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Probabilistic and Scenario Estimates of Losses to Dwellings in California

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INTRODUCTION

The importance of assessing future earthquake losses in California has become even more apparent with the occurrence of the Loma Prieta, California, earthquake in 1989. The estimation of earthquake losses serves a number of needs. Loss estimation can (1) serve as a guide to disaster mitigation in outlining the portions of the state that may experience catastrophic losses in the future; (2) help in establishing the expected catastrophe potential and the average annual loss for economic planning and insurance purposes; and (3) serve as an additional tool in land-use planning.

A number of studies of dwelling losses in California have been published (for example, Algermissen and others, 1970; Algermissen and Steinbrugge, 1978; Steinbrugge and others, 1981; Algermissen and Steinbrugge, 1984; Steinbrugge and Algermissen, 1990). Changing and improved methods of analysis, an improved understanding of the spatial distribution of ground shaking and its effects on the ever-changing numbers of housing units and their value all provide impetus for this study.

Methods used in this paper rely on monetary losses derived from Modified Mercalli intensity evaluations. These methods become necessary when actual loss experience is not available.

OBJECTIVES

The principal objective is to provide estimates of losses to one-to-four family dwellings in California using a variety of techniques. We shall present, in particular:

1. Probabilistic assessment of maximum losses for periods of interest of 10, 50, and 250 years.

2. Average annual losses based on a simulation of the effects of 100 years of historical earthquakes having maximum Modified Mercalli intensities of VII or greater that have occurred from 1890 through 1989.

MATERIALS USED

The principal data used in the assessment of the losses by the various methods were:

1. U.S. Census data for 1980 updated to July 1, 1988, to obtain the numbers of housing units.

2. Observations of Modified Mercalli intensity (MMI) from 53 earthquakes that occurred from April 18, 1906, through November 8, 1980.

3. Replacement costs for dwellings during June 1988.

4. Probabilistic hazard map parameters (seismic source zones and seismicity rates used in the development of ground motion maps for California and the rest of the United States (Algermissen and others, 1990).

Census Data

The number of one-to-four housing units per structure distributed throughout California were obtained from the 1980 U.S. Census Data and updated to July 1, 1988. The dwelling or housing inventory was constructed from the 1980 census of housing as published by the Bureau of the Census (1983a,b,c), augmented by other information since 1980 from the Bureau of the Census publications and other Bureau data (unpublished).

Updating Housing 1980-88

The Census does not make inter-census estimates for housing, but they do for population on a county basis. The latest estimate was for June 30, 1988, which gave births, deaths, and net migration. Since births and deaths probably do not greatly affect housing stock, the update was based on net migration. The number of housing units in 1988 was then calculated assuming that occupancy rates have not changed since 1980 and that new housing is uniform across any county.

Replacement Costs for Dwellings

The replacement cost of a dwelling is taken here to mean the dollar amount (or percentage of the total cash value) required to fully repair, in kind, any one-to-four family dwelling. Only earthquake losses associated with ground shaking are estimated in this paper. The replacement costs for dwellings throughout California were obtained from data supplied by Boards of Realtors distributed throughout California.

Modified Mercalli Intensity (MMI) Data

Vulnerability, the relationship between building damage and earthquake shaking as used in this study, may be related to Modified Mercalli intensity. Intensity data for the 53 earthquakes listed in Table 1 that occurred in California from April 18, 1906 through November 8, 1980 were used. The total number of intensity observations available for the 53 earthquakes is 7307 (fig. 1). The intensity data were used in the following two ways: (1) To obtain mean curves of intensity attenuation with distance; and (2) to establish the approximate magnitude of the site response in each of the Census subdivisions for which estimates of earthquake losses were attempted.

Regression of the intensity data to obtain mean curves of intensity attenuation were undertaken using a relationship of the form

$$I = f(I_0', r, h) \qquad (1)$$

where I is the intensity at any distance, I_0' is the intercept of the mean attenuation function on the intensity axis (Arnold, 1990), r is the distance from the "energy center" on the surface to the point of observation of the intensity I, and h is the fixed average hypocentral depth of the earthquake. Arnold (1990) has shown that I_0' is closely related to the magnitude of the earthquakes.

In practice the earthquake data were organized into three spatial groups to obtain mean attenuation curves for three geographical areas in California (fig. 2). The equations for attenuation of intensity in the three geographical areas of California outlined in Figure 2 are given in Table 2.

Figure 3 shows a typical regression of intensity data with distance for earthquakes in northern California. The deviation of individual intensity observations from the mean curve is called an intensity residual (ΔI) and is taken to represent the contribution of the site geology to the ground shaking (the site response).

The 7307 intensity observations from the 53 earthquakes selected were observed at 2146 locations (fig. 1); and, consequently, there was more than one intensity observation available at many sites. For each intensity observation I_{obs} and each average intensity (I_{ave}) computed at the same point, the quantity

$$\Delta I = I_{obs} - I_{ave} \qquad (2)$$

was computed. In practice, the maximum number of intensity observations at any one site was 23. One thousand three-hundred thirty-six (1336) sites had more than one observed intensity, and the average number of intensity observations per site was 3.4. Table 3 shows the distribution of intensity observations with Census tracts. At every site where more than one intensity observation existed, the mean site response ΔI_m was calculated

$$\Delta I_m = \frac{\Delta I_1 + \Delta I_2 + \ldots + \Delta I_n}{n} \qquad (3)$$

The ΔI_m's were then taken to represent the site response. The ΔI_m's were associated with each Census tract in the following way. Each tract, or in the case of untracted counties, each Census Civil Division (CCD), was considered individually. The distances from the center of population of the tract to the location of each measured ΔI were computed and the closest measured ΔI was assigned to that tract or CCD. Table 4 shows the distribution of the distance from tract center to closest observational site. The unweighted mean distance from tract to observation is 2.82 km even though there are about 100 tracts over 10 km from their corresponding observations. These latter are all associated with regions of low population density.

ESTIMATION OF LOSSES

Two types of loss estimation were undertaken: (1) Deterministic (scenario) estimates for individual earthquakes, and (2) probabilistic loss estimates.

Deterministic (Scenario) Loss Estimates

The objective of the calculation of loss estimates by simulating losses associated with individual earthquakes is to obtain an estimate of the average annual loss associated with earthquakes in California. For this purpose, the effects of the actual earthquakes occurring in California with maximum Modified Mercalli intensities of VII and greater from 1890 through 1989 were simulated (table 5).

Figure 4 shows a schematic of the elements of deterministic and probabilistic loss assessment. In this study, the numbers and values (the inventory) of one-to-four family dwellings were obtained from the U.S. Census data as already discussed. Three different vulnerability relationships were used: (1) a vulnerability relationship developed by K.V. Steinbrugge (Algermissen and others, 1990) slightly modified to exclude mean damage at intensity VI; (2) a vulnerability relationship developed by the Applied Technology Council (1985); and (3) a proprietary relationship developed by one of the authors (KVS).

Vulnerability relationships (1) and (2) are shown in Table 6. The Modified Mercalli intensity I at the center of population of any Census tract a distance r from the earthquake is estimated by

$$I = f\ (I_0', r, h) + \Delta I \tag{4}$$

where ΔI is the site response at the center of population of the Census tract of interest. The estimate of I_0' is derived from magnitude using a relation derived by Arnold (1990). The scenario losses are presented in Table 7.

Probabilistic Loss Estimates

Probabilistic loss estimates were developed applying the model used for the estimation of ground acceleration and velocity shaking in the United States (Algermissen and others, 1990). Figure 5 illustrates the elements of the model. All sources of earthquakes are delineated into seismic source zones (shown as rectangles in part A of Figure 5), or as line sources (faults). The sources of earthquakes are delineated on the bases of historical seismicity and geological structure. For each source zone, the magnitude distribution of earthquakes is determined using the well-known Gutenberg-Richter relationship $\log N_m = a - bM$ where N is the number of earthquakes with magnitudes greater than M, M is magnitude, and a and b are constants to be determined (see B_1, Figure 5). The entire computational process is similar to the estimation of probabilistic ground motion except that percent loss is estimated instead of some ground-motion parameter, such as peak acceleration, velocity, etc. In part B_2 of Figure 5, attenuation of any ground-motion parameter to be calculated in hazard analysis (such as peak acceleration, velocity, etc.) is replaced by the attenuation of percent loss away from the earthquake. We have done this by using relationships developed for intensity (equation 4) to obtain the intensity at the center of population of every Census tract. The intensity in each Census tract is then convolved with the vulnerability relationships listed in Table 6 to produce an attenuation of percent loss such as shown in B_2 of Figure 5.

The cumulative distribution function (F(l)) of percent loss (part C of Figure 5) is then developed. Assuming a Poisson distribution of earthquake occurrence in time, the maximum expected percent loss in various time periods of interest (T, 2T, 4T, etc.; part D of Figure 5) at some level of non-exceedance can be computed. In this study, maximum expected percent losses in each Census tract were converted to maximum expected dollar losses for each Census tract using the number of dwellings and their value in each tract. Maximum expected losses were estimated for 10, 50, and 250 year periods of interest (exposure times T) for a 90 percent chance of nonexceedance (10 percent chance of exceedance) in the time periods of interest. For an extreme probability

$$F_{max,t}(L) = e^{-\phi t[1-F(L)]} \tag{5}$$

where ϕ is the mean rate of occurrence of earthquakes $M \geq M_{min}$ per year, and t is the number of years in a period of interest (exposure time). The return period of a particular percent loss can be defined as

$$R(L) = \frac{1}{1 - F(L)} \tag{6}$$

where R(L) is the average number of earthquakes that must occur to obtain a percent loss exceeding l. The return period in years is given approximately by

$$R_y(L) = \frac{R(L)}{\text{Expected number of events per year } (M \geq M_{min})} \tag{7}$$

From (6) and (7) we obtain

$$\phi t(1-F(L)) = \frac{t}{R_y(L)} \tag{8}$$

From (5) and (8) we obtain

$$F_{max,t}(L) = e^{-t/R_y(L)} \tag{9}$$

and $$\ln(F_{max,t}(L)) = -\frac{t}{R_y(L)}$$

which relates extreme probability, exposure time, and return period. For example, for a loss which has an extreme probability of 0.90 for an exposure time of 10 years, the corresponding return period is

$$\ln(.90) = -\frac{10}{R_y(L)} \qquad (10)$$

$$R_y(L) = 94.9 \text{ years.}$$

Thus, the average return period for a 0.90 extreme probability maximum percent loss in a period of interest (exposure time) of 10 years is about 95 years. Similarly, for the same extreme probability, .90, or a 90 percent chance the maximum loss will not be exceeded, periods of time of interest (exposure times) of 50 and 250 years yield average return periods of 474.4 and 2371.9 years.

LOSS CALCULATIONS

Using a 100-year record of earthquakes in California with maximum Modified Mercalli intensities of VII or greater (Table 5) produces the simulated losses shown in Table 7. The counties are ranked in descending order of estimated losses using the USGS (Steinbrugge, 1986) vulnerability relationship, the Applied Technology Council (1986) vulnerability, and a proprietory vulnerability relationship. Table 7 also shows the maximum single loss for each county, using the three vulnerability relationships discussed.

Maximum expected losses by county and aggregated for the whole state for periods of interest of 10, 50, and 250 years (corresponding to average return periods of 94.9, 474.4, and 2371.9 years) are shown in Tables 8 through 10. Maximum expected losses have been computed using both the USGS vulnerability and the Applied Technology Council vulnerability as explained above.

DISCUSSION OF RESULTS

Table 7 provides an interesting comparison of simulated losses using three different vulnerability relationships, but calculated using the same 100-year record of damaging earthquakes in California. The 100-year simulated losses for the entire state vary by about a factor of about two depending upon the vulnerability relationship used. This variability in estimates shows that more data are required to construct vulnerability functions and/or techniques for measuring losses. Improvement of this type of variability can only be reduced by further analyses of actual losses during earthquakes (see, for example, Steinbrugge and Algermissen, 1990).

The largest simulated losses occur in Los Angeles County. Losses in other counties fall by almost a factor of ten from those in Los Angeles County. This commanding lead in estimated losses is to some extent related to the size of Los Angeles County. For example, the nine San Francisco Bay area counties (San Francisco, Alameda, Contra Costa, Marin, Napa, San Mateo, Santa Clara, Solano, and Sonoma Counties) have an aggregated loss of $21.9 billion or about 58 percent of the Los Angeles County losses in the same time period.

At any rate, the annual losses of $77 to $140 billions estimated using the 100-year historical record of damaging earthquakes in California provides a basis both for planning and for judging the uncertainties introduced by various estimates of the vulnerabilities involved.

The probabilistic maximum losses computed for each county for 10, 50, and 250 year periods of interest (average return periods of 94.9, 474.4, and 2371.9 years) provides a guide to the maximum losses likely to be experienced in the time periods given. The 250 year estimates probably represent a useful planning tool for the estimation of long-term earthquake catastrophe potential in California.

The limitations of the Modified Mercalli scale should not be overlooked (Steinbrugge and Algermissen, 1990, page A-56). However, whenever actual loss experience is not available, then methods such as those discussed herein are necessary.

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Table 1. California and Nevada earthquakes providing intensity observations for this study. The individual observations of intensity and magnitudes were supplied in computer readable form by the National Geophysical Data Center, Boulder, Colorado (1984).

Year	Date Mo	Day	Time UT	Lat Deg	Long Deg	M
1906	04	18	13:12	33.00N	115.00W	8.3
1918	04	21	22:32	33.75N	117.00W	6.8
1930	08	31	00:40	33.90N	118.60W	5.3
1932	06	06	08:44	40.75N	124.30W	6.4
1932	12	21	06:10	38.73N	117.82W	7.3
1933	03	11	01:54	33.58N	117.98W	6.3
1934	01	30	20:17	38.28N	118.37W	6.5
1934	06	08	04:48	35.93N	120.48W	6.0
1934	12	31	18:45	31.80N	115.10W	7.1
1937	03	25	16:49	33.47N	116.58W	6.0
1940	02	08	08:05	39.75N	121.25W	6.0
1940	05	19	04:36	32.73N	115.45W	7.1
1941	07	01	07:50	34.33N	119.53W	5.9
1941	11	14	08:41	33.78N	118.25W	5.4
1942	10	21	16:22	32.97N	116.00W	6.5
1946	03	15	13:49	35.73N	118.04W	6.3
1947	04	10	15:58	34.97N	116.53W	6.4
1948	12	04	23:43	33.88N	116.33W	6.5
1948	12	29	12:53	39.55N	120.08W	6.0
1949	03	09	12:28	37.02N	121.48W	5.3
1950	12	14	13:24	40.10N	120.10W	5.6
1952	07	21	11:52	35.00N	119.03W	7.7
1952	08	22	22:41	35.33N	118.92W	5.8
1952	11	22	07:46	35.83N	121.17W	6.0
1954	01	12	23:33	35.00N	119.02W	5.9
1954	04	25	20:33	36.93N	121.68W	5.3
1954	08	24	05:51	39.58N	118.45W	6.8
1954	12	16	11:07	39.32N	118.20W	7.1
1954	12	21	19:56	40.82N	124.08W	6.6
1955	09	05	02:01	37.37N	121.78W	5.8
1955	10	24	04:10	37.97N	122.05W	5.4
1957	03	22	19:44	37.67N	122.47W	5.3
1959	04	01	18:18	39.72N	120.20W	5.6
1961	04	09	07:23	36.68N	121.30W	5.6
1964	11	16	02:46	37.00N	121.72W	5.3
1966	06	28	04:26	35.90N	120.90W	5.3
1966	09	12	16:41	39.40N	120.10W	6.5
1968	04	09	02:28	33.20N	116.11W	6.5
1969	04	28	23:20	33.35N	116.35W	5.9
1969	10	02	04:56	38.46N	122.69W	5.6
1970	09	12	14:30	34.27N	117.54W	5.4
1971	02	09	14:00	34.41N	118.40W	6.4
1971	03	31	14:52	34.29N	118.52W	4.6
1973	02	21	14:45	34.10N	119.00W	5.9
1975	06	01	01:38	34.52N	116.50W	5.2
1975	08	01	20:20	39.44N	121.53W	5.8
1979	03	15	21:07	34.32N	116.45W	5.7
1979	08	06	17:05	37.10N	121.50W	5.9
1979	10	15	23:16	32.63N	115.33W	7.0
1980	01	24	19:00	37.83N	121.79W	5.8
1980	01	27	02:33	37.75N	121.71W	5.4
1980	05	25	16:33	37.59N	118.85W	6.1
1980	11	08	10:27	41.12N	124.66W	6.2

Table 2. Mean intensity attenuation relationships for the three regions of California shown in Figure 2.

Region (from Figure 2)	No. of earthquakes used in regression	Regression equation for mean intensity I
1	16	$I-I_o' = 0.006r-1.2898\log_{10}\{1+\frac{r}{10}\}$
2	24	$I-I_o' = 0.006r-0.58066\log_{10}\{1+\frac{r}{10}\}$
3	14	$I-I_o' = -0.004r-1.26046\log_{10}\{1+\frac{r}{25}\}$

Table 3. Number of Modified Mercalli intensity observations at each geographic location used in the calculation of ΔI.

There were 2146 distinct observational sites which recorded 7307 observations of intensity for an average of 3.40 observations each. These were distributed in the following way:

Obs/site	Sites	Obs/site	Sites
1	910	13	16
2	309	14	6
3	176	15	3
4	155	16	7
5	147	17	2
6	97	18	2
7	86	19	0
8	73	20	0
9	57	21	1
10	45	22	0
11	34	23	1
12	19		

Table 4. Distribution of distances of intensity observations to Census tract to which a ΔI was assigned.

Mean Dist (Km)	Number Tracts	Mean Dist (Km)	Number Tracts
0.13	191	4.25	245
0.38	143	4.75	166
0.63	200	6.0	361
0.88	236	8.0	121
1.13	308	10.0	43
1.38	322	12.0	25
1.63	352	14.0	13
1.88	323	16.0	4
2.25	644	18.0	11
2.75	526	20.0	4
3.25	396	>20.	8
3.75	298		

Table 5. Earthquakes with maximum Modified Mercalli intensities VII and greater in California from 1890 through 1989 for which ground shaking effects are simulated in this study. These data were derived from the catalogues developed for Algermissen and others (1982) augmented by data from the NEIC hypocenter data file.

Earthquakes used for the 100 Year Loss Simulation

Date Yr	Mo	Day	Time UT	Lat Deg	Long Deg	Io
1890	04	24	11:36	37.00N	121.50W	7
1891	10	12	06:28	38.50N	122.50W	7
1892	04	19	10:50	38.50N	122.50W	9
1892	04	21	17:43	38.50N	122.00W	9
1893	04	04	19:40	34.50N	118.50W	8
1893	08	09	09:15	38.50N	122.50W	7
1894	10	23	23:03	33.00N	117.00W	7
1897	06	20	20:14	37.00N	121.50W	8
1898	03	31	07:43	38.00N	122.00W	7
1899	07	06	20:09	36.90N	121.80W	7
1899	07	22	20:32	34.50N	117.50W	8
1899	10	13	05:00	38.50N	122.50W	7
1899	12	25	12:25	33.50N	116.50W	8
1899	12	26	00:00	33.80N	117.00W	7
1901	03	03	07:45	36.00N	120.50W	7
1902	05	19	18:31	38.50N	122.00W	7
1902	07	28	06:57	34.50N	120.50W	8
1902	07	31	09:20	34.80N	120.30W	7
1902	08	01	03:30	34.80N	120.30W	7
1902	12	12	00:00	34.50N	120.50W	7
1903	06	11	13:12	37.50N	122.00W	7
1903	07	24	20:26	39.50N	122.20W	7
1903	08	03	06:49	37.50N	122.00W	7
*1906	04	18	13:12	38.00N	123.00W	11
1906	04	19	00:30	33.00N	115.00W	8
1907	09	20	01:54	34.10N	117.30W	7
1908	11	04	08:37	36.00N	117.00W	7
1909	06	23	07:24	39.50N	121.00W	7
1910	04	11	07:57	34.10N	117.30W	7
1911	07	01	22:00	37.20N	121.70W	8
1914	11	09	02:31	37.00N	122.00W	7
1915	01	12	04:31	34.50N	120.50W	8
1915	02	22	00:00	40.50N	121.00W	7
1916	08	06	19:38	36.50N	121.00W	7
1916	10	23	02:44	34.90N	118.90W	7
1916	12	01	22:53	35.00N	121.00W	7
1917	05	28	06:06	33.00N	115.50W	7
1918	04	21	22:32	33.80N	117.00W	9
1919	02	16	15:57	35.00N	119.00W	7
1920	06	22	02:49	34.00N	118.40W	8
1920	07	23	03:55	40.50N	121.50W	7
1922	03	10	11:21	35.80N	120.30W	8
1923	07	23	07:30	34.00N	117.30W	7
1925	06	29	14:42	34.30N	119.80W	10
1926	06	29	23:21	34.50N	119.50W	7
1926	10	22	12:35	36.80N	122.00W	8
1926	10	22	13:35	36.80N	122.00W	8
1927	09	18	02:07	37.50N	118.80W	7
1928	06	03	00:00	40.70N	123.00W	7

Table 5 (Continued)

1929	07	08	16:46	34.00N	118.00W	7
1929	11	28	19:49	36.90N	118.20W	7
1930	01	16	00:24	34.20N	116.90W	7
1930	02	26	02:30	33.00N	115.50W	8
1930	03	01	23:44	33.00N	115.50W	8
1930	08	05	11:25	34.50N	119.50W	7
1934	06	08	04:47	35.80N	120.30W	8
1937	03	08	10:31	37.80N	122.20W	7
1937	03	25	16:49	33.50N	116.60W	7
1939	06	24	13:01	36.40N	121.00W	7
1940	02	08	08:05	39.70N	121.20W	7
*1940	05	19	04:51	34.00N	116.30W	7
1941	07	01	07:50	34.30N	119.60W	8
1941	09	14	16:43	37.60N	118.70W	7
1941	09	14	18:21	37.60N	118.70W	7
1941	09	14	18:39	37.60N	118.70W	7
1942	10	21	16:22	33.00N	116.00W	7
1942	10	22	01:50	33.20N	115.70W	7
1943	12	22	15:50	34.30N	115.80W	7
1946	03	15	13:49	35.70N	118.00W	8
*1947	04	10	15:58	35.00N	116.50W	7
1948	12	04	23:43	33.90N	116.40W	7
1948	12	29	12:53	39.50N	120.10W	7
1949	01	01	01:17	36.90N	121.60W	7
1949	03	09	12:28	37.00N	121.50W	7
1950	07	28	17:50	33.10N	115.60W	7
1950	07	29	14:36	33.10N	115.60W	8
*1950	12	14	13:24	40.10N	120.10W	7
1951	01	24	07:17	33.10N	115.60W	7
1951	12	05	15:53	33.10N	115.40W	7
*1952	07	21	11:52	35.00N	119.00W	11
1952	07	21	12:02	35.00N	119.00W	7
1952	07	21	19:41	35.10N	118.80W	7
1952	07	23	07:53	35.00N	118.80W	7
1952	07	23	13:17	35.20N	118.80W	7
1952	07	25	19:09	35.30N	118.50W	7
1952	07	25	19:43	35.30N	118.50W	7
1952	07	29	07:03	35.40N	118.80W	7
1952	08	22	22:41	35.30N	118.90W	8
1954	01	12	23:33	35.00N	119.00W	7
1954	03	19	10:21	33.30N	116.20W	7
1954	04	25	20:33	36.90N	121.70W	8
1955	09	05	02:01	37.40N	121.80W	7
1955	10	24	04:10	38.00N	122.00W	7
1955	12	17	06:07	33.00N	115.50W	7
1957	03	22	19:44	37.70N	122.50W	7
1957	04	25	21:57	33.20N	115.80W	7
1959	04	01	18:18	39.70N	120.20W	7
1961	04	09	07:23	36.70N	121.30W	7
1961	04	09	07:25	36.70N	121.30W	7
1961	10	19	05:09	35.80N	117.80W	7
1963	09	14	19:46	36.90N	121.60W	7
1964	11	16	02:46	36.90N	121.80W	7
1965	09	25	17:43	34.70N	116.50W	7
*1966	06	28	04:26	35.90N	120.50W	7

Table 5 (Continued)

*1966	09	12	16:41	39.40N	120.10W	7
*1968	04	09	02:28	33.10N	116.10W	8
1968	07	05	00:45	34.10N	119.70W	7
1969	04	28	23:20	33.30N	116.30W	7
1969	10	02	04:56	38.50N	122.70W	8
1970	09	12	14:30	34.30N	117.50W	7
*1971	02	09	14:00	34.40N	118.40W	8
1973	02	21	14:45	34.10N	119.00W	7
1975	08	01	20:20	39.44N	121.53W	9
1977	11	22	21:15	39.448N	123.259W	8
1978	08	13	22:54	34.351N	119.700W	7
1979	02	03	09:58	40.890N	124.413W	7
1979	03	15	21:07	34.317N	116.450W	8
1979	08	06	17:05	37.102N	121.503W	7
1979	10	15	23:16	32.633N	115.333W	9
1980	01	24	19:00	37.852N	121.815W	7
1980	05	25	16:33	37.600N	118.840W	7
1980	05	25	19:44	37.569N	118.820W	7
1980	11	08	10:27	41.117N	124.253W	7
1981	04	26	12:09	33.133N	115.650W	7
1983	05	02	23:42	36.219N	120.317W	8
1984	04	24	21:15	37.320N	121.698W	7
1986	07	08	09:20	34.000N	116.610W	7
1987	10	01	14:42	34.060N	118.080W	8
1987	11	24	13:15	33.010N	115.840W	7
1987	11	24	13:15	33.010N	115.840W	7
*1989	10	18	00:04	37.036N	121.883W	9

* Indicates earthquakes for which a finite fault was simulated.

Table 6. Vulnerability relationships used in this study.

	MM Intensity						
	VI	VII	VIII	IX	X	XI	XII
USGS (Modified from K.V. Steinbrugge; see Algermissen and others, 1990)	0.08*	3.2	5.6	8.0	9.0	9.0	9.0
Applied Technology Council (1985)	1.0	1.5	4.0	8.0	20.0	24.0	36.0

*Percent replacement cost for a dwelling experiencing the Modified Mercalli (MM) intensity indicated. The percent replacement cost of a dwelling is taken to mean the percentage of the total cash value of a dwelling required to fully repair, in kind, any one-to-four family dwelling.

Table 7. Simulated losses, 100 year earthquake history in California, using the earthquakes listed in Table 5. The countries are ranked in descending order of estimated losses for the 100 year period. Losses are given in millions of June 30, 1988 dollars. GS means losses computed using a vulnerability relationship and only slightly modified developed by K.V. Steinbrugge (see Algermissen and others, 1990; ATC means losses computed using a vulnerability relationship developed by the Applied Technology Council (1985), and KVS means losses computed using a proprietory vulnerability relationship developed by one of the authors (KVS).

Housing Units	Value $m	Losses GS $m	Losses ATC $m	Losses KVS $m	Max Loss GS	Max Loss ATC	Max Loss KVS	County
1970954	284484.3	37441.4	39209.7	42593.0	6027.6	4062.0	13814.2	Los Angeles County
354640	66639.0	6231.4	6976.6	23947.7	3749.5	3093.4	6900.1	Santa Clara County
556494	108347.1	3805.9	7954.0	8457.2	860.5	1038.0	4928.1	Orange County
170002	39041.3	3760.6	4546.9	7890.9	2542.5	2513.5	4685.6	San Mateo County
585664	86890.8	3710.9	6538.0	1906.3	933.2	875.7	1887.3	San Diego County
191132	38700.2	3103.3	3290.8	9430.8	2178.2	1903.5	4475.4	San Francisco County
338340	38952.5	2717.1	3148.5	7809.3	1783.4	1283.3	2440.6	Alameda County
118435	14602.7	2247.4	2103.5	3797.7	865.6	734.7	977.0	Sonoma County
226411	34797.2	1835.0	2319.4	7654.0	1458.8	924.1	2010.0	Contra Costa County
69914	10574.0	1408.0	1470.6	5683.9	598.4	532.6	1097.9	Santa Cruz County
71941	22310.6	1234.6	1179.4	2701.0	1170.5	840.4	2260.5	Marin County
162474	23786.4	1211.6	1705.3	1172.5	551.1	353.2	869.1	Ventura County
86910	15772.6	1176.3	1241.3	4027.8	581.9	351.1	1037.7	Santa Barbara County
290005	21203.6	962.5	1344.7	27.2	315.0	306.0	27.2	Sacramento County
83174	12478.6	893.9	971.0	2098.7	507.4	337.2	487.4	Monterey County
295744	25706.3	802.6	2029.3	2984.9	503.7	322.6	679.1	Riverside County
401252	27273.8	616.3	1765.9	3693.4	316.5	280.4	972.9	San Bernardino County
141755	7098.6	452.7	634.1	1054.8	238.6	160.5	391.6	Kern County
32747	3835.5	439.0	407.7	866.7	172.9	116.2	213.8	Napa County
85500	6163.3	415.8	381.6	647.9	232.9	139.6	219.5	Solano County
130217	7625.3	308.7	366.7	0.0	216.2	122.2	0.0	San Joaquin County
63555	6321.5	272.7	384.0	5.4	116.9	68.7	2.7	San Luis Obispo County
22885	1819.9	265.7	290.6	97.9	131.4	150.3	66.1	Mendocino County
37045	2170.4	229.4	298.6	0.0	80.0	44.3	0.0	Shasta County
100524	6038.6	214.7	258.9	0.0	191.3	104.6	0.0	Stanislaus County
35702	1747.2	169.5	139.7	30.7	67.6	39.1	21.7	Humboldt County
33060	2605.0	164.4	180.6	169.1	58.5	39.9	112.4	Yolo County
78690	3693.2	153.6	164.5	0.0	97.1	55.9	0.0	Tulare County
159502	10705.3	143.8	195.4	21.4	72.3	71.8	14.9	Fresno County
18123	1028.1	131.1	131.3	4.1	54.7	45.4	3.5	Lake County
24095	963.6	90.1	145.3	399.9	28.7	15.4	87.7	Imperial County
44676	2009.8	67.4	79.6	0.2	60.3	36.1	0.2	Merced County
7189	505.1	49.3	41.4	6.3	8.4	4.9	2.3	Plumas County
51624	2904.1	44.1	71.4	96.4	31.4	27.1	92.8	Butte County
24403	1000.3	43.2	50.3	3.0	23.5	13.2	1.0	Kings County
8868	778.1	40.6	43.0	362.0	38.0	25.6	71.4	San Benito County
43816	5076.8	29.4	72.0	0.0	29.4	24.0	0.0	El Dorado County
4311	194.3	23.6	24.5	11.5	8.1	4.9	11.5	Trinity County
14100	560.6	16.5	22.1	16.6	7.2	7.0	14.6	Yuba County
13411	585.6	14.5	32.0	0.0	10.1	6.9	0.0	Siskiyou County
13551	552.0	12.5	17.6	0.0	7.9	6.7	0.0	Tehama County
4893	261.2	10.8	14.5	0.0	7.0	3.6	0.0	Mariposa County
6986	259.1	7.8	11.7	15.1	5.2	3.2	15.1	Glenn County
16910	924.0	5.8	21.4	19.4	4.1	8.7	19.4	Sutter County
3545	745.7	5.7	40.8	207.3	5.7	7.1	62.4	Mono County
19620	1374.0	5.3	15.9	0.0	5.3	12.2	0.0	Tuolumne County
28397	2887.3	4.5	23.5	103.2	4.5	10.2	59.4	Nevada County
24381	1504.6	2.5	7.0	0.0	2.5	4.6	0.0	Madera County
11505	800.4	2.4	6.7	0.0	2.4	5.4	0.0	Amador County
1577	87.4	2.3	3.0	6.9	0.6	0.5	3.6	Sierra County
49670	5435.9	1.9	55.7	27.4	1.1	26.3	24.6	Placer County
6596	265.8	1.6	2.0	4.7	0.5	0.6	2.4	Lassen County
4681	447.5	1.1	4.2	2.6	1.1	3.5	2.6	Inyo County
4720	184.8	0.1	0.1	0.0	0.1	0.1	0.0	Colusa County
5363	229.2	0.1	4.4	0.0	0.1	1.7	0.0	Del Norte County
529	60.1	0.0	0.0	0.0	0.0	0.0	0.0	Alpine County
15019	973.6	0.0	5.8	0.0	0.0	5.8	0.0	Calaveras County
2214	69.4	0.0	0.0	0.0	0.0	0.0	0.0	Modoc County
7369441	964054.2	77003.0	92444.3	140056.8				Totals

Table 8. Maximum estimated dollar losses in a period of time of interest (exposure time) of 10 years (average return period of 94.9 years) by county in California. The losses tabulated are estimated to have a 10 percent chance of being exceeded. Losses are given in millions of June 30, 1988 dollars. USGS means losses computed using a vulnerability relationship developed by K.V. Steinbrugge (see Algermissen and others, 1990) and only slightly modified; ATC means losses computed using a vulnerability relationship developed by the Applied Technology Council (1985).

Number Units (1-4)	Value $m	USGS Losses $m	ATC Losses $m	County
1970954	284484.3	6691.3	4266.7	Los Angeles County
556494	108347.1	1880.7	1306.9	Orange County
585664	86890.8	1843.1	1255.0	San Diego County
354640	66639.0	1396.6	936.9	Santa Clara County
170002	39041.3	998.5	628.4	San Mateo County
338340	38952.5	710.9	489.7	Alameda County
191132	38700.2	705.6	532.5	San Francisco County
226411	34797.2	527.8	392.7	Contra Costa County
295744	25706.3	527.2	324.8	Riverside County
401252	27273.8	416.8	310.6	San Bernardino County
118435	14602.7	348.6	242.0	Sonoma County
162474	23786.4	332.5	273.5	Ventura County
86910	15772.6	297.8	197.5	Santa Barbara County
71941	22310.6	267.1	242.0	Marin County
69914	10574.0	236.3	158.5	Santa Cruz County
83174	12478.6	157.7	152.5	Monterey County
290005	21203.6	142.1	145.2	Sacramento County
63555	6321.5	115.1	66.2	San Luis Obispo County
35702	1747.2	110.9	93.4	Humboldt County
37045	2170.4	91.5	55.5	Shasta County
22885	1819.9	84.9	56.2	Mendocino County
85500	6163.3	76.6	63.6	Solano County
141755	7098.6	69.5	56.1	Kern County
32747	3835.5	65.6	50.0	Napa County
100524	6038.6	39.0	57.3	Stanislaus County
18123	1028.1	30.9	21.5	Lake County
24095	963.6	29.2	15.2	Imperial County
78690	3693.2	26.3	29.0	Tulare County
130217	7625.3	23.3	69.4	San Joaquin County
13411	585.6	21.3	11.8	Siskiyou County
44676	2009.8	13.8	16.2	Merced County
43816	5076.8	13.4	18.7	El Dorado County
33060	2605.0	12.6	20.1	Yolo County
8868	778.1	10.8	8.7	San Benito County
4311	194.3	9.8	6.7	Trinity County
5363	229.2	9.7	5.9	Del Norte County
7189	505.1	9.7	6.6	Plumas County
51624	2904.1	7.6	12.9	Butte County
3545	745.7	7.4	7.7	Mono County
24403	1000.3	7.4	9.8	Kings County
159502	10705.3	7.1	41.3	Fresno County
13551	552.0	6.8	6.1	Tehama County
4893	261.2	3.8	3.0	Mariposa County
19620	1374.0	2.5	5.9	Tuolumne County
6986	259.1	2.3	2.5	Glenn County
49670	5435.9	1.7	11.4	Placer County
14100	560.6	1.6	3.1	Yuba County
1577	87.4	0.8	0.6	Sierra County
6596	265.8	0.7	1.4	Lassen County
2214	69.4	0.1	0.1	Modoc County
4681	447.5	0.1	2.7	Inyo County
15019	973.6	0.0	1.8	Calaveras County
28397	2887.3	0.0	6.6	Nevada County
24381	1504.6	0.0	0.7	Madera County
11505	800.4	0.0	2.7	Amador County
16910	924.0	0.0	3.3	Sutter County
4720	184.8	0.0	0.0	Colusa County
529	60.1	0.0	0.0	Alpine County
7369441	964054.2	18394.4	12707.4	Totals
Units	Value $m	Losses $m	Losses $m	

Table 9. Maximum estimated dollar losses in a period of time of interest (exposure time) of 50 years (average return period of 474.4 years) by county in California. The losses tabulated are estimated to have a 10 percent chance of being exceeded. Losses are given in millions of June 30, 1988 dollars. USGS means losses computed using a vulnerability relationship developed by K.V. Steinbrugge (see Algermissen and others, 1990) and only slightly modified; ATC means losses computed using a vulnerability relationship developed by the Applied Technology Council (1985).

Number Units (1-4)	Value $m	USGS Losses $m	ATC Losses $m	County
1970954	284484.3	10186.6	6470.7	Los Angeles County
556494	108347.1	3185.4	1735.3	Orange County
354640	66639.0	2958.3	1953.8	Santa Clara County
585664	86890.8	2795.1	1660.4	San Diego County
170002	39041.3	2025.6	1529.3	San Mateo County
191132	38700.2	1679.4	1119.0	San Francisco County
338340	38952.5	1484.8	966.5	Alameda County
226411	34797.2	1248.0	745.2	Contra Costa County
295744	25706.3	911.4	516.5	Riverside County
401252	27273.8	871.3	492.7	San Bernardino County
71941	22310.6	840.5	490.6	Marin County
118435	14602.7	686.2	493.8	Sonoma County
162474	23786.4	682.5	409.8	Ventura County
86910	15772.6	505.7	298.5	Santa Barbara County
69914	10574.0	471.3	334.0	Santa Cruz County
83174	12478.6	452.9	282.4	Monterey County
290005	21203.6	240.4	266.8	Sacramento County
63555	6321.5	196.3	131.3	San Luis Obispo County
85500	6163.3	194.4	111.0	Solano County
130217	7625.3	170.5	108.1	San Joaquin County
141755	7098.6	160.7	112.8	Kern County
32747	3835.5	143.5	86.4	Napa County
100524	6038.6	140.9	82.0	Stanislaus County
35702	1747.2	138.5	163.2	Humboldt County
37045	2170.4	128.5	100.0	Shasta County
22885	1819.9	119.5	103.1	Mendocino County
159502	10705.3	87.0	86.3	Fresno County
78690	3693.2	70.3	43.5	Tulare County
18123	1028.1	50.8	40.2	Lake County
33060	2605.0	46.6	34.6	Yolo County
44676	2009.8	44.7	26.6	Merced County
24095	963.6	43.9	28.2	Imperial County
43816	5076.8	36.7	36.3	El Dorado County
8868	778.1	31.8	18.8	San Benito County
13411	585.6	31.7	22.7	Siskiyou County
24403	1000.3	27.1	14.2	Kings County
51624	2904.1	20.1	25.5	Butte County
3545	745.7	18.3	10.0	Mono County
7189	505.1	16.0	11.8	Plumas County
13551	552.0	15.2	8.5	Tehama County
5363	229.2	14.1	11.3	Del Norte County
4311	194.3	13.5	12.2	Trinity County
28397	2887.3	13.1	16.8	Nevada County
49670	5435.9	10.3	36.5	Placer County
4893	261.2	7.2	3.7	Mariposa County
6986	259.1	6.5	3.5	Glenn County
19620	1374.0	5.4	12.2	Tuolumne County
4681	447.5	5.3	4.9	Inyo County
14100	560.6	5.0	6.2	Yuba County
6596	265.8	2.6	3.0	Lassen County
11505	800.4	2.4	6.1	Amador County
24381	1504.6	1.6	4.7	Madera County
16910	924.0	1.5	7.8	Sutter County
1577	87.4	1.3	1.1	Sierra County
2214	69.4	0.2	0.3	Modoc County
4720	184.8	0.1	0.1	Colusa County
15019	973.6	0.0	6.1	Calaveras County
529	60.1	0.0	0.3	Alpine County
7369441	964054.2	33248.4	21307.3	Totals
Units	Value $m	Losses $m	Losses $m	

Table 10. Maximum estimated dollar losses in a period of time of interest (exposure time) of 250 years (average return period of 2371.9 years) by county in California. The losses tabulated are estimated to have a 10 percent chance of being exceeded. Losses are given in millions of June 30, 1988 dollars. USGS means losses computed using a vulnerability relationship developed by K.V. Steinbrugge (see Algermissen and others, 1990) and only slightly modified; ATC means losses computed using a vulnerability relationship developed by the Applied Technology Council (1985).

Number Units (1-4)	Value $m	USGS Losses $m	ATC Losses $m	County
1970954	284484.3	13196.9	9501.4	Los Angeles County
354640	66639.0	3977.6	3465.7	Santa Clara County
556494	108347.1	3909.0	2219.1	Orange County
585664	86890.8	3360.1	2066.2	San Diego County
170002	39041.3	2656.4	2747.3	San Mateo County
191132	38700.2	2294.6	2077.1	San Francisco County
338340	38952.5	1999.3	1558.9	Alameda County
226411	34797.2	1676.8	1150.2	Contra Costa County
401252	27273.8	1230.8	799.8	San Bernardino County
295744	25706.3	1205.3	792.1	Riverside County
71941	22310.6	1189.3	863.2	Marin County
162474	23786.4	915.3	548.6	Ventura County
118435	14602.7	891.7	809.6	Sonoma County
86910	15772.6	699.4	465.8	Santa Barbara County
69914	10574.0	630.3	586.7	Santa Cruz County
83174	12478.6	601.2	435.4	Monterey County
290005	21203.6	463.0	354.6	Sacramento County
63555	6321.5	271.1	194.1	San Luis Obispo County
85500	6163.3	266.4	171.1	Solano County
130217	7625.3	253.0	135.7	San Joaquin County
141755	7098.6	233.4	161.9	Kern County
100524	6038.6	213.9	118.9	Stanislaus County
32747	3835.5	190.9	136.2	Napa County
159502	10705.3	171.8	130.3	Fresno County
35702	1747.2	146.1	232.8	Humboldt County
37045	2170.4	145.2	126.3	Shasta County
22885	1819.9	139.1	171.0	Mendocino County
78690	3693.2	104.8	62.6	Tulare County
44676	2009.8	70.9	42.9	Merced County
33060	2605.0	68.6	45.1	Yolo County
18123	1028.1	65.2	57.6	Lake County
24095	963.6	56.5	43.4	Imperial County
43816	5076.8	51.6	50.7	El Dorado County
51624	2904.1	48.4	34.5	Butte County
49670	5435.9	44.9	52.8	Placer County
8868	778.1	44.9	33.3	San Benito County
24403	1000.3	41.1	24.4	Kings County
13411	585.6	36.0	29.0	Siskiyou County
3545	745.7	27.2	14.7	Mono County
28397	2887.3	26.8	27.1	Nevada County
7189	505.1	22.3	17.0	Plumas County
13551	552.0	20.4	11.8	Tehama County
19620	1374.0	19.0	15.4	Tuolumne County
5363	229.2	16.8	15.9	Del Norte County
4311	194.3	15.3	16.6	Trinity County
16910	924.0	11.0	10.0	Sutter County
4681	447.5	10.9	6.1	Inyo County
4893	261.2	9.6	5.4	Mariposa County
6986	259.1	8.6	5.0	Glenn County
14100	560.6	8.1	7.5	Yuba County
11505	800.4	6.8	7.5	Amador County
6596	265.8	6.1	3.9	Lassen County
24381	1504.6	6.0	8.6	Madera County
15019	973.6	4.4	9.4	Calaveras County
1577	87.4	2.6	1.8	Sierra County
529	60.1	0.5	0.6	Alpine County
2214	69.4	0.2	0.6	Modoc County
4720	184.8	0.1	0.1	Colusa County
7369441	964054.2	43783.3	32681.4	Totals
Units	Value $m	Losses $m	Losses $m	

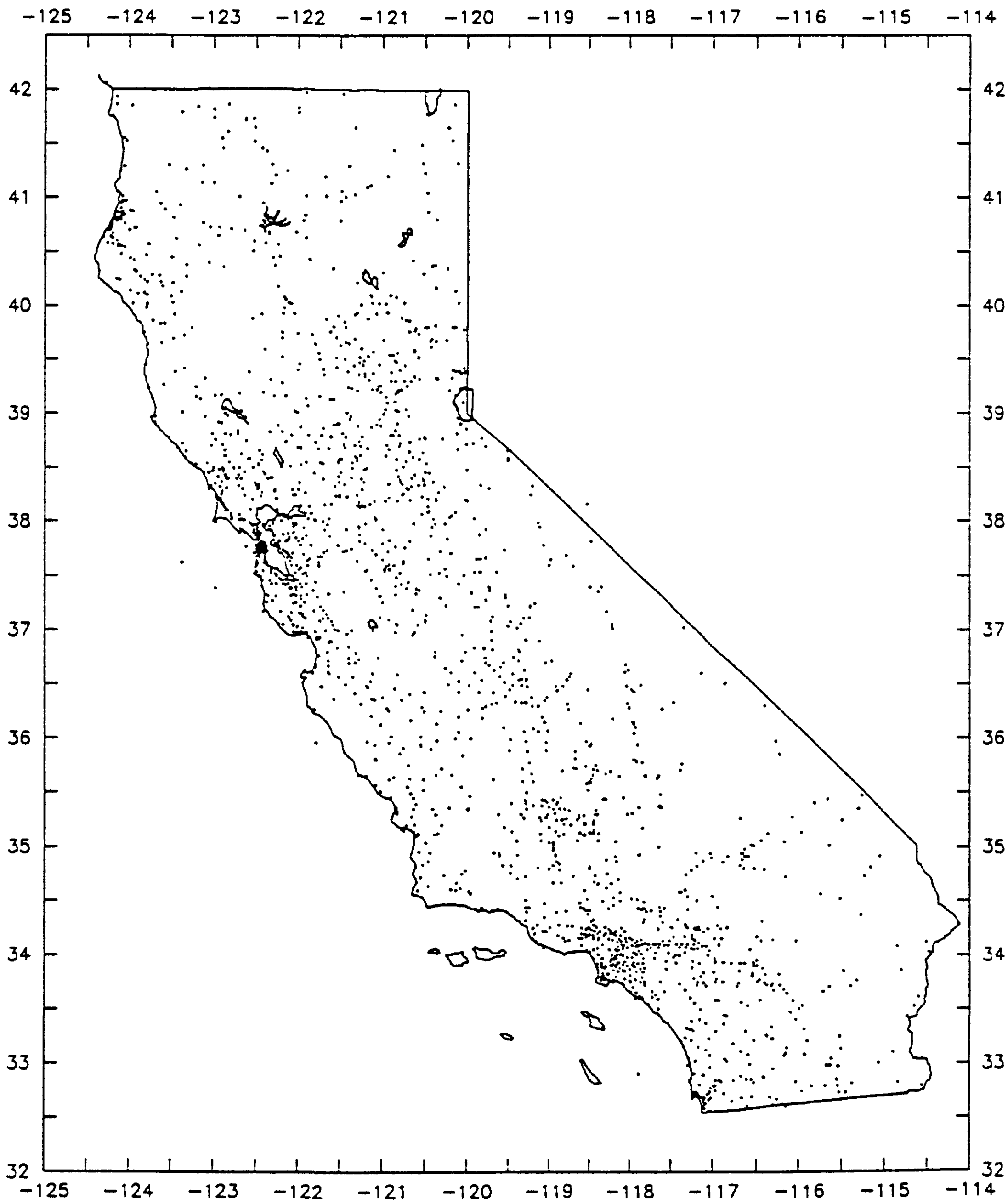

Figure 1. Spatial distribution of 7307 intensity observations noted at 2146 sites used in this study.

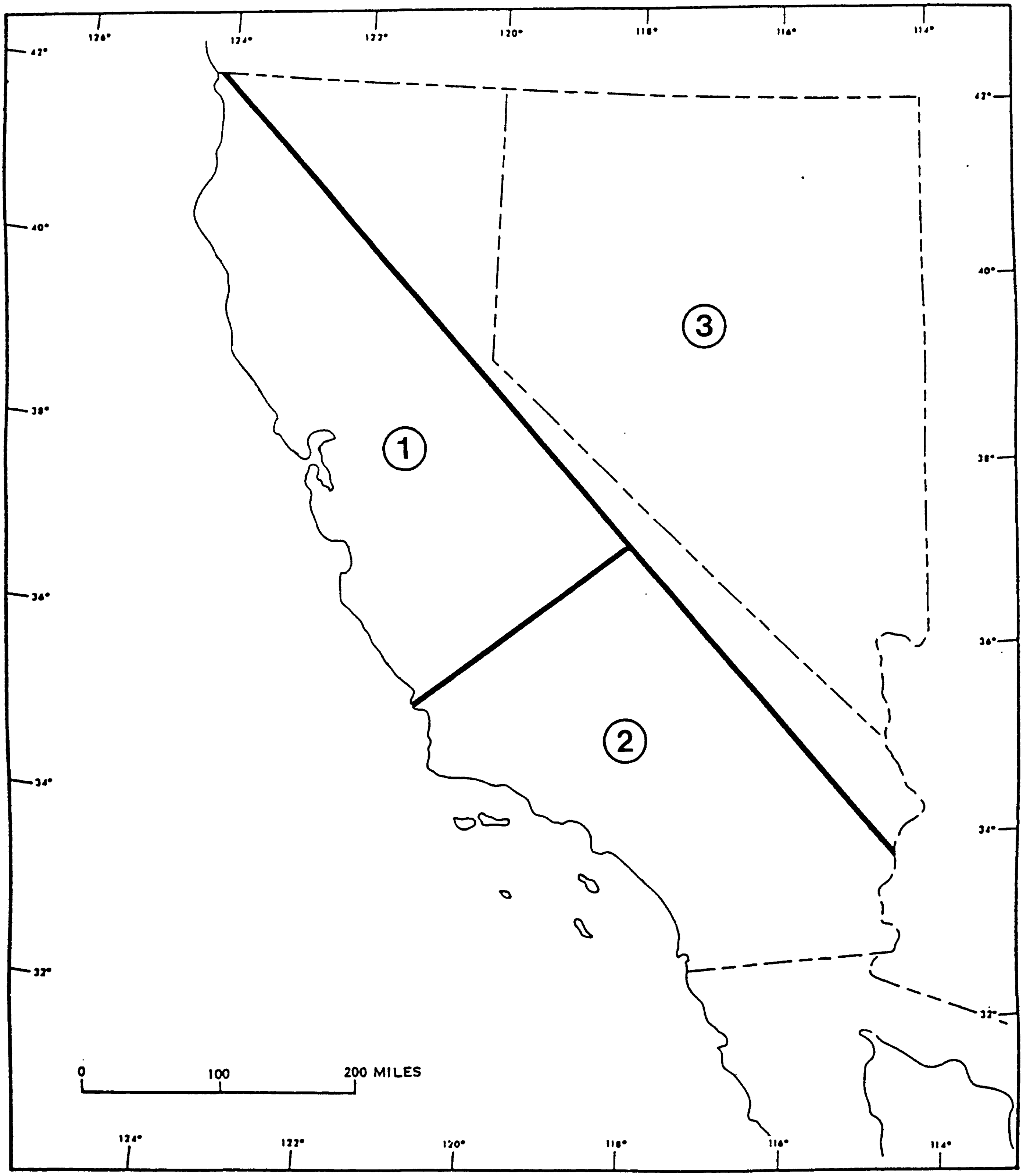

Figure 2. Areas of California for which different Modified Mercalli intensity attenuations are developed. Regression equations for intensities in each region are given in Table 2.

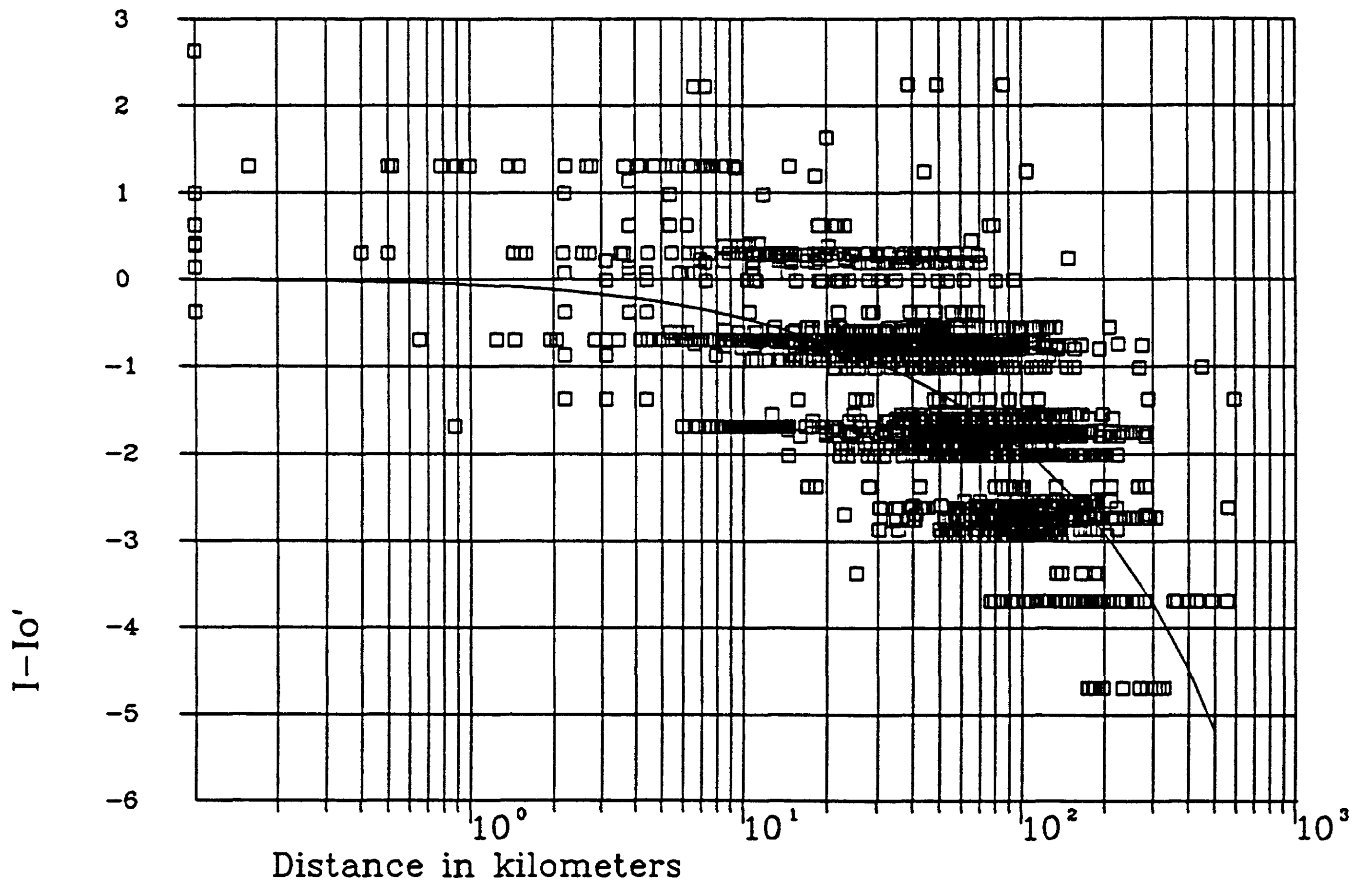

Figure 3. Intensity observations and mean (average) attenuation of Modified Mercalli intensity with distance for 16 earthquakes in northern California. The mean attenuation is

$$I - I_o' = -0.0060r - 1.2898\log_{10}\{1 + \frac{r}{10}\}.$$

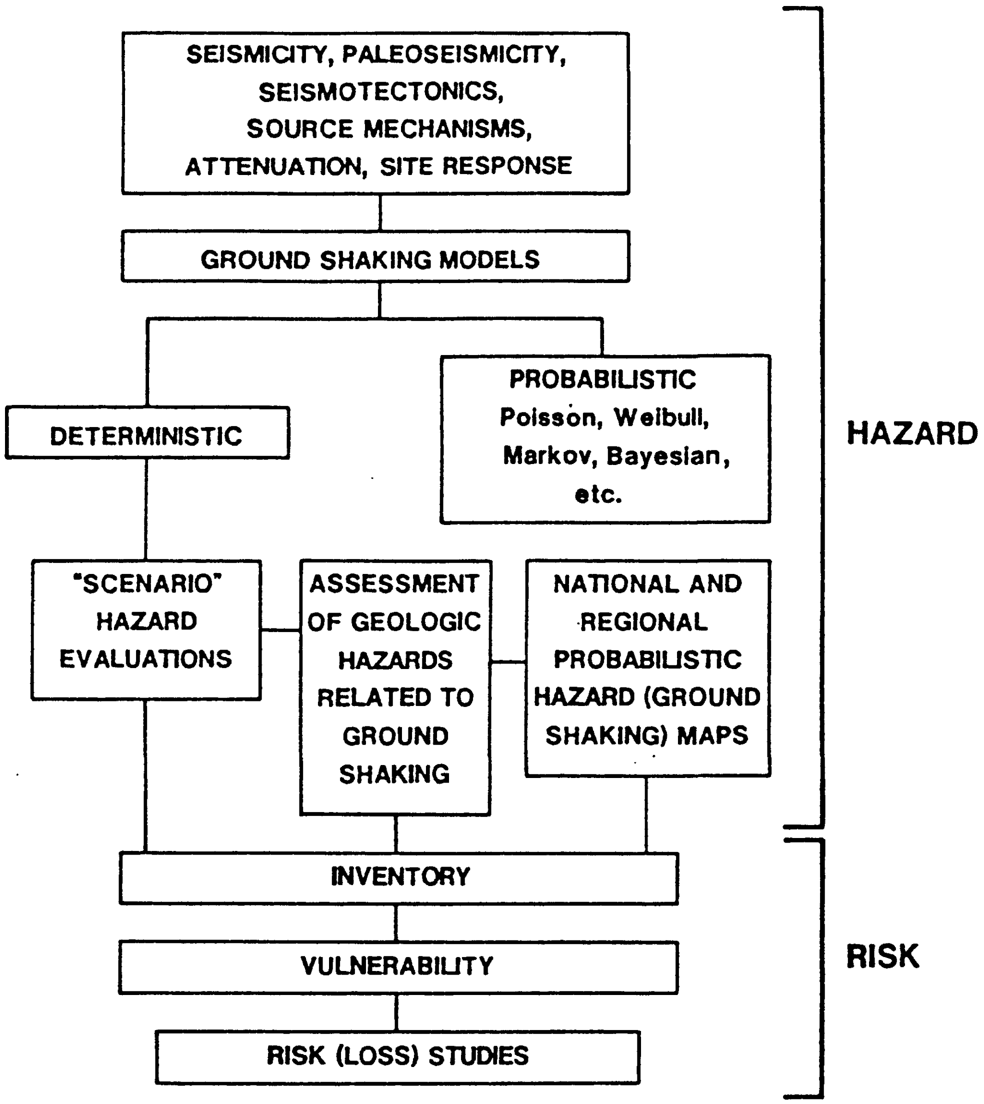

Figure 4. Elements of deterministic (scenario) and probabilistic loss assessment.

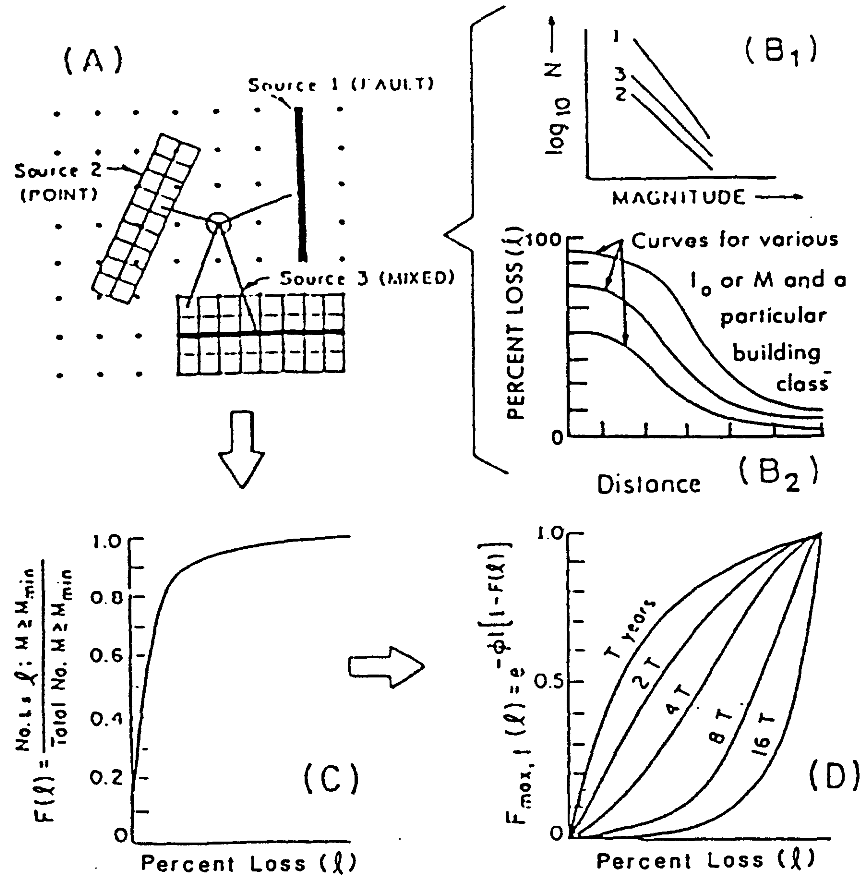

Figure 5. Elements of the probabilistic seismic risk (loss) assessment process. The model (and its description) is the same as for probabilistic hazard assessment with the exception that the quantity mapped is "percent loss." Percent loss is obtained by substituting the attenuation of percent loss with distance for the attenuation of intensity with distance. Thus, the maximum expected loss in various time periods of interest (T, 2T, 4T, etc.) at some level of nonexceedance is obtained (part D of figure). See text for further explanation.