	~430 km		8.2	7.7
August 6, 1979	Calaveras	14.4-21 km		5.7	
January 24, 1980	Greenville	4.2-6.2 km		5.9, 5.2	
January 27, 1980	Greenville	1.1 km		5.3	

Earthquakes of 1838-1906 are referenced in Toppozada and others (1979) and Wesson and others (1975).
Earthquakes of 1979 and 1980 are discussed in Herd and others (1979), Lee and others (1980), Bonilla and others (1980), and Cockerham and others (1980).
Moment magnitude of the 1906 event after Hanks and Kanamori (1979).

SEISMIC SLIP

Seismic slip rates can be determined or inferred for most of the recently active faults in the San Francisco Bay region (fig. 3). Long-term offset rates, which include both seismic and aseismic slip, have been determined geologically on several faults in the San Francisco Bay area (fig. 1; table 2). The contribution of aseismic fault creep to fault slip in the San Francisco Bay region is well known (fig. 2). For the majority of the other faults, long-term rates can also be deduced from geologic information.

An average of 3.7 cm/yr of total slip occurs along the San Andreas fault zone south of Hollister. Part of the displacement (currently as much as 3.6 cm/yr) occurs locally as creep. North of Hollister, near San Francisco, only 2 cm/yr of total slip has been documented along the San Andreas fault zone, but creep is not discernible. About 1.0 cm/yr of total slip has been documented on the San Gregorio fault. This slip increases the long-term offset rate on the San Andreas north of the city, where these two faults join, to about 3.0 cm/yr.

Most of the 1.7 cm/yr of total slip that is not carried northward along the San Andreas beyond Hollister occurs on the Calaveras-Paicines fault, which branches eastward from the San Andreas just south of the town. Although the total offset rate along the Calaveras-Paicines fault has not been directly measured (a minimum offset rate of 0.14-0.71 cm/yr has been geologically established (Nakata, 1977)), the rate is believed to be about 1.5 cm/yr--slightly more than the 1.0-1.2 cm/yr creep rate.[2/]

Slip along the Calaveras-Paicines fault zone is apportioned at San Jose between the Hayward and Calaveras-Sunol faults (fig. 1). Although geologic rates of offset have not been locally determined along either fault, the measurement of 0.6 cm/yr of creep on both the Hayward and Concord (the northern en echelon prolongation of the Calaveras-Sunol, fig. 1) faults at about the same latitude suggests that the 1.5 cm/yr of slip along the Calaveras-Paicines is equally divided between the two. Displacement rates for the northward continuations of the two faults are unknown, but are assumed to be equal to or less than the probable 0.75 cm/yr long-term slip rate on the Hayward and Calaveras-Sunol faults. About 0.02 cm/yr of movement has occurred on the Verona fault, the thrust fault east of the Calaveras-Sunol, during approximately the last 70,000 years (table 2). This slip rate is presumed to

---

[2/] Large historic earthquakes accompanied by surface faulting occurred in the last century on the Hayward and Calaveras-Sunol faults (table 1), branches of the Calaveras-Paicines fault. If observed creep rates in the San Francisco Bay area have been constant through the recent geologic past, there must be a few millimeters of seismic slip on the Calaveras-Paicines fault that is unrepresented in the fault creep rate. However, not all of the missing 1.7 cm/yr of fault slip can be ascribed to the Calaveras-Paicines fault. A portion of the slip (0.2 cm/yr?) is shared with other faults that lie between the San Andreas and Calaveras, or that parallel them to the east.

TABLE 2

GEOLOGICALLY DETERMINED RATES OF OFFSET ON FAULTS IN THE SAN FRANCISCO BAY AREA

Fault	Offset unit	Age (m.y.)	Rate (cm/yr)	Reference
Calaveras	Volcanic rocks	3.5	>0.14-0.71	Nakata (1977)
Midway	Tulare-age erosion surface	[1]0.6	0.005	This report
O'Neill	Corcoran Clay	0.6	0.01	Herd (1979a)
San Andreas	Merced(?) and Santa Clara Formations	1.8-5.0	0.6-2.2	Addicott (1969)
San Andreas	Santa Clara Formation	1-3	1-3	Cummings (1968)
San Andreas	Stream channel	0.003	3.7	Hall and Sieh (1977)
San Gregorio	Marine terraces	0.20	0.63-1.3	Weber and Lajoie (1977)
San Joaquin	Tulare Formation	[1]0.6	0.02	Herd (1979b)
Verona	Buried soils	0.070	0.02	Herd and Brabb (1980)

[1]Along the east side of the Coast Ranges near the San Joaquin and Midway faults, the Corcoran, a regionally extensive 600,000-year-old nonmarine clay (Janda, 1965), occurs near the base of the Tulare (Herd, 1979a).

be comparable with that of the other two thrust faults in the San Francisco Bay region--the Monte Vista and Evergreen faults.[3]

The northeast-trending left-slip Las Positas fault is assumed to move at a rate comparable to the 0.02 cm/yr on the Verona, since the two are directly connected. The Greenville fault zone, a northwest-trending right-slip fault which truncates the Las Positas, is also presumed to move at a rate of about 0.02 cm/yr. The fault is conjugate to the Las Positas, but is not connected to any of the other principal, recently active right-slip faults in the Bay area.

Slip rates of the Midway, San Joaquin, and O'Neill faults at the east side of the central Coast Ranges can be deduced from their apparent vertical offset of the Tulare Formation (table 2). Because the Ortigalita fault lies beyond the westernmost extent of the Tulare Formation, a direct estimate of its geologic slip rate cannot be made. However, the fault is presumed to move at a rate equal to that (0.01 cm/yr) on the nearby O'Neill fault.

EARTHQUAKE MAGNITUDE

It is necessary to estimate the maximum earthquake magnitude that can occur on the faults in the San Francisco Bay region to calculate the frequency of occurrence of damaging earthquakes. The maximum magnitude (Richter) can be calculated from fault length using Slemmon's (1977) linear regressions of earthquake magnitude on length of surface rupture:

for strike-slip faults, $M = 0.597 + 1.351 \log_{10}(L)$

for reverse faults (including thrust faults),

$$M = 4.145 + 0.717 \log_{10}(L)$$

and for normal faults $M = 1.845 + 1.51 \log_{10}(L)$

where M is magnitude and L is fault length in meters.

It should be noted that other analyses (for example, Wesson and others, 1975) have assumed that only one-half a fault's entire length could rupture during a maximum earthquake. Although rupture of the total length of a fault is unlikely, it is not unprecedented (Bonilla, 1979).

---

[3] Little is known about either fault, except that both offset Pliocene and Pleistocene Santa Clara Formation gravels and younger late Pleistocene alluvium. If both faults dip at about 45°, the 30-m-high scarp on the Monte Vista and the 20-m-high scarp on the Evergreen could have been formed in about 424,000 and 280,000 years, respectively, at a slip rate of 0.01 cm/yr.

RATES OF OCCURRENCE OF EARTHQUAKES

Consider, for generality, an arbitrary earthquake magnitude scale. With the distribution of earthquake magnitudes specified (by a magnitude range and Richter b-value) and with seismic slip rate estimated, we can determine an annual rate of occurrence (expected number of events per year in the magnitude range) for each fault in the San Francisco Bay region. To do this, we modify the theory of Molnar (1979) to include a non-zero lower-bound M^{ℓ} on magnitude.

The magnitude distribution for earthquakes on each fault, a truncated exponential distribution, is

$$f_M(M) = k\beta e^{-\beta(M - M^{\ell})} \quad \text{where} \quad M^{\ell} < M < M^M,$$

$$k = (1 - \exp(-\beta(M^M - M^{\ell})))^{-1},$$

and $\beta = \ell n 10 \cdot b$ (b is the slope of the log-number versus magnitude relation, or the so-called "Richter b" value. M^M is the maximum magnitude.)

Thus, the cumulative distribution function on M is

$$F_M(m) = k(1 - e^{-\beta(m - M^{\ell})}).$$

Seismic moment M_o is related to magnitude M through:

$$\log_{10} M_o = cM + d$$

$$\text{or} \quad M = \frac{1}{c} \log_{10} M_o - \frac{d}{c} \,.$$

We seek the probability density function on M_o. The cumulative function is

$$F_{M_o}(M_o) = F_M \left(\frac{1}{c} \log_{10} M_o - d/c\right)$$

$$= k - ka \; M_o^{-\beta/2.3c}$$

where $a = \exp\left(\frac{d\beta}{c} + \beta M^{\ell}\right)$

Differentiating, we obtain the probability density function:

$$f_{M_o}(M_o) = ka \; \frac{\beta}{2.3c} \; M_o^{\frac{-\beta}{2.3c} - 1} \,.$$

The expected seismic moment, then, is

$$E[M_o] = \int_{M_o^{\ell}}^{M_o^{M}} M_o \, f_{M_o}(M_o) dM_o$$

where M_o^{ℓ} and M_o^{M} can be obtained substituting M^{ℓ} and M^{M} into the relation:

$$M_o = 10^{cM + d}.$$

For $E[M_o]$ we get

$$E[M_o] = \frac{ka \;\; \beta/2.3c}{1 - \beta/2.3c} \; [M_o^{M \; 1-\beta/2.3c} - M_o^{\ell \; 1-\beta/2.3c}].$$

The activity rate of a fault is calculated through the "rate of occurrence of seismic moments" which Molnar calls $\dot{M}_o^{\Sigma}$. It is just γ, the rate of occurrence of earthquakes, times $E[M_o]$: $\dot{M}_o^{\Sigma} = \gamma \, E[M_o]$. Also, it is equal to:

$$\dot{M}_o^{\Sigma} = \mu AS$$

where S is the seismic slip rate. Equating the last two, and solving for the rate, gives:

$$\gamma = \frac{\mu AS}{E[M_o]} .$$

Here, μ is the shear modulus and A is the area of the entire fault (not just the section which is expected to rupture). This gives us a method of calculating γ from the fault parameters and S.

For the San Francisco Bay region, the following values were used (Hanks and Karamori, 1979):

$\mu = 3 \times 10^{11}$ dynes/cm^2
A = 10 km x length
c = 1.5
d = 16.

The frequency of occurrence of damaging earthquakes on recently active faults in the San Francisco Bay area (table 3) has been calculated from seismic slip and seismic moment using the method described in this paper, and using Richter magnitude as the description of earthquake size. Table 3 is ordered by fault, but is constructed to reflect differences in slip rates or in earthquake behavior on segments of the same fault where they occur.

TABLE 3

FAULT SYSTEMS IN THE SAN FRANCISCO BAY AREA,
AND MEAN VALUES OF ASSOCIATED PARAMETERS

	Fault	Magnitude Range M (Richter)	Richter[2] b	Length (km)	Seismic Slip (cm/yr)	Creep (cm/yr)	Total Slip (cm/yr)	E[Mo]	Activity Rate[1] (event/yr)	Recurrence Interval (years)
1)	Northern San Andreas Peninsular San Andreas	7.6-8.2	.72	430	1.90	0	--[1]	6.89x10^{27}	.0036	278
2)	Northern San Andreas San Gregorio	7.5-8.2	.72	410	.95	0	--[1]	5.82x10^{27}	.0020	500
3)	Northern San Andreas	6.7-7.9	.72	270	.15	0	3	8.86x10^{26}	.0014	729
4)	Peninsular San Andreas	5 -7.6	.72	160	.10	0	2	3.03x10^{25}	.0159	63
5)	Central San Andreas	5 -7.7	.72	170	.10	3.6	3.7	3,62xk0^{25}	.0141	71
6)	San Gregorio	5 -7.5	.75	140	.05	0	1	2.29x10^{25}	.0092	109
7)	Hosgri	5 -7.8	.75	200	1.00	0	1	3.85x10^{25}	.1559	6
8)	Rodgers Creek	5 -6.9	.75	50	.75	0	.75	8.15x10^{24}	.1381	7
9)	Maacama	5 -7.5	.75	140	.55	.2	.75	2.29x10^{25}	.1007	10
10)	Calaveras-Paicines Calaveras-Sunol	5 -7.7	.9	170	.15	.6[4]	.75	1.86x10^{25}	.0411	24
11)	Calaveras-Paicines Hayward	5 -7.7	.9	190	.15	.6	.75	1.86x10^{25}	.0459	22
12)	Calaveras-Sunol	5 -7.1	.9	70	.35[3]	.25	.75	7.95x10^{24}	.0925	11
13)	Green Valley	5 -7.3	.75	90	.72	.03	.75	1.62x10^{25}	.1196	8
14)	Concord	5 -6.4	.9	20	.15	.6	.75	2.86x10^{24}	.0315	32
15)	Sargent	5 -6.4	.72	20	.1	.3	.75	3.57x10^{24}	.0168	60
16)	Quien Sabe	5 -6.4	.9	20	.1	0	.1	2.86x10^{24}	.0210	48
17)	Greenville	5 -7.0	.9	50	.02	0	.02	6.89x10^{24}	.0044	227
18)	Las Positas	5 -6.2	.9	14	.02	0	.02	2.12x10^{24}	.0040	250
19)	Monte Vista	5 -7.2	.75	20	.02	0	.02	1.37x10^{25}	.0009	1111
20)	Evergreen	5 -7.1	.75	14	.02	0	.02	1.15x10^{25}	.0007	1429
21)	Midway	5 -7.0	.9	11	.005	0	.005	6.89x10^{24}	.0002	5000
22)	Verona	5 -7.0	.9	10	.02[2]	0	.02	6.89x10^{24}	.0009	1111
23)	O'Neill	5 -7.3	.9	24	.01	0	.01	1.06x10^{25}	.0007	1429
24)	Ortigalita	5 -7.6	.9	60	.01	0	.01	1.62x10^{25}	.0011	909
25)	North San Joaquin	5 -7.3	.9	60	.02	0	.02	1.06x10^{25}	.0034	294
26)	Middle San Joaquin	5 -6.6	.9	14	.02	0	.02	3.85x10^{24}	.0022	455
27)	South San Joaquin	5 -6.8	.9	20	.02	0	.02	5.16x10^{24}	.0023	435

1. Total slip is counted in faults 3, 4, and 5.
2. It should be noted that an annual average slip rate of 0.01 cm/yr has been determined for the Verona fault when the cumulative apparent dip-slip separation of gravels of Pliocene and Pleistocene age is also considered (Herd and Brabb, 1980). As a consequence, the rates of the Greenville, Las Positas, Monte Vista, and Evergreen faults may be similarly reduced.
3. Total seismic slip for the Calaveras-Sunol is .5 cm/yr when the .15 cm/yr from #8 is added.
4. 0.6 cm/yr creep is assigned to the Calaveras section only.

The San Andreas and Calaveras faults have been divided into segments and grouped into fault systems to reflect differences in slip rates and historic seismicity along these fault systems. The long-term rate of movement along the San Andreas decreases from 3.7 cm/yr south of Hollister to about 2 cm/yr between Hollister and San Francisco. North of San Francisco, the slip rate increases to about 3 cm/yr. The part of the San Andreas fault between San Francisco and Hollister (herein referred to as the peninsular San Andreas) has been seismically active since the San Francisco earthquake of 1906. The portion of the San Andreas north of San Francisco (the northern San Andreas) has been practically aseismic since 1906 (Eaton, in press). Apparently only large earthquakes (magnitude 6.5-8 earthquakes) occur on the northern San Andreas. Similarly the rate of long-term slip along the Calaveras-Paicines fault falls from about 1.5 cm/yr north of Hollister to about 0.75 cm/yr east of San Jose, where the Hayward fault splays westward from the Calaveras-Sunol.

The northern San Andreas fault has been coupled with both the peninsular San Andreas and the San Gregorio faults to reflect the differences in slip rates along the San Andreas north of Hollister, as well as to explain the apparent absence of small and moderate earthquakes on the San Andreas north of San Francisco (Eaton, in press). Because both the peninsular and northern San Andreas faults ruptured continuously in 1906, great earthquakes on the San Andreas can apparently break through portions of the fault that have different slip rates. A fault system composed of both the northern and peninsular portions of the San Andreas fault (table 3) has been assigned earthquake magnitudes assuming that only great earthquakes can occur on that fault combination. The maximum earthquake for the fault combination has been determined assuming that the entire combined length of the two fault segments (430 km) would break in the maximum earthquake. The lower bounding magnitude (7.6) is the earthquake that most likely would occur if the peninsular or northern sections ruptured in totality. A lower bound magnitude of 5.0 has been used on other faults and fault combinations because, in the context of seismic hazard analysis, small events rarely produce ground motions of engineering concern.

Hanks and Kanamori (1979) introduced a moment-magnitude scale M which is uniformly valid for M_L and $M_S \leq 7.5$, and $M_W > 7.5$, where M_W is the magnitude scale introduced by Kanamori (1977). This energy-based scale does not saturate and hence is a better measure of earthquake source strength than magnitude scales reliant on instrument response. Table 4 of this report contains recurrence intervals based on M rather than Richter magnitude. The magnitude (**M**) range has been recalculated for each fault, using the relationships suggested by Abe (1975):

$$M_o = 1.23 \times 10^{22} A^{3/2} \text{ dyne/cm}$$ where A is the fault area (10 km x length),

and Hanks and Kanamori (1979):

$$\mathbf{M} = 2/3 \log M_o - 10.7.$$

TABLE 4

FAULT SYSTEMS IN THE SAN FRANCISCO BAY AREA, AND MEAN VALUES OF ASSOCIATED PARAMETERS

	Fault	Magnitude Range M	Richter b	Length (km)	Seismic Slip (cm/yr)	E[Mo]	Activity Rate (events/year) 5.0≤M<6.0	6.0≤M<7.0	7.0≤M	Total 5.0≤M	Recurrence Interval (years)
1)	Northern San Andreas Peninsular San Andreas	7.2-7.7	.72	430	1.90	$1.46x10^{2/}$			.0168	.0168	59
2)	Northern San Andreas San Gregorio	7.2-7.6	.72	410	.95	$1.22x10^{2/}$			.0096	.0096	105
3)	Northern San Andreas	6.4-7.5	.72	270	.15	$2.64x10^{26}$		.0029	.0017	.0046	217
4)	Peninsular San Andreas	5 -7.2	.72	160	.10	$1.48x10^{25}$	.0263	.0051	.0011	.0324	31
5)	Central San Andreas	5 -7.3	.72	170	.10	$1.77x10^{25}$	.0234	.0044	.0010	.0288	35
6)	San Gregorio	5 -7.3	.75	180	.05	$1.62x10^{25}$	.0136	.0025	.0005	.0166	60
7)	Hosgri	5 -7.3	.75	200	1.00	$1.62x10^{25}$	.3036	.0050	.0117	.3693	3
8)	Rodgers Creek	5 -6.7	.75	50	.75	$5.77x10^{24}$	.1602	.0347		.1949	5
9)	Maacama	5 -7.2	.75	140	.55	$1.37x10^{25}$	.1389	.0226	.0074	.1689	6
10)	Calaveras-Paicines Calaveras-Sunol	5 -7.3	.9	170	.15	$1.06x10^{25}$	.0625	.0083	.0015	.0723	14
11)	Calaveras-Paicines Hayward	5 -7.3	.9	190	.15	$1.06x10^{25}$	.0699	.0083	.0017	.0809	12
12)	Calaveras-Sunol	5 -6.9	.9	70	.35	$5.96x10^{24}$	.1058	.0175		.1233	8
13)	Green Valley	5 -7.0	.75	90	.72	$9.68x10^{24}$	.1651	.0293	.0064	.2008	5
14)	Concord	5 -6.3	.9	20	.15	$2.46x10^{24}$	.0309	.0056		.0365	27
15)	Sargent	5 -6.3	.72	20	.10	$2.99x10^{24}$	.0164	.0037		.0201	50
16)	Quien Sabe	5 -6.3	.9	20	.10	$2.46x10^{24}$	.0207	.0037		.0244	41
17)	Greenville	5 -6.7	.9	50	.01	$4.46x10^{24}$	.0031	.0003		.0034	297
18)	Las Positas[1]	5 -6.2	.9	14	.01	$2.12x10^{24}$	.0017	.0003		.0020	504
19)	Monte Vista[1]	5 -6.5	.75	20	.01	$4.09x10^{24}$	.0012	.0003		.0015	681
20)	Evergreen[1]	5 -6.3	.75	14	.01	$2.89x10^{24}$	.0012	.0003		.0015	689
21)	Midway[1]	5 -6.2	.9	11	.005	$2.12x10^{24}$	.0007	.0001		.0008	1283
22)	Verona[1]	5 -6.0	.9	10	.01	$1.56x10^{24}$	.0016	.0003		.0019	520
23)	O'Neill[1]	5 -6.6	.9	24	.01	$3.85x10^{24}$	.0016	.0003		.0019	534
24)	Ortigalita	5 -6.8	.9	60	.01	$5.16x10^{24}$	.0030	.0005		.0035	286
25)	North San Joaquin[1]	5 -7.0	.9	60	.02	$6.89x10^{24}$	.0045	.0006	.0001	.0052	191
26)	Middle San Joaquin[1]	5 -6.3	.9	14	.02	$2.46x10^{24}$	.0029	.0005		.0034	293
27)	South San Joaquin[1]	5 -6.5	.9	20	.02	$3.32x10^{24}$	.0031	.0005		.0036	277

[1] All faults are assumed to dip at a 45° angle.

The result is a smaller upper bound magnitude, M^M, for each fault. This change in the magnitude range reduces the expected moment for each fault because the interval of integration is smaller. The resulting recurrence intervals for each fault are thus shorter than those calculated using Richter magnitude. For most of the smaller faults in the Bay Area, $M_S^M \lesssim 7.2$), the recurrence intervals are shortened by a factor of no more than 2-3, which is close to the average accuracy of the relationship between M_o and M_s calculated in the described manner (Percaru and Berckheimer, 1978).

The major differences between Table 3 and Table 4 are in the recurrence intervals calculated for the large faults ($M_S^M \gtrsim 7.2$) where the M_S, M_L scales saturate. For the most active faults in the San Andreas system (#1-4 in Table 4), the recurrence intervals are decreased by a factor of ~5. This translates to a recurrence interval of about 30 years for a moderate to large earthquake on the northern San Andreas fault. Such a recurrence rate has not been observed this century; in fact, the northern San Andreas has been rather quiescent since the 1906 event. The long-term behavior of this part of the San Andreas fault may be characterized by alternating periods of quiescence and activity, with a periodicity on the order of centuries (Herd et al., 1981). The average recurrence interval indicated in Table 4 is consistent with this characterization.

SUMMARY

We have developed and applied a logical rationale for taking geologic and tectonic information into account for the estimation of average rates of occurrence of earthquakes. A note of caution is appropriate: Not all of the data necessary for confident application of the methodology are available in the San Francisco Bay region. Some values given in Table 3 and 4, in particular those for seismic slip rates on some faults, represent only guesses on the basis of data available at other locations and of an understanding of the regional tectonic framework. A second possible source of error is in the division of total slip between seismic slip and creep. On the Rodgers Creek, Maacama, Calaveras-Sunol and Green Valley faults, little creep is discernible so the bulk of the total slip has been attributed to seismic activity. This results in activity rates four to five times higher than those observed in the recent past. Clearly, the relationship between creep, total slip, seismic activity, and recent earthquake history is not well understood for these faults.

The choice of magnitude scale has an important influence on calculated rates of seismic activity. The use of Richter magnitude, with upper bounds on magnitude of the order of 8.2, indicate recurrence intervals of about 150 years for large ($M > 7.5$) earthquakes on the northern San Andreas. These upper bounds also indicate inordinately large displacements on the San Andreas, which have not been observed historically. The use of moment magnitude, with lower maximum magnitudes, indicates recurrence intervals on the order of 40 years for $M > 7.2$. Upper bound values of M indicate displacement consistent with those observed during the 1906 San Francisco earthquake. The small recurrence intervals obtained using M, while not observed in the recent past, may be a better estimate of average activity over long time intervals than estimates consistent with recent observations. For this reason, and because moment magnitude is a more consistent measure of earthquake size than Richter magnitude, a consistency which aids the theory presented here, we generally prefer estimates of recurrence intervals which are based on moment magnitude.

The ultimate purpose of calculating seismic recurrence rates is the evaluation and mitigation of seismic hazard. To best serve these ends, the seismic activity rates presented here must be scrutinized to ensure either that the seismic hazard they imply is consistent with historical observations or that reasons for differences are well understood. Only by examining all relevant theories and data, and by understanding their implications in light of historical observations and prehistorical evidence, can we make rational assessments of earthquake hazards.

REFERENCES CITED

Addicott, W. A., 1969, Late Pliocene mollusks from San Francisco Peninsula, California, and their paleogeographic significance: Proceedings of the California Academy of Sciences, Fourth Series, v. 7, no. 3, p. 57-93.

Abe, K., 1975, Reliable estimation of the seismic moment of large earthquakes: Journal of Physical Earth, no. 23, p. 381-390.

Bonilla, M. G., 1979, Historic surface faulting--Map patterns, relation to subsurface faulting, and relation to preexisting faults: U.S. Geological Survey Open-file Report 79-1239, p. 36-65.

Bonilla, M. G., Lienkaemper, J. J., and Tinsley, J. C., 1980, Surface faulting near Livermore, California, associated with the January 1980 earthquakes: U.S. Geological Survey Open-file Report 80-523, 32 p.

Cockerham, R. S., Lester, S. W., and Ellsworth, W. L., 1980, A preliminary report on the Livermore Valley earthquake sequence January 24-February 26, 1980: U. S. Geological Survey Open-file Report 80-714, 45 p.

Cummings, J. C., 1968, The Santa Clara Formation and possibly post-Pliocene slip on the San Andreas fault in central California, in Dickinson, W. R., and Grantz, Arthur, eds., Proceedings of conference on geologic problems of San Andreas fault system: Stanford University Publications in the Geological Sciences, v. 11, p. 191-207.

Eaton, J. P., in press, Temporal variations in the pattern of seismicity in central California: International Symposium on Earthquake Prediction, Proceedings, Paris, France, April 1979.

Frizzell, V. A., Jr., and Brown, R. D., Jr., 1976, Map showing recently active breaks along the Green Valley fault, Napa and Solano Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-743, scale 1:24,000, 1 sheet.

Hall, N. T., and Sieh, K. E., 1977, Late Holocene rate of slip on the San Andreas fault in the northern Carrizo Plain, San Luis Obispo County, California (abs.): Geological Society of America Abstracts with Programs, v. 9, no. 4, p. 428-249.

Hanks, T. C. and Kanamori, H., 1979, A moment magnitude scale: Journal Geophysical Research, v. 84, no. B5, p. 2348-2350.

Harsh, P. W., Pampeyan, E. H., and Coakley, J. M., 1978, Slip on the Willits fault, California (abs.): Seismological Society of America Earthquake Notes, v. 49, no. 1, p. 22.

Herd, D. G., 1979a, Geologic map of O'Neill Forebay, Western Merced County, California: U.S. Geological Survey Open-file Report 79-359, scale 1:24,000, 2 sheets, 11 p. text.

Herd, D. G., 1979b, The San Joaquin fault zone--Evidence for late Quaternary faulting along the west side of the northern San Joaquin Valley, California: Geological Society of America Abstracts with Programs, v. 11, no. 3, p. 83.

Herd, D. G., and Brabb, E. E., 1980 Faults at the General Electric Test Reactor site, Vallecitos Nuclear Center, Pleasanton, California: U.S. Geological Survey Administrative Report, 77.

Herd, D. G., Shedlock, K. M., Ellsworth, W. L., and Lindh, A. G., 1981, The next great 1906 San Francisco earthquake: [in press].

Herd, D. G., McLaughlin, R. J., Sarna-Wojcicki, A. M., Clark, M. M., Lee, W. H. K., Sharp, R. V., Sorg, D. H., Stuart, W. D., Harsh, P. W., and Mark, R. K., 1979, Surface faulting accompanying the August 6, 1979 Coyote Lake earthquake (abs.): EOS, v. 60, no. 46, p. 889.

Janda, R. J., 1965, Quaternary alluvium near Friant, California, in Schultz, C. B., and Smith, H. T. U., eds., International Association for Quaternary Research, VIIIth Congress, Guidebook for Field Conference I, Northern Great Basin and California: Nebraska Academy of Sciences, Lincoln, p. 128-133.

Kanamori, H., 1977, The energy release in great earthquakes: Journal Geophysical Research, v. 82, no. 20, p. 2981-2987

Lee, W. H. K., Herd, D. G., Cagnetti, V., Bakun, W. H., and Rapport, A., 1979, A preliminary study of the Coyote Lake earthquake of August 6, 1979 and its major aftershocks: U.S. Geological Survey Open-file Report 79-1621, 40 p.

Molnar, Peter, 1979, Earthquake recurrence intervals and plate tectonics: Seismological Society of America Bulletin, v. 69, p. 115-133.

Nakata, J. K., 1977, Distribution and petrology of the Anderson-Coyote Reservoir volcanic rocks: San Jose State University, Calif., Master of Science Thesis, 105 p.

Percaru, G., and Berckheimer, H., 1978, A magnitude scale for very large earthquakes: Tectonophysics, no. 49, 189-198.

Prescott, W. H., and Burford, R. O., 1976, Slip on the Sargent fault: Seismological Society of America Bulletin, v. 66, no. 3, p. 1013-1016.

Savage, J. C., and Burford, R. O., 1973, Geodetic determination of relative plate motion in central California: Journal of Geophysical Research, v. 78, no. 5, p. 832-845.

Slemmons, D. B., 1977, State-of-the-art for assessing earthquake hazards in the United States: U.S. Army Engineer Waterways Experiment Station Miscellaneous Paper S-73-1, Report 6, var. p.

Thenhaus, P. C., Perkins, D. M., Ziony, J. I., and Algermissen, S. T., 1979, Probabilistic estimates of maximum seismic acceleration in rock in coastal California and the adjacent outer continental shelf: U.S. Geological Survey Open-file Report 80-924, 61 p.

Toppozada, T. R., Real, C. R., Bezore, S. P., and Parke, D. L., 1979, Compilation of pre-1900 California earthquake history: California Division of Mines and Geology Open-file Report OFR 79-6 SAC, 271 p.

Weber, G. E., and Lajoie, K. R., 1977, Late Pleistocene and Holocene tectonics of the San Gregorio fault zone between Moss Beach and Point Ano Nuevo, San Mateo County, California (abs.): Geological Society of America Abstracts with Programs, v. 9, no. 4, p. 524.

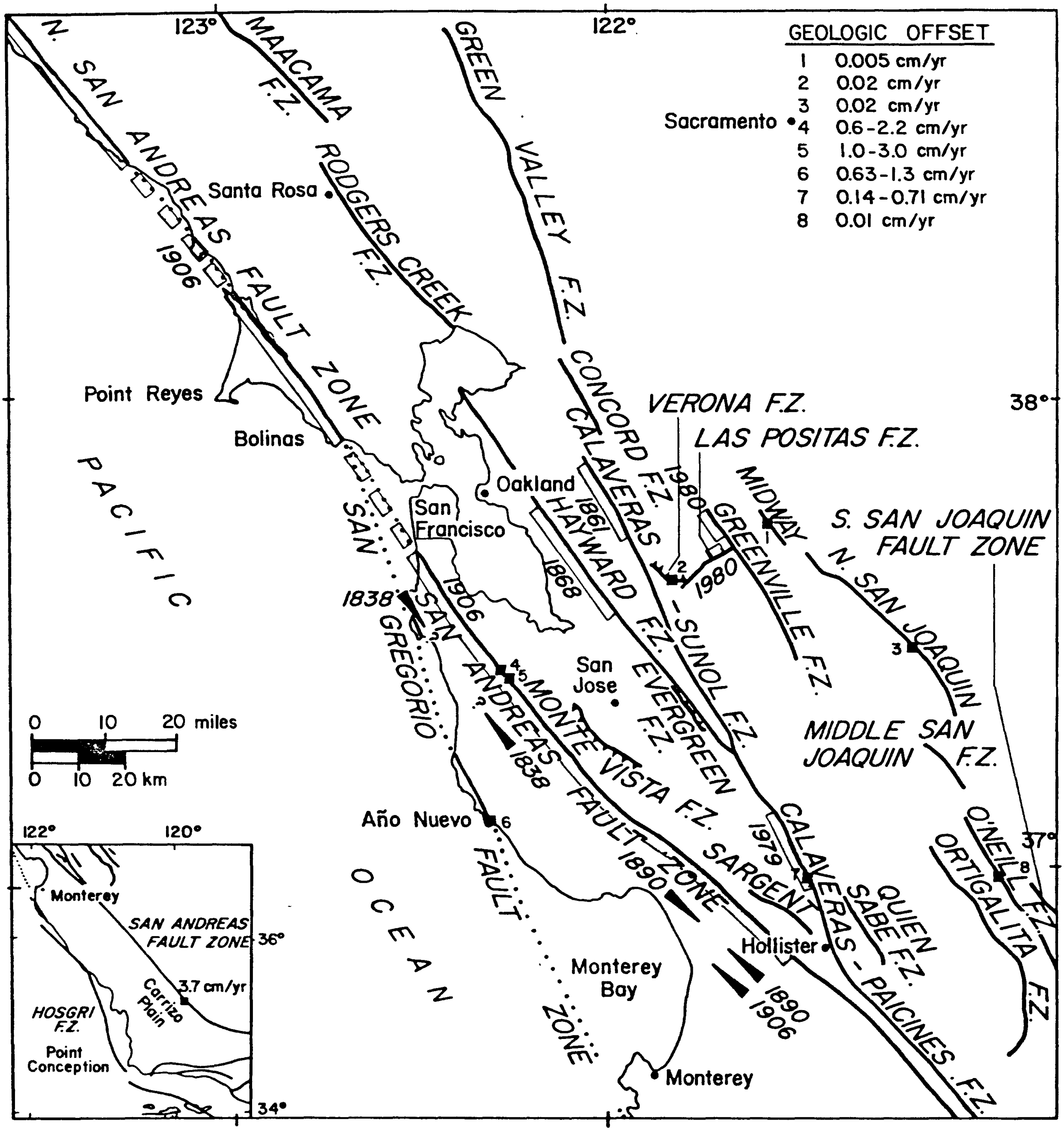
Wesson, R. L., Helley, E. J., Lajoie, K. R., and Wentworth, C. M., 1975, Faults and future earthquakes, in Borcherdt, R. D., ed., Studies for seismic zonation of the San Francisco Bay region: U.S. Geological Survey Professional Paper 941-A, p. A5-A30.

FIGURE CAPTIONS

Figure 1. Map of principal recently active faults in the San Francisco Bay region, showing zones of surface rupture associated with historic earthquakes (table 1). Solid squares denote locally determined rates of geologic offset (table 2).

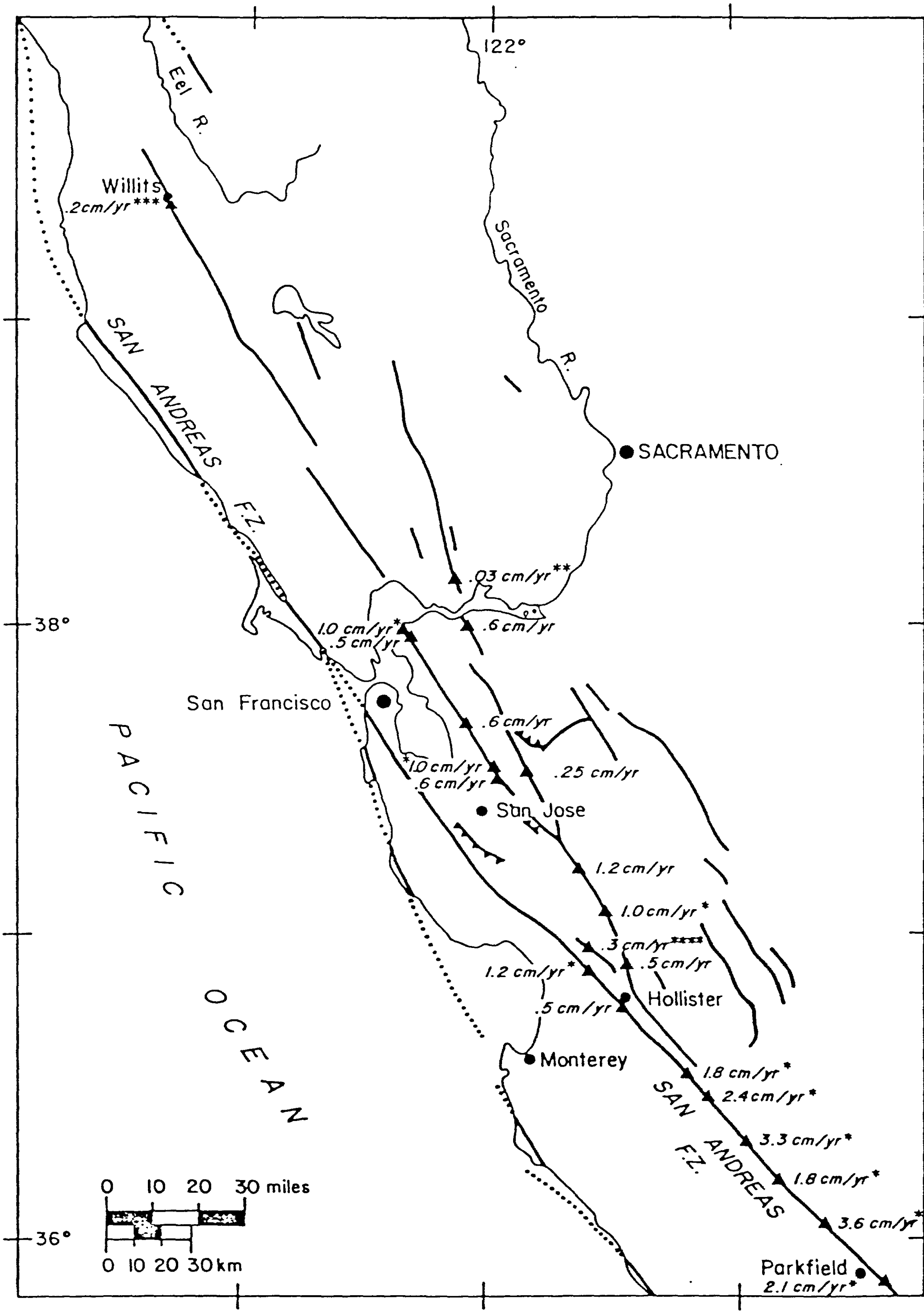
Figure 2. Documented fault creep in central coastal California. Rates marked by * are from Savage and Burford (1973), ** from Frizzell and Brown (1976), *** from Harsh and others (1978), **** from Thenhaus and others (1979). All others are from Wesson and others (1975).

Figure 3. Rates of fault slip in the San Francisco Bay region. Long-term geologic slip rates appear first. Seismic slip rates (geologic slip minus fault creep) follow in parentheses.



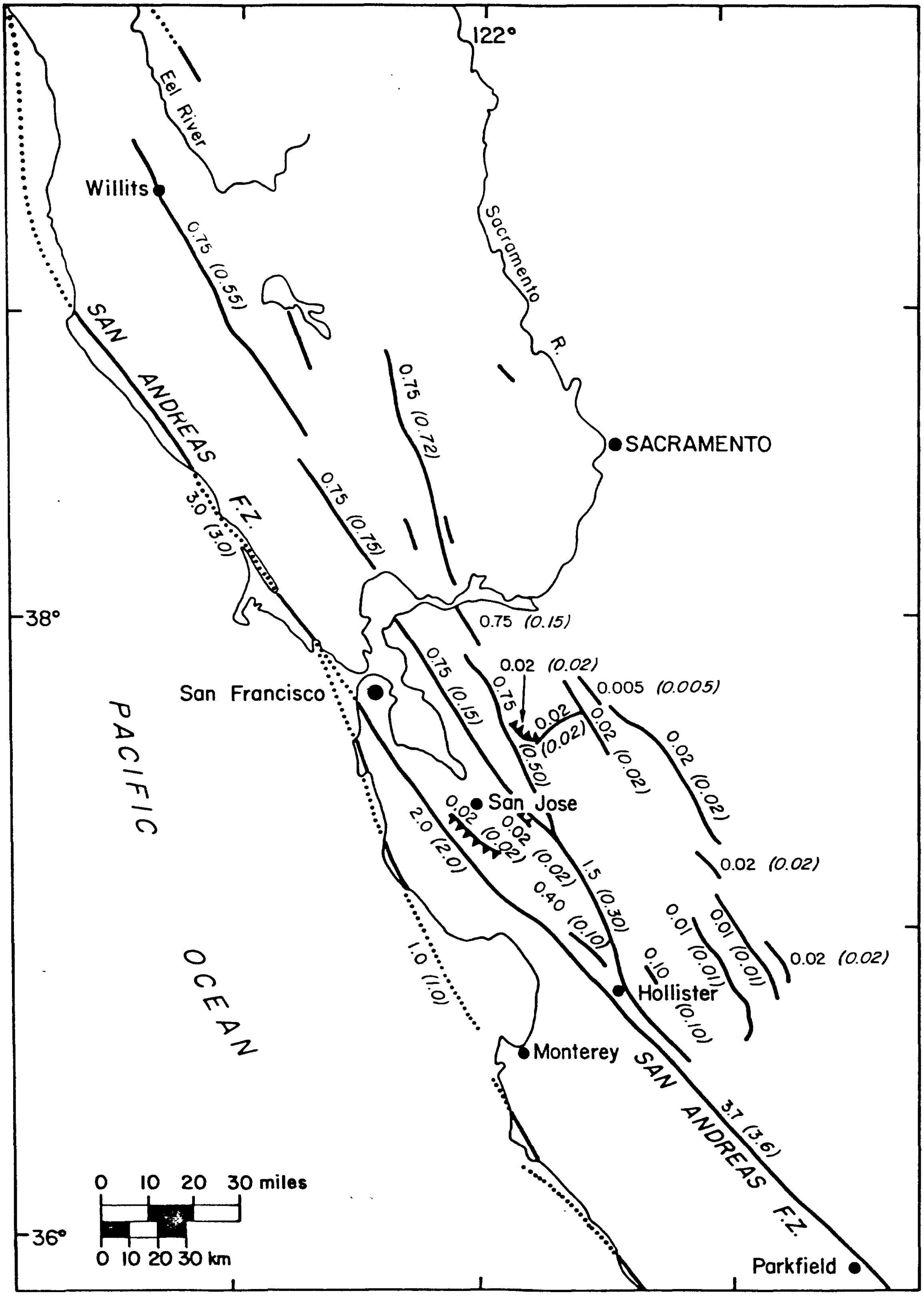
123°
122°
38°
37°
GEOLOGIC OFFSET
1 0.005 cm/yr
2 0.02 cm/yr
3 0.02 cm/yr
4 0.6-2.2 cm/yr
5 1.0-3.0 cm/yr
6 0.63-1.3 cm/yr
7 0.14-0.71 cm/yr
8 0.01 cm/yr
N. SAN ANDREAS FAULT ZONE
MAACAMA F.Z.
GREEN VALLEY F.Z.
RODGERS CREEK F.Z.
Sacramento
Santa Rosa
1906
Point Reyes
Bolinas
PACIFIC OCEAN
CONCORD F.Z.
CALAVERAS - SUNOL F.Z.
VERONA F.Z.
LAS POSITAS F.Z.
MIDWAY
GREENVILLE F.Z.
S. SAN JOAQUIN FAULT ZONE
N. SAN JOAQUIN
MIDDLE SAN JOAQUIN F.Z.
Oakland
San Francisco
1861
1868
HAYWARD F.Z.
1980
SAN GREGORIO FAULT ZONE
1838
SAN ANDREAS FAULT ZONE
MONTE VISTA F.Z.
San Jose
EVERGREEN F.Z.
SARGENT
CALAVERAS - PAICINES F.Z.
1979
QUIEN SABE F.Z.
O'NEILL F.Z.
ORTIGALITA F.Z.
Año Nuevo
1890
1906
Hollister
Monterey Bay
Monterey
0 10 20 miles
0 10 20 km
122°
120°
Monterey
SAN ANDREAS FAULT ZONE
36°
3.7 cm/yr
Carrizo Plain
HOSGRI F.Z.
Point Conception
34°

Figure 1.



122°
Eel R.
Willits
.2cm/yr***
Sacramento R.
SACRAMENTO
SAN ANDREAS F.Z.
.03 cm/yr**
.6 cm/yr
38°
1.0 cm/yr*
.5 cm/yr
San Francisco
.6 cm/yr
*1.0 cm/yr
.6 cm/yr
.25 cm/yr
San Jose
PACIFIC OCEAN
1.2 cm/yr
1.0 cm/yr*
.3 cm/yr****
.5 cm/yr
1.2 cm/yr*
Hollister
.5 cm/yr
Monterey
1.8 cm/yr*
2.4 cm/yr*
SAN ANDREAS F.Z.
3.3 cm/yr*
1.8 cm/yr*
3.6 cm/yr*
0 10 20 30 miles
36°
0 10 20 30 km
Parkfield
2.1 cm/yr*

Figure 2.



122°
Eel River
Willits
Sacramento R.
SACRAMENTO
SAN ANDREAS F.Z.
0.75 (0.55)
0.75 (0.72)
0.75 (0.75)
3.0 (3.0)
38°
0.75 (0.15)
San Francisco
0.75 (0.15)
0.75 (0.50)
0.02 (0.02)
0.02 (0.02)
0.005 (0.005)
0.02 (0.02)
0.02 (0.02)
PACIFIC
San Jose
0.02 (0.02)
0.02 (0.02)
2.0 (2.0)
0.40 (0.10)
1.5 (0.30)
0.02 (0.02)
0.01 (0.01)
0.01 (0.01)
0.02 (0.02)
0.10 (0.10)
OCEAN
1.0 (1.0)
Hollister
Monterey
SAN ANDREAS F.Z.
3.7 (3.6)
0 10 20 30 miles
36°
0 10 20 30 km
Parkfield

Figure 3.