

Global Seismicity.

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I. - Large earthquakes in the world.

During the past 80 years, about 10 earthquakes larger than M_s (surface wave magnitude) = 7 occurred per year in the world. Table I lists the earthquakes with $M_s \geq 8$. The magnitude-frequency relation is shown in table II and fig. 1. In terms of the energy released in seismic waves, this level of ac-

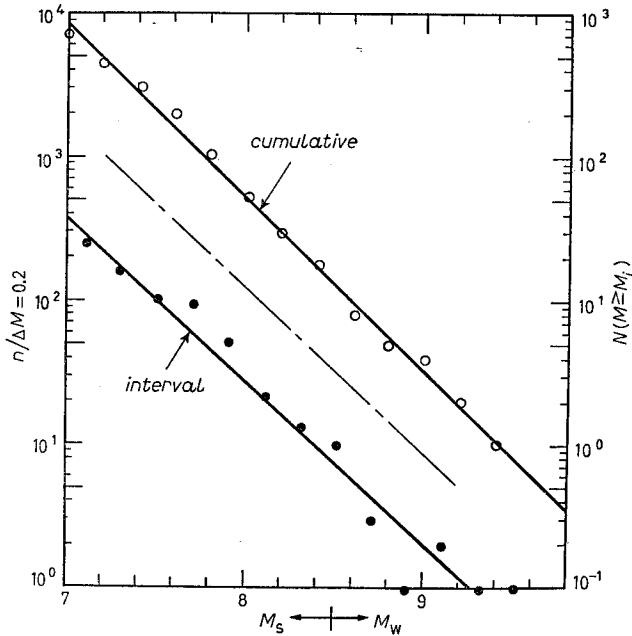


Fig. 1. - The magnitude-frequency relation for the earthquakes in the world during the period from 1904 to 1980. The surface wave magnitude M_s listed in [1] is used for all the events except those with $M_w \geq 8.5$ for which M_w is used. The ordinate on the left is for the interval frequency ($\log n = (10.42 \pm 0.57) - (1.13 \pm 0.7)M$) (n_2 in table II, the number of events per 0.2 magnitude unit for the period 1904 to 1980), and that on the right is for the cumulative frequency ($\log N = (11.41 \pm 0.19) - (1.21 \pm 0.02)M$) (N_2 in table II). The straight lines are the least-squares fit for the entire range.

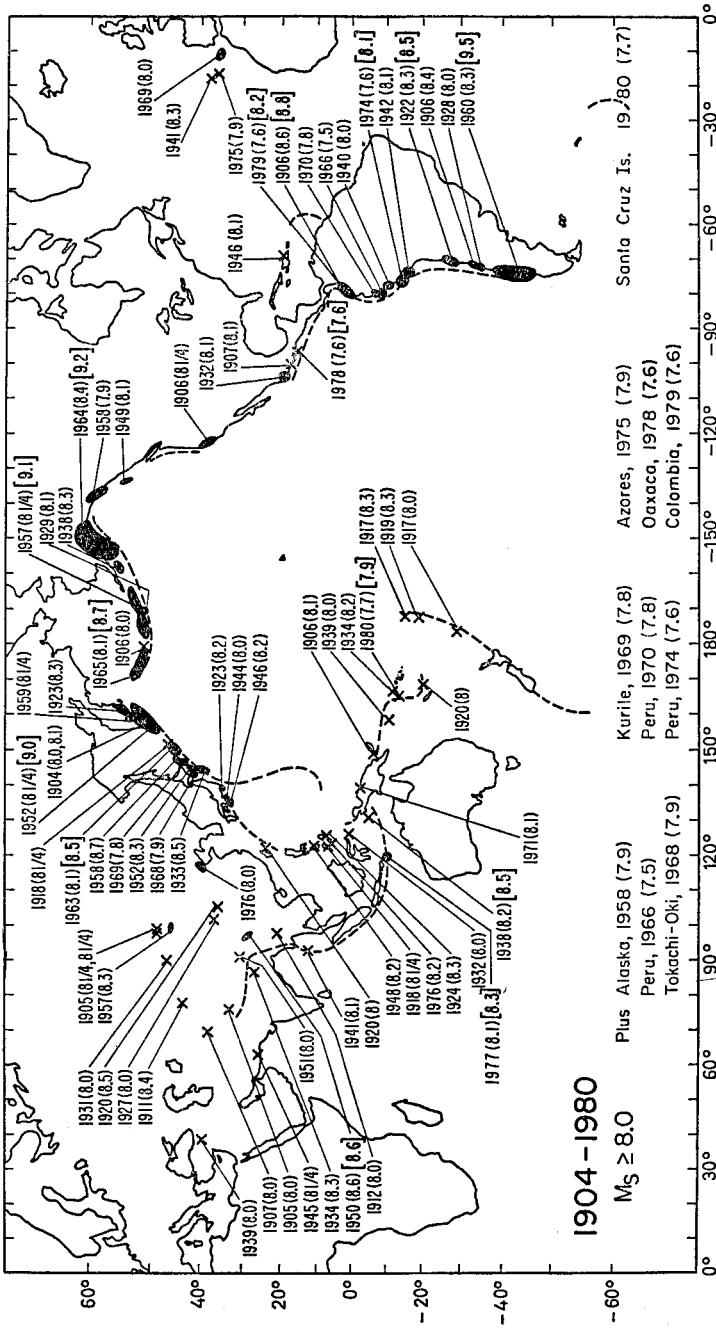


Fig. 2. - Great and large earthquakes for the period from 1904 to 1980. The surface wave magnitude M_s is given in parentheses and M_w is given in brackets for some earthquakes, including the ten largest earthquakes. Major rupture zones are indicated by dark zones. This figure is modified from that in [2], and the magnitude values differ slightly from those listed in table I.

TABLE Ia). — *Large earthquakes with $M_S \geq 8.0$ for the period 1904 to 1980 (data from [3]).*

Date	Time	Region	Latitude	Longitude	M_S	M_w
25.06.1904	21 h 00.5 min	Kamchatka	52	159	8.0	
4.04.1905	00 50.0	E. Kashmir	33	76	8.1	
9.07.1905	09 40.4	Mongolia	49	99	8.4	8.4
23.07.1905	02 46.2	Mongolia	49	98	8.4	8.4
31.01.1906	15 36.0	Ecuador	1	— 81.5	8.7	8.8
18.04.1906	13 12.0	California	38	— 123	8.3	7.9
17.08.1906	00 10.7	Aleutian Is.	51	179	8.2	
17.08.1906	00 40.0	Chile	— 33	— 72	8.4	8.2
14.09.1906	16 04.3	New Britain	— 7	149	8.1	
15.04.1907	06 08.1	Mexico	17	— 100	8.0	
3.01.1911	23 25.8	Turkestan	43.5	77.5	8.4	
23.05.1912	02 24.1	Burma	21	97	8.0	
26.05.1914	14 22.7	W. New Guinea	— 2	137	8.0	
1.05.1915	05 00.0	Kurile Is.	47	155	8.0	
26.06.1917	05 49.7	Samoa Is.	— 15.5	— 173	8.4	
15.08.1918	12 18.2	Mindanao Is.	5.5	123	8.0	
7.09.1918	17 16.2	Kurile Is.	45.5	151.5	8.2	
30.04.1919	07 17.1	Tonga Is.	— 19	— 172.5	8.2	
5.06.1920	04 21.5	Taiwan	23.5	122	8.0	
16.12.1920	12 05.8	Kansu, China	36	105	8.6	
11.11.1922	04 32.6	Chile	— 28.5	— 70	8.3	8.5

TABLE Ia). — (continued).

Date	Time			Region	Latitude	Longitude	M_s	M_w
3.02.1923	16 h	01 min	41 s	Kamchatka	54	161	8.3	8.5
1.09.1923	02	58	36	Kanto	35.25	139.5	8.2	7.9
14.04.1924	16	20	23	Mindanao	6.5	126.5	8.3	
1.12.1928	04	06	10	Chile	— 35	— 72	8.0	
14.05.1932	13	11	00	Molucca Passage	0.5	126	8.0	
3.06.1932	10	36	50	Mexico	19.5	— 104.25	8.2	
2.03.1933	17	30	54	Sanriku	39.25	144.5	8.5	8.4
15.01.1934	08	43	18	Nepal/India	26.5	86.5	8.3	
18.07.1934	19	40	15	Santa Cruz Is.	— 11.75	166.5	8.1	
1.02.1938	19	04	18	Banda Sea	— 5.25	130.5	8.2	8.5
10.11.1938	20	18	43	Alaska	55.5	— 158.0	8.3	8.2
30.04.1939	02	55	30	Solomon Is.	— 10.5	158.5	8.0	
25.11.1941	18	03	55	N. Atlantic	37.5	— 18.5	8.2	
24.08.1942	22	50	27	Peru	— 15.0	— 76.0	8.2	
7.12.1944	04	35	42	Tonanki	33.75	136.0	8.0	8.1
27.11.1945	21	56	50	W. Pakistan	24.5	63.0	8.0	
4.08.1946	17	51	05	Dominican Rep.	19.25	— 69.0	8.0	
20.12.1946	19	19	05	Nankaido	32.5	134.5	8.2	8.1
22.08.1949	04	01	11	Queen Charlotte Is.	53.75	— 133.25	8.1	8.1
15.08.1950	14	09	30	Assam	28.5	96.5	8.6	8.6
18.11.1951	09	35	47	Tibet	30.5	91.0	8.0	7.5
4.03.1952	01	22	43	Tokachi-Oki	42.5	143.0	8.3	8.1
4.11.1952	16	58	26	Kamchatka	52.75	159.5	8.2	9.0

TABLE Ia). - (continued).

Date	Time	Region	Latitude	Longitude	M_S	M_W
9.03.1957	14 h 22 min 28 s	Aleutian Is.	51.3	-175.8	8.1	9.1
4.12.1957	03 37 48	Mongolia	45.2	99.2	8.0	8.1
6.11.1958	22 58 06	Kurile Is.	44.4	148.6	8.1	8.3
22.05.1960	19 11 14	Chile	-38.2	-72.6	8.5	9.5
13.10.1963	05 17 51	Kurile Is.	44.9	149.6	8.1	8.5
28.03.1964	03 36 14	Alaska	61.1	-147.5	8.4	9.2
4.02.1965	05 01 22	Aleutian Is.	51.3	178.6	8.2	8.7
16.05.1968	00 48 57	Tokachi-Oki	40.9	143.4	8.1	8.2
19.08.1977	06 08 55	Sumbawa	-11.2	118.4	8.1	8.3

M_W for the 1977 Sumbawa earthquake is from [4].

M_W for the other events is from [2].

TABLE Ib). - Some large earthquakes with $M_W \sim 8$ (data from [1]).

Date	Time	Region	Latitude	Longitude	M_S	M_W
10.07.1958	06 h 15 min 56 s	Alaska	58.3	-136.5	7.9	7.7
17.10.1966	21 41 57	Peru	-10.7	-78.6	7.8	8.1
11.08.1969	21 27 36	Kurile Is.	43.4	147.8	7.8	8.2
31.05.1970	20 23 28	Peru	-9.2	-78.8	7.6	7.9
3.10.1974	14 21 29	Peru	-12.2	-77.6	7.6	8.1
26.05.1975	09 11 52	Azores	36.0	-17.6	7.8	7.7
16.08.1976	16 11 05	Mindanao Is.	6.2	124.1	7.8	8.1
29.11.1978	19 52 49	Mexico	16.1	-96.6	7.6	7.6
12.12.1979	07 59 03	Colombia	1.6	-79.4	7.6	8.2
17.07.1980	19 42 23	Santa Cruz Is.	-12.5	165.9	7.7	7.9

References for M_W are 1958 Alaska, [5]; 1976 Mindanao, [6]; 1978 Oaxaca, [7]; 1979 Colombia, [8]; 1980 Santa Cruz Is., [9]; others, see [2].

TABLE II. - Frequency-magnitude relation, 1904-1980 (data from [1]).

Interval			Cumulative		
$\leq M_S <$	$n_1^{(a)}$	$n_2^{(b)}$	$M_S \geq$	$N_1^{(c)}$	$N_2^{(d)}$
7.0 7.2	252	252	7.0	720	720
7.2 7.4	162	162	7.2	468	468
7.4 7.6	104	104	7.4	306	306
7.6 7.8	97	97	7.6	202	202
7.8 8.0	52	52	7.8	105	105
8.0 8.2	25	22	8.0	53	53
8.2 8.4	17	13	8.2	28	31
8.4 8.6	8	10	8.4	11	18
8.6 8.8	3	3	8.6	3	8
8.8 9.0		1	8.8		5
9.0 9.2		2	9.0		4
9.2 9.4		1	9.2		2
9.4 9.6		1	9.4		1

- (a) n_1 is the number of events within the magnitude range of 0.2 for the period 1904 to 1980.
- (b) Same as (a) with M_S replaced by M_w for the ten largest events with $M_w \geq 8.5$ listed below.
- (c) N_1 is the total number of events larger than the given M_S for the period 1904 to 1980.
- (d) Same as (c) with M_S replaced by M_w for the ten largest events with $M_w \geq 8.5$ listed below. 1960 Chile ($M_S = 8.5$; $M_w = 9.5$), 1964 Alaska (8.4; 9.2), 1957 Aleutian Is. (8.1; 9.1), 1952 Kamchatka (8.2; 9.0), 1906 Colombia (8.6; 8.8), 1965 Aleutian Is. (8.2; 8.7), 1950 Assam (8.6; 8.6), 1938 Banda Sea (8.2; 8.5), 1963 Kurile Is. (8.1; 8.5), 1922 Chile (8.3; 8.5).

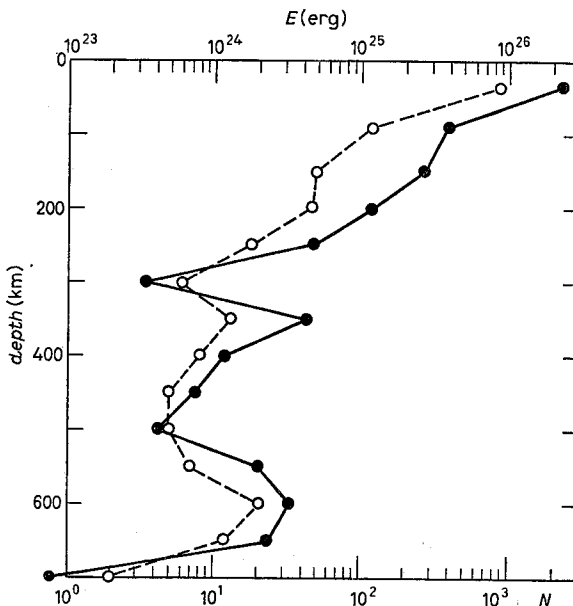


Fig. 3. - The variation of seismic activity as a function of depth. The solid curve shows the energy and the dashed curve the number of events with $m_B \geq 7$. The scale at the top indicates the energy (E) and that at the bottom the number (N). Each data point represents the value for a depth range of 50 km centered at the depth of each data point and for the time period of 75 years from 1904 to 1974 [10].

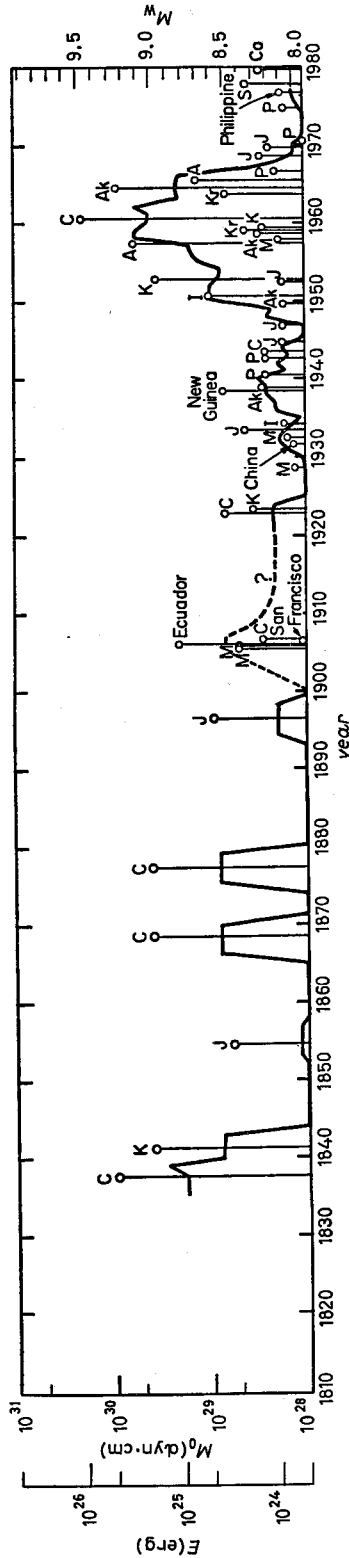


Fig. 4. — The seismic moment M_0 , the seismic energy E and the magnitude M_w of great and large earthquakes as a function of time (A, Aleutian; Ak, Alaska; C, Chile; Co, Colombia; I, India; J, Japan; K, Kamchatka; Kr, Kurile; M, Mongolia; P, Peru; S, Sumbawa). The solid curve shows unlagged 5-year running average (in erg per year) taken at the center of the interval (modified from [2]). For the period from 1835 to 1900, tsunami magnitude M_s [1] is used to estimate M_0 , E and M_w .

tivity corresponds to about $4.5 \cdot 10^{24}$ erg/year. This value may be compared to the amount of heat flow from the Earth's interior (10^{23} erg/year) and the energy (mainly thermal energy) released by volcanic eruptions ($1.7 \cdot 10^{25}$ erg/year, see, *e.g.*, [11]).

The spatial distribution of large earthquakes is not uniform. Most great earthquakes occur along the subduction zones in the Pacific, as shown in fig. 2. The variation of activity with depth is also very nonuniform, as shown in fig. 3.

2. - Temporal variation.

The temporal variation of earthquake energy release (fig. 4) shows a pronounced peak for the period from 1952 to 1965. The data for this century are considered to be complete for great earthquakes. The data for the 19th

TABLE III. - *World's worst earthquakes* [12] (1900-1979).

Date	Region	Latitude	Longitude	M_s	Lives lost
27.07.1976	Tangshan	39.5	117.9	7.9	240 000
16.12.1920	Kansu	36.5	105.7	8.6	200 000
1.09.1923	Kanto	35.3	139.5	8.2	99 331
31.05.1970	Peru	— 9.1	— 78.8	7.6	66 794
28.12.1908	Messina	38.3	15.6	7.2	58 000
22.05.1927	Tsinghai	37.6	102.6	7.9	40 912
26.12.1939	Turkey	39.7	39.5	7.8	32 700
13.01.1915	Italy	42.1	13.4	6.9	32 610
25.01.1939	Chile	— 36.2	— 72.2	7.8	28 000
30.05.1935	Pakistan	29.5	66.7	7.6	25 000
4.02.1976	Guatemala	15.3	— 89.1	7.5	23 000
10.05.1974	Szechwan	28.2	104.0	6.8	20 000
5.10.1948	Iran	38.0	58.3	7.3	19 800
4.04.1905	E. Kashmir	33.0	76.0	8.1	19 000
16.09.1978	Iran	33.2	57.4	7.2	15 000
21.01.1917	Bali Is.	— 8.0	115.4		(15 000)
1.09.1962	Iran	35.6	49.9	6.9	12 225
31.08.1968	Iran	34.0	59.0	7.1	12 100
21.10.1907	Afghanistan	38.0	69.0	7.7	12 000
29.02.1960	Morocco	30.4	— 9.6	5.9	12 000
15.01.1934	Nepal/India	26.5	86.5	8.3	10 700
25.08.1933	Szechwan	32.0	103.7	7.5	10 000
13.02.1918	Yunnan	23.5	117.0	7.4	10 000

The values of M_s are from [1] whenever available.

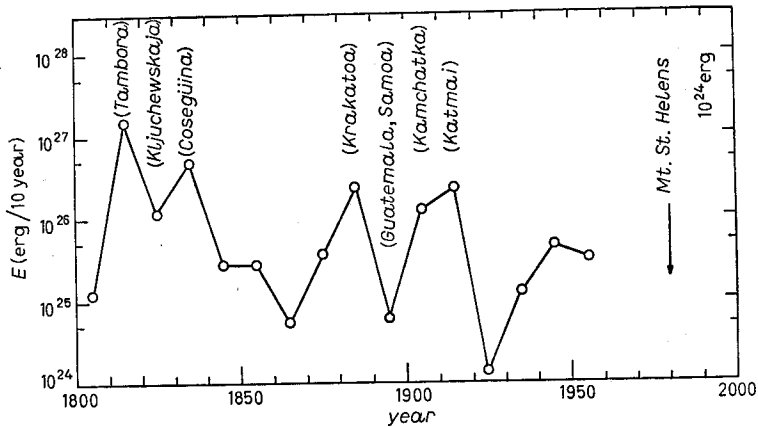


Fig. 5. — The energy release in major volcanic eruptions calculated from the table given in [11]. Each data point represents the energy released in each 10-year period. The average is $1.7 \cdot 10^{25}$ erg/year. The names of the volcanoes which erupted during each period are indicated in parentheses. The estimate of the energy is based mainly on the thermal energy carried by the ejecta or lava, and is subject to considerable uncertainty. This graph is intended to show the gross feature of the temporal variation of volcanic activity.

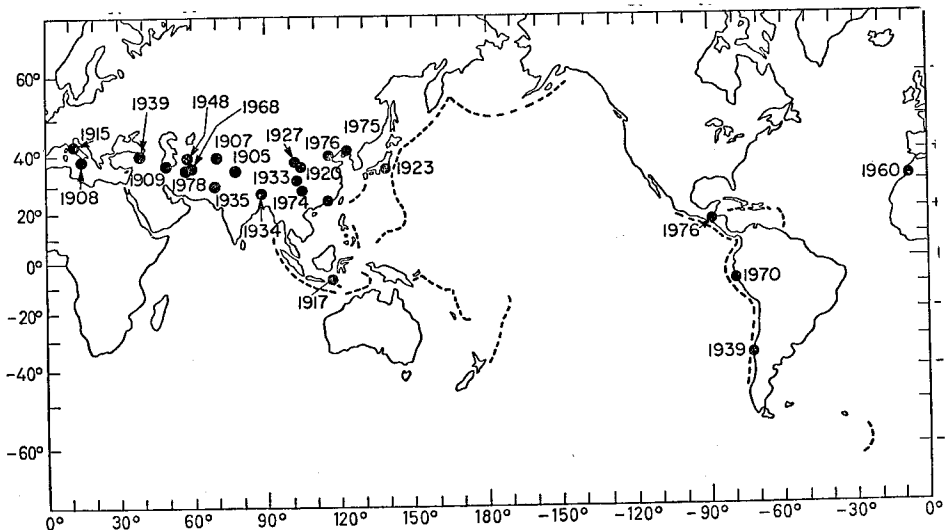


Fig. 6. — Locations of destructive earthquakes listed in table III.

century shown in fig. 4 are obtained from tsunami data [1] and are somewhat incomplete; however, it is probably true that during the period from 1835 to 1900 there is no peak comparable to that for the period 1952 to 1965. It is clear that the global seismic activity is very nonuniform in time at least on a

time scale of 100 years or so. The same is true for the energy release in volcanic eruptions, as shown in fig. 5.

3. - Destructive earthquakes.

Large earthquakes are not necessarily most damaging. In fact, most destructive (in terms of property damage and number of casualties) earthquakes are very often relatively small (magnitude 6.5 to 7.5), as shown in fig. 6 and 7 and in table III. This is not surprising, because the damage caused

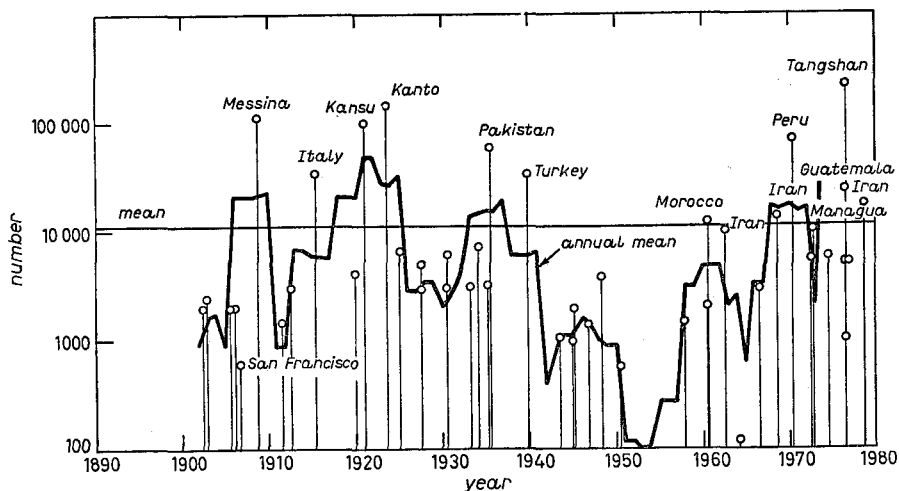


Fig. 7. - Loss of life caused by major destructive earthquakes. The vertical bars are for the individual event and the solid curve shows the annual average (unlagged 5-year running average). This figure is modified from fig. 1 in [13], and the numbers differ slightly from those in table III.

by earthquakes depends mainly on the location and time of the earthquakes, the population in the area, the construction of the structure and the secondary effects caused by the earthquake (*e.g.*, fire, failure of dam, etc.). Furthermore, moderate earthquakes are more numerous than large earthquakes.

4. - Seismicity and plate motion.

As shown in fig. 2, most great earthquakes occur along subduction zones. These events are considered to be due to interaction between the subducting oceanic plate and the upper (continental) plate. The stronger the interaction, the higher seismic activity would be expected. RUFF and KANAMORI [14] considered that the level of seismic activity for the individual subduction

TABLE IV. - *Maximum M_w (also M'_w), age of the subducting plate (in million years) and convergence rate (in cm/year).*

Zone	M_w	M'_w	T (10^6 y)	V (cm/y)
Marianas	7.2	7.2	150	4.0
Java	7.1	7.1	135	7.1
Izu-Bonin	7.2	7.2	150	6.1
N.E. Japan	8.2	8.35	130	9.7
Tonga	8.3	8.3	120	8.9
Kermadec	8.1	8.1	120	6.4
Kuriles	8.5	8.8	100	9.3
Kamchatka	9.0	9.0	80	9.3
New Zealand	7.8	7.8	120	5.5
New Hebrides	7.9	7.9	60	2.7
Ryukyus	8.0	8.0	60	5.6
Aleutians	9.1	9.1	60	7.5
Sumatra	7.9	7.9	80	6.6
Alaska	9.2	9.1	40	5.9
Central America	8.1	8.4	45	8.0
Central Chile	8.5	8.65	50	11.0
S. Chile	9.5	9.45	20	11.1
Peru	8.2	8.6	45	10.0
Caribbean	7.5	7.5	100	2.0
Scotia Arc	7.0	7.0	65	2.0
Colombia	8.8	8.8	20	7.7
S.W. Japan	8.0	8.6	40	3.8

zones may be represented by the magnitude M_w of the largest earthquake ever recorded for that subduction zone. The strength of interaction may be controlled by many factors, such as the plate convergence rate, the age of the subducting plate, the Benioff-zone dip angle, the length of the slab, etc. RUFF and KANAMORI examined their correlation with M_w and found that the convergence rate, V , and the age, T , jointly correlate well with M_w : RUFF and KANAMORI modified M_w by correcting for the difference in the repeat time and the length among different subduction zones. However, the modified magnitude M'_w differs only very slightly from M_w , so that replacing M_w by M'_w does not affect the overall correlation. The data are summarized in table IV and the three-parameter (M'_w , T , V) regression is shown in fig. 8. This result

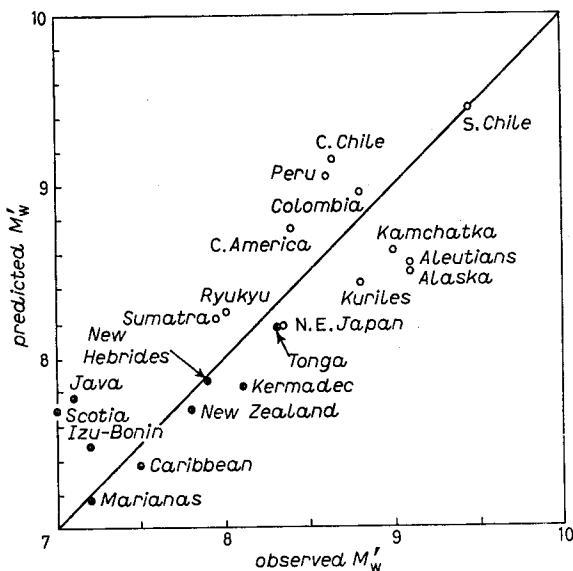


Fig. 8. - M'_w predicted from the age of the subducting plate in million years (T) and the convergence rate in cm/y (V), $M'_w = -0.00953 T + 0.143 V + 8.01$. This diagram is constructed from fig. A1 of [14]. The closed circles indicate the subduction zones with active back-arc basins. Note that these subduction zones have small M'_w indicating a weak interaction (or mechanical coupling).

suggests that the faster the convergence, the stronger the interaction and, the older the subducting slab, the weaker the interaction. Although the details of the mechanism are not fully understood (see [15]), the gross plate parameters, such as the convergence rate and the plate age, seem to be controlling the subduction zone seismicity to the first order.

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