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Magnitudes of Central American earthquakes 1898–1930

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SUMMARY

This paper presents the results of the calculation of surface-wave magnitudes of Central American earthquakes between 1898 and 1930. Some 168 events are identified for which magnitudes can be calculated either on early Milne instruments or later damped seismographs. This is about six times as many as listed in regional or global catalogues. The locations of the more important events were revised using a combination of instrumental readings and macroseismic information.

Key words: Central America, earthquakes, Pacific region, surface waves.

INTRODUCTION

The initial aim of this study was to investigate the attenuation of intensities and ground accelerations with source distance and magnitude in Central America. Such a study required reliable epicentral distances and focal depths, uniformly calculated average magnitudes for shallow and intermediate depth earthquakes and an estimate of the associated errors. The lack of these data, particularly for the first half of the century, led us to the systematic reappraisal of earthquakes in the region from the beginning of the instrumental period to the start of ISC analysis in 1964, from the point of view of location and magnitude. The results of this reappraisal will appear elsewhere (Ambraseys & Adams 1995).

One of the results of our study—the subject matter of this paper—is the uniform evaluation of magnitudes of Central American earthquakes of the early part of this century. I have chosen to present here the results for the period 1898–1930 inclusive, not only because of the relatively high seismic activity of the region during that period but also because of the very small number of earthquakes for which instrumental magnitudes are known. Of the 340 shocks we have identified in Central America during this period, only 28 have been assigned instrumental magnitudes by Gutenberg (1956), Gutenberg & Richter (1965), Duda (1965), Abe (1981), and Abe & Noguchi (1983). My intention here is to redress this problem by presenting magnitudes that could be used with confidence for the study of local and regional tectonics and seismicity. A substantial advantage can be gained by calculating surface-wave magnitudes for which world-wide reported data are available, using an internationally accepted technique in preference to correcting the conflicting non-instrumental values reported today in various regional and global catalogues, and to adding empirical relations to the long list already existing. Surface-wave magnitude M_S, as defined by the Prague formula (Vanek *et al.* 1962), can be calculated easily. It is a tedious, boring but essential job that can be done using teleseismic data. All that is required is access to station bulletins and seismograms world-wide. The systematic evaluation of magnitude for events of the first half of this century was initiated by Gutenberg & Richter (1965) and continued by Karnik (1968), Kanamori & Abe (1979), Margottini (1993) and others.

DATA AND METHOD OF ANALYSIS

This investigation is concerned with an area defined by the coordinates 7°–16.5°N latitude and 79°–92.5°W longitude. It incorporates the whole of Central America and parts of the Pacific and Caribbean Sea (Fig. 1).

For the period 1898–1930 the total number of earthquakes identified, regardless of depth, is 340. Recorded body- and surface-wave information that can be used to calculate magnitude values was found for 169 events, and is listed in Table 1.

For the calculation of magnitudes we need relatively good epicentral locations, an estimate of the focal depth as well as amplitude, and period data of different phases from an azimuthally well-distributed number of stations.

Epicentral locations

Because of the lack of reliable macroseismic information and of near seismographic stations, the instrumental and macroseismic location of many of the events in the region is poorly known. Although precise location has relatively little relevance in the assessment of magnitude, many of the more important events were revised.

Reliable macroseismic positions in Table 1 are marked by M. They correspond to the centre of the area of highest intensity and their location errors are unlikely to be greater than 20 km, but for some of them the uncertainty in depth is still considerable.

For earthquakes on land or near the shore for which there

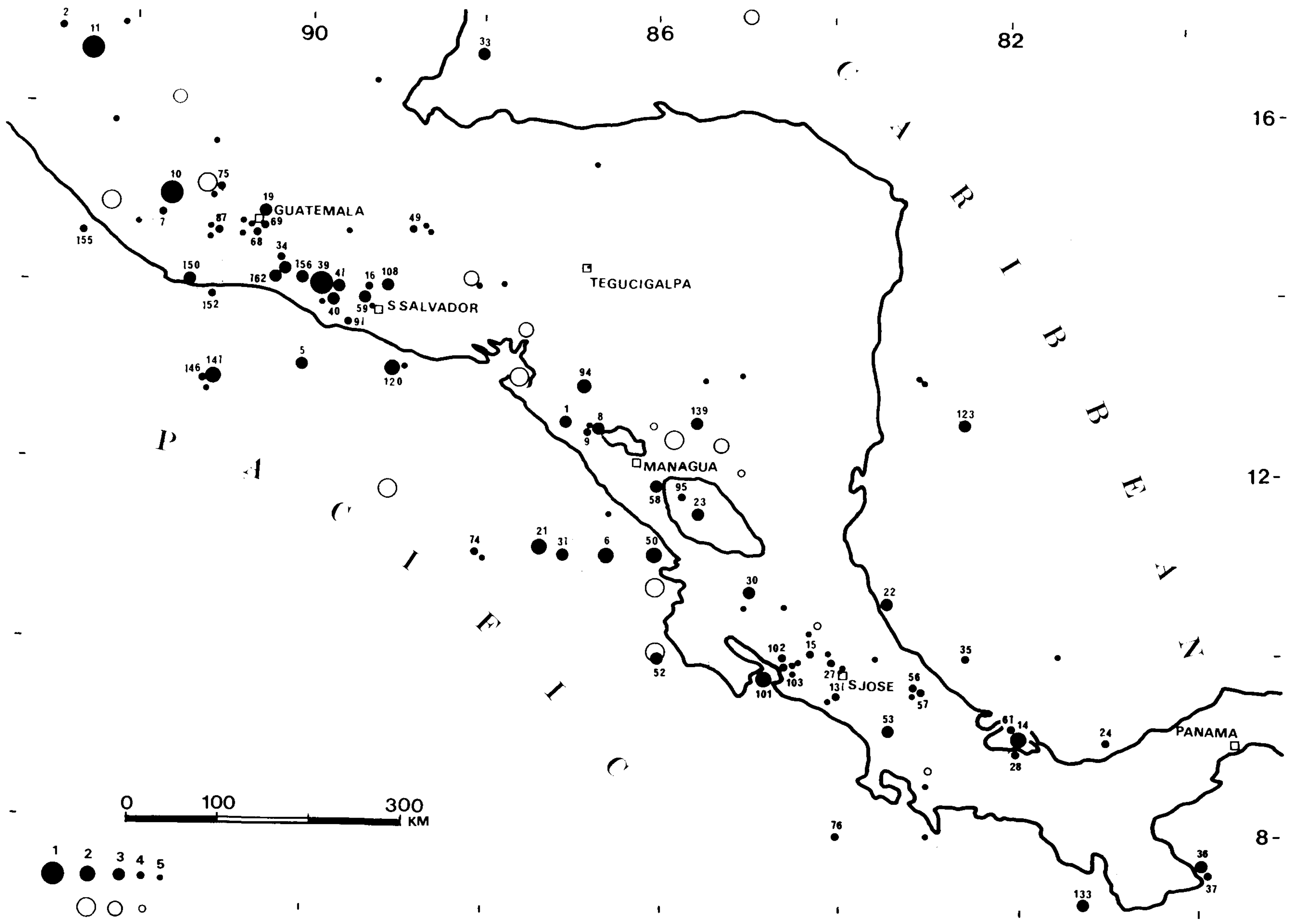

Figure 1. Seismicity of Central America during the period 1898–1930. Locations are from Ambraseys & Adams (1995) and only those of $M_s > 5.4$ have been included. Crustal earthquakes are shown by solid circles: 1, $M_s > 7.5$; 2, $7.0 < M_s < 7.5$; 3, $6.5 < M_s < 7.0$; 4, $6.0 < M_s < 6.5$; 5, $5.5 < M_s < 6.0$. Those with depths greater than 50 km are indicated by open circles. Numbers refer to entries in Table 1.

Table 1. Magnitude determination of Central American earthquakes 1898–1930.

	Date	OT (GMT)	Epicentre N° W°	h	M_S	n_S	m_B	n_B	M_M	n_M	M_C	N
1	1898 Apr 29	1617--	12.56-86.96M	n	-	-	-	-	6.75	3	7.5	8+
2	1899 Mar 25	1427--	16.80-92.80m	n	-	-	-	-	6.24	3	-	6+
3	1899 Mar 25	1700--	13.65-88.80M	n-	-	-	-	-	<5.30	-	-	2
4	1900 Jun 21	2058--	10.00-86.00r	n+	-	-	-	-	7.21	9	7.5	20+
5	1900 Nov 9	1608--	13.00-90.00r	n	-	-	-	-	6.93	10	7.3	-
6	1901 Oct 8	0216--	11.00-86.50r	n	-	-	-	-	7.04	12	7.0	-
7	1902 Jan 18	2323--	14.71-91.59M	n	-	-	-	-	6.31	12	-	-
8	1902 Mar 24	1755--	12.38-86.62M	n-	-	-	-	-	6.55	8	-	-
9	1902 Mar 25*	0322--	12.40-86.70m	n-	-	-	-	-	6.32	4	-	-
10	1902 Apr 19	0224--	14.93-91.50M	n	-	-	-	-	7.49	22	7.7	-
11	1902 Sep 23	2018--	16.50-92.50M	n	-	-	-	-	7.57	26	7.8	-
12	1902 Oct 24	0418--	14.70-91.60m	n-	-	-	-	-	5.16	2	-	-
13	1903 Feb 28	0945--	10.50-84.50R	n	-	-	-	-	5.86	12	-	-
14	1904 Dec 20	0542--	9.00-82.00m	n	7.45	3	7.7	4	7.30	25	7.7	-
15	1905 Jan 20	1808--	10.00-84.25M	n	6.47	3	-	-	6.28	8	-	-
16	1906 Jun 20	0225--	13.90-89.30M	n	6.07	2	6.1	3	6.03	9	-	-
17	1906 Jun 22	0319--	16.00-91.50m	n+	5.32	2	6.5	3	5.69	3	-	-
18	1907 Jul 1	130913	13.00-87.50R	n+	7.38	6	6.6	7	6.87	16	-	54+
19	1907 Sep 23	2135--	14.80-90.50m	n	6.53	7	6.2	1	6.65	9	-	33+
20	1907 Oct 6	0048--	10.00-84.00m	n	5.78	5	5.9	2	5.77	3	-	16+
21	1907 Dec 30	052652	11.10-87.30R	n	7.44	8	6.7	4	7.11	20	-	60
22	1908 Feb 1	2312--	10.50-83.50r	n	6.58	6	6.4	1	6.56	12	-	-
23	1909 Aug 16	0655--	11.50-85.50m	n	6.86	11	6.4	5	6.78	20	-	-
24	1909 Aug 30	1318--	9.00-81.00m	n	6.14	6	6.2	3	6.23	7	-	-
25	1910 Jan 1	1102--	17.00-85.00m	n+	6.92	10	6.9	10	6.99	23	7.1	-
26	1910 Apr 13*	0640--	9.82-83.91M	n-	5.62	3	-	-	5.72	5	-	10+
27	1910 May 5	0026--	9.84-84.05M	n-	6.05	9	6.4	1	6.10	11	-	17+
28	1910 Dec 21	1024--	9.00-82.00m	n	6.22	3	-	-	6.16	11	-	20+
29	1911 Aug 29	0343--	10.22-84.30M	n-	5.80	5	-	-	5.93	8	-	15+
30	1911 Oct 10	1312--	10.61-84.89M	n-	6.53	17	6.3	3	6.76	21	-	36+
31	1911 Nov 1	0925--	11.00-87.00R	n	6.67	12	-	-	6.66	19	-	33+
32	1912 Jun 6	0612--	10.25-84.30M	n-	5.12	1	-	-	-	-	-	2+
33	1912 Jun 12	124442	16.50-88.00r	n	6.80	18	6.6	9	6.68	22	6.8	42+
34	1913 Mar 8	1605--	14.26-90.27M	n-	6.44	14	6.9	1	6.45	18	-	45
35	1913 Jul 25	123806	10.00-82.50r	n	6.18	12	-	-	6.16	15	6.3	42
36	1913 Oct 2	042328	7.50-80.00M	n-	6.69	10	6.8	1	6.38	16	-	47
37	1913 Oct 23*	150032	7.50-80.00m	n-	5.98	3	-	-	6.11	11	-	25
38	1914*May 28	032416	10.90-73.60R	n+	6.39	8	6.9	5	-	-	7.2	47
39	1915 Sep 7	012052	13.90-89.70M	n	7.66	24	7.5	11	7.76	1	7.8	65
40	1915 Sep 7*	0318--	13.80-89.70m	n	6.42	3	-	-	-	-	-	-
41	1915 Sep 7*	0423--	13.80-89.70m	n	6.64	1	-	-	-	-	-	-
42	1915 Sep 7*	0458--	13.80-89.70m	n	6.02	3	-	-	-	-	-	-
43	1915 Sep 7*	0531--	13.80-89.70m	n	5.23	1	-	-	-	-	-	-
44	1915 Sep 7*	1247--	13.80-89.70m	n	5.90	3	-	-	-	-	-	-
45	1915 Sep 7*	2039--	13.80-89.70m	n	5.61	2	-	-	-	-	-	-
46	1915 Sep 8*	1256--	13.80-89.70m	n	5.21	2	-	-	-	-	-	-
47	1915 Dec 26*	0911--	14.60-88.60M	n-	5.68	2	-	-	-	-	-	-
48	1915 Dec 27*	0409--	14.60-88.60m	n-	5.47	1	-	-	-	-	-	-
49	1915 Dec 28	2354--	14.56-88.76M	n-	6.37	8	6.6	1	6.57	2	-	10+
50	1916 Feb 27	202123	11.00-86.00R	n	7.31	15	7.4	8	-	-	7.5	61
51	1916 Apr 24	080216	10.70-86.00R	n+	7.35	17	7.1	11	-	-	7.3	53
52	1916 Apr 24*	0831--	10.00-86.00m	n	6.58	1	-	-	-	-	-	5+
53	1916 Apr 26	022128	9.10-83.40R	n	6.86	13	6.8	7	-	-	7.3	44
54	1916 Apr 26*	062515	9.60-83.10m	n	5.95	3	6.3	1	-	-	-	5+
55	1916 Apr 26*	071556	9.60-83.10m	n	5.95	4	6.5	1	-	-	-	5+
56	1916 May 10*	213614	9.60-83.10m	n	6.09	5	6.4	2	-	-	-	5+
57	1916 Jul 28*	173732	9.60-83.10m	n	6.05	3	-	-	-	-	-	4+
58	1916 Sep 23	054301	11.90-86.00R	n	6.65	6	6.9	2	-	-	-	34
59	1917 Jun 8	005151	13.82-89.31M	n-	6.65	14	6.3	2	6.84	3	-	48
60	1917 Jun 8*	025400	13.77-89.50m	n-	5.39	1	-	-	-	-	-	4+
61	1917 Jun 27	122635	9.00-82.00r	n	6.09	3	-	-	-	-	-	19
62	1917*Jun 30	175038	7.20-77.80R	n	6.08	4	6.3	1	-	-	-	27
63	1917 Oct 22	072000	13.00-83.00I	n	5.93	3	-	-	-	-	-	27
64	1917 Dec 26*	043000	14.60-90.60m	n-	5.59	3	-	-	-	-	-	7+
65	1917 Dec 26*	052100	14.63-90.67M	n-	5.59	5	-	-	-	-	-	11
66	1917 Dec 26*	061810	14.60-90.60m	n-	5.06	3	-	-	-	-	-	5
67	1917 Dec 29*	2013--	14.60-90.60m	n-	5.24	2	-	-	-	-	-	4

Table 1. (*Continued.*)

	Date	OT (GMT)	Epicentre N° W°	h	M_s	n_s	m_B	n_B	M_M	n_M	M_C	N
68	1918 Jan 4*	043241	14.56-90.55M	n-	5.98	6	6.4	1	-	-	-	36
69	1918 Jan 25*	012049	14.60-90.50M	n-	6.16	4	6.6	1	-	-	-	39
70	1918 Apr 27	144345	8.70-83.00I	n	5.38	2	-	-	-	-	-	19
71	1918 Jun 13	085858	15.30-86.70R	n	5.54	3	-	-	-	-	-	17
72	1918 Jun 16	122746	12.50-86.00R	n+	5.60	3	6.1	1	-	-	-	22
73	1918 Jun 22	220530	9.50-84.00A	n	5.66	1	-	-	-	-	-	19
74	1918 Jul 31	143643	11.00-88.00I	n	6.17	6	-	-	-	-	-	52
75	1918 Oct 19	032245	15.00-91.00m	n	6.20	8	-	-	-	-	-	48
76	1918 Oct 29	122600	8.00-84.00A	n	5.90	1	-	-	-	-	-	16
77	1919 Apr 17	205303	14.80-92.20m	n+	6.96	9	7.1	2	-	-	7.0	69
78	1919 Apr 28	064545	13.69-89.19m	n-	5.94	3	-	-	-	-	-	23
79	1919 Jun 29	231422	13.50-87.50m	n+	6.69	8	-	-	-	-	6.7	59
80	1919 Jul 1	213025	14.50-91.00A	n	5.39	1	-	-	-	-	-	6
81	1919 Jul 6	070410	14.50-91.00A	n	5.94	5	-	-	-	-	-	27
82	1919 Jul 17	161934	11.00-88.00A	n	5.91	4	-	-	-	-	-	23
83	1919 Jul 22	220135	12.00-85.00G	n+	5.61	3	6.1	1	-	-	6.5	25
84	1919 Oct 14	165540	14.50-90.69m	n	5.71	2	-	-	-	-	-	10
85	1919 Oct 28	072320	13.00-83.00A	n	5.60	1	-	-	-	-	-	7
86	1919 Dec 5	001526	13.00-85.40I	n	5.89	2	-	-	-	-	-	14
87	1920 Mar 23	152148	14.50-91.00A	n	6.12	5	-	-	-	-	-	32
88	1920 Jul 16	171415	10.50-85.00m	n	5.79	3	-	-	-	-	6.0	23
89	1920*Oct 8	165045	15.40-93.50m	n	6.12	6	6.7	1	-	-	-	28
90	1920 Nov 6	104430	14.50-89.50m	n	5.79	3	-	-	-	-	-	13
91	1920 Dec 11	212218	13.50-89.50m	n	6.26	5	-	-	-	-	-	32
92	1921 Feb 4	082244	15.00-91.00G	n+	7.20	11	7.3	3	-	-	7.5	72
93	1921 Feb 11	223936	9.50-84.00A	n	5.41	1	-	-	-	-	-	9
94	1921 Mar 28	074939	12.90-86.80R	n+	7.41	10	7.2	2	-	-	7.3	76
95	1922 Feb 16	031448	11.70-85.70M	n	6.35	10	-	-	-	-	-	53
96	1922 Apr 20	054818	15.50-91.00m	n	5.70	2	-	-	-	-	-	16
97	1922 Aug 18	195026	13.00-85.40A	n	5.55	2	-	-	-	-	-	8
98	1922 Dec 8	080840	10.00-83.89m	n	5.11	1	-	-	-	-	-	8
99	1923 Dec 26	0756--	14.50-90.65m	n	4.82	1	-	-	-	-	-	3
100	1924 Mar 4*	020612	9.70-85.00m	n	5.20	1	-	-	-	-	-	6
101	1924 Mar 4	100742	9.80-84.70M	n	7.03	15	6.6	3	-	-	7.0	85
102	1924 Mar 4*	114336	9.80-84.70m	n	6.44	6	-	-	-	-	-	34
103	1924 Mar 11*	104108	9.90-84.60m	n	6.30	11	-	-	-	-	-	51
104	1924 Mar 11*	203406	9.80-84.50m	n	5.71	2	-	-	-	-	-	19
	1924 Mar 12*	025020	9.80-84.50m	n	5.50	m	-	-	-	-	-	16
	1924 Mar 20*	095612	9.80-84.50m	n	5.40	m	-	-	-	-	-	12
	1924 Mar 24*	114015	9.80-84.50m	n	5.20	m	-	-	-	-	-	7
105	1924 Mar 24*	202900	9.80-84.50m	n	5.94	3	-	-	-	-	-	39
106	1924 Mar 25*	140700	9.60-84.30R	n+	6.19	7	-	-	-	-	-	39
107	1924 Mar 25*	150332	9.60-84.30R	n	5.87	4	-	-	-	-	-	31
	1924 Mar 27*	082945	9.80-84.20m	n	5.50	m	-	-	-	-	-	14
	1924 Mar 28*	045700	9.80-84.20m	n	4.80	m	-	-	-	-	-	4
108	1924 May 1	195415	14.00-89.00I	n	6.58	14	6.6	1	-	-	-	80
109	1924 May 21	101250	14.50-88.70I	n	5.35	2	-	-	-	-	-	18
110	1924*Jun 4	160930	16.10-93.80m	n	5.75	5	-	-	-	-	-	26
111	1924 Oct 10	21----	14.42-90.48M	n	4.86	1	-	-	-	-	-	4
112	1924 Nov 1	045515	11.50-86.50r	n	5.95	3	-	-	-	-	-	25
113	1925 Jan 26	190206	8.70-83.00A	n+	6.15	12	-	-	-	-	-	55
114	1925 Jan 28*	105830	8.70-83.00A	n	5.90	5	-	-	-	-	-	26
115	1925 Feb 9	055330	14.90-92.10m	n	5.05	3	-	-	-	-	-	9
116	1925*May 26	082024	16.50-94.40r	n+	5.75	9	6.2	1	-	-	-	28
117	1925 Sep 4	103600	16.00-91.50m	n	5.21	6	-	-	-	-	-	11
118	1925 Oct 5	040902	12.25-85.25G	n+	6.35	16	6.8	4	-	-	6.8	78
119	1925 Nov 28	123325	16.80-92.10m	n	5.54	7	-	-	-	-	-	22
120	1926 Feb 8	151749	13.00-89.00G	n	7.14	23	7.1	8	-	-	7.1	108
121	1926 Feb 10	144820	13.00-85.40A	n	5.71	6	-	-	-	-	-	24
122	1926 Feb 15	025948	11.75-89.50G	n+	6.61	20	7.0	4	-	-	6.9	94
123	1926 Mar 17	115336	12.50-82.50G	n	6.81	21	6.7	3	-	-	6.9	94
124	1926 Mar 24	105442	15.70-92.20m	n	5.60	5	-	-	-	-	-	12
125	1926 May 26	175330	14.50-88.70A	n	5.26	6	6.1	1	-	-	-	20
126	1926 Jun 28	1858--	14.90-91.00m	n	5.5	4	-	-	-	-	-	5+
127	1926 Jul 21	022300	14.50-88.70A	n	5.02	1	-	-	-	-	-	6
128	1926 Oct 19	204830	10.00-83.50m	n	5.78	9	5.6	1	-	-	-	39
129	1926 Nov 5	075538	12.30-85.80G	n+	6.93	26	7.0	8	-	-	7.2	104

Table 1. (*Continued.*)

	Date	OT (GMT)	Epicentre N° W°	h	M_S	n_S	m_B	n_B	M_M	n_M	M_G	N
130	1927 Feb 24	041352	14.50-91.00A	n	5.72	8	-	-	-	-	-	24
131	1927 Mar 9	161315	9.50-84.00A	n	6.00	11	-	-	-	-	-	41
132	1927*May 9	200540	16.70-93.70m	n	6.11	19	6.2	1	-	-	-	57
133	1927 Aug 10	013522	7.30-81.30r	n	6.64	33	6.8	5	-	-	-	88
134	1927 Aug 22	025133	9.50-84.00A	n	5.28	3	-	-	-	-	-	13
135	1927 Oct 2	044745	14.00-88.00A	n+	6.03	15	6.6	2	-	-	-	48
136	1927 Oct 2*	092915	14.00-88.00A	n	5.05	3	-	-	-	-	-	19
137	1927 Dec 27	203145	16.50-89.50A	n	4.91	3	-	-	-	-	-	6
138	1928 Mar 27	050928	16.20-89.20m	n	5.60	9	-	-	-	-	-	29
139	1928 Oct 25	123248	12.50-85.50m	n	6.67	32	6.9	2	-	-	-	87
140	1929 Jan 19	031754	10.00-81.50G	n	5.91	10	-	-	-	-	6.0	35
141	1929 Jan 24	203628	12.80-91.00A	n	7.08	33	6.9	5	-	-	-	114
142	1929 Jan 24*	232900	12.80-91.00A	n	5.48	5	-	-	-	-	-	13
143	1929 Jan 25*	012812	12.80-91.00A	n	5.68	8	-	-	-	-	-	27
144	1929 Jan 26*	023040	12.80-91.00A	n	5.48	5	-	-	-	-	-	19
145	1929 Jan 28*	215642	12.80-91.00A	n	5.81	9	-	-	-	-	-	25
146	1929 Jan 31*	180517	12.80-91.00A	n	6.23	16	-	-	-	-	-	42
147	1929 Feb 3*	180040	12.80-91.00A	n	5.58	9	-	-	-	-	-	24
148	1929 Feb 4	101934	14.00-88.00A	n	5.50	4	-	-	-	-	-	24
149	1929 Feb 10	033704	12.30-93.80A	n	5.44	8	-	-	-	-	-	23
150	1929 Feb 10	153904	13.90-91.20I	n	6.63	31	-	-	-	-	-	80
151	1929 Feb 13*	221320	13.90-91.20A	n	6.02	11	-	-	-	-	-	33
152	1929 Feb 15*	080424	12.80-91.00A	n	6.20	18	6.1	1	-	-	-	56
153	1929 Mar 1*	153940	13.90-91.20A	n	5.58	6	-	-	-	-	-	22
154	1929 Mar 1*	205700	13.90-91.20A	n	5.43	3	-	-	-	-	-	10
155	1929 Mar 19	205342	14.50-92.50m	n	6.30	24	6.1	1	-	-	-	72
156	1929 Mar 21	023656	14.00-90.00m	n	6.46	32	6.2	1	-	-	-	88
157	1929 May 12	093430	12.80-91.00A	n	5.91	13	-	-	-	-	-	33
158	1929 Jun 9*	010245	12.80-91.00A	n	5.20	5	-	-	-	-	-	13
159	1929 Jul 30	074334	13.90-91.20A	n	5.85	15	-	-	-	-	-	29
160	1929 Aug 20	173654	10.50-87.00I	n	5.53	7	-	-	-	-	-	24
161	1929 Dec 20	102702	14.60-91.40M	n	5.34	5	-	-	-	-	-	17
162	1930 Jul 7*	133311	14.10-90.25M	n	6.16	22	5.9	1	-	-	-	52
163	1930 Jul 7*	204252	14.10-90.28m	n	5.23	1	-	-	-	-	-	15
164	1930 Jul 14	224044	14.12-90.25M	n	6.85	43	6.5	6	-	-	-	113
165	1930 Jul 17*	183016	14.00-90.00m	n	5.53	8	-	-	-	-	-	15
166	1930 Jul 27	185844	14.00-87.70m	n	5.81	13	5.9	1	-	-	-	43
167	1930 Jul 29	062406	12.40-86.70I	n	5.81	10	-	-	-	-	-	33
168	1930 Aug 29	082740	8.50-83.00m	n	5.67	8	-	-	-	-	-	39
169	1930 Sep 26	042214	13.90-91.20A	n	5.03	1	-	-	-	-	-	11

Notes

Date and origin time are GMT. Years marked with an asterisk refer to earthquakes which appeared in other sources, but which can be shown to be mislocated into our study area. Dates marked with an asterisk refer to aftershocks or foreshocks.

Epicentres followed by M are well-located macroseismic positions; less well-located events of scanty data or near the shore epicentres are shown by m. Most of these locations have been checked using instrumental data.

Recomputed locations from teleseismic data are followed by R (Ambraseys & Adams 1995). Rough relocations merely confirming a macroseismic or instrumental position or the general area of an event are shown by r.

Locations adopted from other sources are G: Gutenberg (1958) or Gutenberg & Richter (1965); I: BAAS/ISS; and A is for positions 'adopted' by ISS without calculation.

n indicates shallow depth ($h < 40$–60 km); estimated upper-crustal events are shown by $n-$ ($h < 20$ km); $n+$ refers to subcrustal depth ($h > 40$–60).

M_s is the average surface-wave magnitude calculated in this study with station corrections, and n_S is the number of single-station magnitudes used.

m_B is the average long-period body-wave magnitude calculated from PZ, PH, SH PPH and PPZ phases assuming shallow depth, and n_B is the number of single-station magnitudes used.

M_M is the equivalent surface-wave magnitude calculated from maximum amplitudes on Milne instruments from eq. (1) and n_M is the number of single-stations used.

M_G is the magnitude determined by Gutenberg (1958) or Gutenberg & Richter (1965).

n is the number of seismographic stations that recorded the event; $n+$ indicates that the actual number of stations is not known and that it is larger than shown.

is no clear evidence for the location of their epicentral area I find that the combined use of instrumental readings and macroseismic information gives the best control of location, but location errors are unlikely to be smaller than 40 km. These cases are marked by m in Table 1.

Relocated events in Table 1 are marked by R and they have been taken from Ambraseys & Adams (1995). In many cases solutions were improved and ambiguities of location were resolved by invoking macroseismic reports. In general, earthquakes were relocated closer to regions of known seismicity, and some major shifts were established, particularly relative to the listings of the British Association for the Advancement of Science (BAAS) and of the International Seismological Summary (ISS).

Preliminary relocations which are still under investigation are shown by r, while events which are so poorly recorded that no improvement could be made on adopted positions assumed at the time by Gutenberg (1958), Gutenberg & Richter (1965) or BAAS/ISS are shown in Table 1 by G, I or A (Ambraseys & Adams 1995).

Focal depths

For events in Central America, the lack of close seismograph stations before the 1950s makes the determination of depth within the upper hundred kilometres or so very difficult, but in our revision some events are clearly verified as subcrustal. In the early periods being considered, depth phases such as *pP* and *sS* do not appear to be well reported, and cannot be used to resolve ambiguities in depth. However, for a number of cases additional clues regarding depth could be found from macroseismic patterns and the relative values of body-wave and surface-wave magnitudes.

In Table 1, *n* indicates shallow depth ($h < 40$–60 km) while estimated upper-crustal events are shown by $n-$ ($h < 20$ km); $n+$ refers to subcrustal depth ($h > 40$–60).

Magnitude determination

Effective surface-wave magnitude assessment of earthquakes in the Central American region begins in 1898 with the recordings by Milne undamped instruments at Toronto, San Fernando, Shide, Kew, Bidston and Nikolaev of the earthquake in Nicaragua of 1898 April 29 at 16.30 hours (BAAS 1899).

However, the first earthquakes in the region recorded by proper medium-period damped seismographs were the two large shocks of 1902 April 19 and 1904 December 20, events which were also recorded by other primitive recorders including standard Milne instruments.

From 1903 to 1913 the number of stations reporting useful ground amplitude and period data of surface waves and of other phases increased very rapidly: from two stations in 1903 to 47 in 1913 world-wide. The nearest network of stations from which we have data is that of Tacubaya, which was equipped with short-period Wiechert instruments (not ideal for magnitude determination). However, this rapid improvement was arrested by the First World War during which some stations suspended operation and others ceased to report information other than onset times, amplitude-period data becoming very scanty during the period 1914–19, particularly in bulletins of European stations.

A new rapid increase in magnitude data reporting began in 1920, and lasted for almost a decade. During that period not only did more detailed information become available, but there was also an improvement in instrumentation, particularly in timekeeping. Unfortunately, this improvement was not accompanied by an equal amelioration in the reporting of other features of the seismic record, particularly of ground amplitude-period data.

Seismographic stations

Table 2 lists the seismographic stations used for the calculation of station surface- and body-wave magnitudes. They were chosen because they reported ground amplitudes and periods of different phases mostly from medium-period instruments.

Figure 2, an azimuthal equidistant plot centred on Central America, shows the location of the stations listed in Table 2. Their distribution is such that for the bulk of the readings the surface-wave path is oceanic (that is, it involves less than 10 per cent continental crust) and to a lesser extent mixed, with only very few stations being on a purely continental path.

Table 2. Station corrections.

(1)	(2) Y	(3) Δ°	(4) Az	(5) Path	(6) Stat.Corrections
ADE*	1912	134°	234°	O	
ALC	1921	82	54	O	1921-30:+0.36(0.18)
ATH	1915	97	49	M	F
AZO*	1904	59	53	O	
BAK	1924	114	35	M	1927-30:-0.37(0.12)
BAL	1902	29	16	M	F
BEY*	1907	108	48	M	
BID*	1901	76	38	O	
BOM*	1902	142	34	M	
BOM	1926	142	34	M	1926-30:-0.17(0.33)
BRK	1911	41	315	C	E
BRO*	1909	77	38	O	
BUD	1914	91	41	M	1914-30:+0.11(0.27)
CAL*	1901	145	9	M	
CGH*	1900	109	122	M	
CHE	1910	86	40	M	F
CHR*	1902	106	228	O	
CLH*	1903	28	15	M	
COC*	1910	156	37	M	
COP	1927	85	34	O	F
CRT	1910	77	54	O	1910-34: 0.00(0.10)
DBN	1909	81	38	O	1909-30:-0.24(0.16)
DEN	1912	32	332	M	F
DJA*	1900	166	293	O	
DJA	1912	166	293	O	F
EDI*	1900	76	35	O	
EKA*	1910	76	36	O	
FBR	1915	81	49	O	F
FNR*	1911	56	103	M	
GRA	1912	89	42	O	1912-30:+0.17(0.16)
GRE	1924	83	45	O	F
GTT	1904	84	38	O	1904-30:+0.10(0.18)
GUA	1925	19	300	C	E
CUI*	1910	78	40	O	
HAM	1909	84	36	O	1909-30:-0.09(0.14)

Table 2. (*Continued.*)

(1)	(2) Y	(3) Δ°	(4) Az	(5) Path	(6) Stat.Corrections
HLW*	1902	107	53	M	
HON*	1904	69	288	O	
HSL*	1907	78	40	O	
IRK*	1902	115	353	M	
IRK	1913	115	353	M	1913-30:-0.04(0.22)
JEN	1912	85	39	O	1926-30:+0.12(0.18)
KEW*	1898	78	39	O	
KEW	1927	78	39	O	1927-30:-0.07(0.10)
KOD*	1902	152	37	M	
KRA	1915	91	38	M	F
KUC	1925	98	28	M	1927-30:+0.15(0.20)
LEI	1903	86	38	O	1903-30:+0.06(0.12)
LEN	1924	92	27	M	1924-27: 0.00(0.30)
LIK	1912	41	315	C	E
LIM*	1907	26	159	M	
LPZ	1913	34	149	M	1913-18:+0.02(0.21) 1919-30:+0.32(0.25)
LVV	1915	93	37	M	F
MAK	1924	102	35	M	1927-30:-0.13(0.17)
MAN	1926	19	294	C	E
MAU*	1900	144	109	M	
MAZ	1910	22	303	C	E
MER	1911	10	339	C	E
MLT*	1907	91	53	M	
OAX	1911	12	297	C	E
OSA	1902	119	321	M	1910-29:-0.18(0.21)
OTT	1911	35	13	M	1911-30:+0.11(0.21)
PAI*	1902	75	35	O	
PAR	1921	80	42	O	1921-30:-0.07(0.12)
PDD	1924	81	45	O	F
PER*	1901	152	222	M	
PIL*	1900	49	155	M	
POL	1915	88	44	M	F
POT	1902	86	37	O	1902-06:+0.07(0.10) 1907-30:-0.12(0.18)
PUL	1924	92	27	M	1927-30:+0.12(0.13)
RIO*	1911	74	54	O	
RIV	1910	124	237	O	1910-18:-0.10(0.13) 1919-30:+0.19(0.23)
SFS*	1898	75	55	O	
SHI*	1898	77	40	O	
STO*	1910	76	37	O	
STO	1929	76	37	O	F
STR	1907	83	42	O	1907-12:+0.05(0.21) 1913-30:-0.16(0.14)
SVE	1924	105	18	M	1927-30:+0.03(0.17)
SYD*	1907	124	237	O	
TAC	1909	15	301	C	E
TAS	1924	122	22	M	1924-30:-0.12(0.14)
TIF*	1903	110	37	M	
TNT*	1898	32	9	M	
TNT	1925	32	9	M	1925-30:-0.07(0.22)
TOK*	1902	116	320	M	
TRI	1915	88	44	M	F
TRN*	1901	24	91	O	
UCC	1910	81	40	O	1910-11:+0.24(0.21) 1912-30:-0.06(0.14)
UPP	1905	86	29	O	1905-30:+0.17(0.15)
VER	1924	12	308	C	E
VIC*	1899	48	327	M	
VIC	1924	48	327	M	1924-25:+0.22(0.16) 1926-30:-0.04(0.20)
VIE	1907	89	41	M	1907-30:-0.05(0.20)

Table 2. (*Continued.*)

(1)	(2) Y	(3) Δ°	(4) Az	(5) Path	(6) Stat.Corrections
VQS*	1904	21	70	O	
WEL*	1902	105	230	O	
WAS	1916	28	15	M	F
ZKW	1912	129	329	M	F

Notes.

(1) Asterisked codes refer to stations equipped with Milne recorders. For codes of seismographic stations see Poppe *et al.* (1978).

(2) Year in which the first event in Central America was recorded by the Milne recorder, the station reporting trace amplitude of maximum phase, or the year in which the first event in Central America was recorded at a station operating a medium-period instrument.

(3) Distance of station from Central America (12°N, 86°W) in degrees.

(4) Azimuth of station from Central America.

(5) Path: O: Oceanic (less than 10 per cent continental crust). C: Continental (less than 10 per cent oceanic crust); M: Mixed.

(6) Average station correction, standard deviation and associated duration of station reporting. E indicates erratic variations of station correction with time and F too few readings.

Surface-wave magnitudes

For the events in Table 1, magnitudes were calculated using the procedure put forward by the Commission on Practice (Willmore 1979), a procedure that obviates the use of a hybrid magnitude system for the assessment of regional seismicity. The main reason for the choice of the Prague formula is that the world, and in particular the European seismological network, is more than capable of providing reliable data for the uniform determination of M_S values, not only of recent events, but also of earlier earthquakes, allowing for calibration by comparing with modern instruments. Another reason is that M_S values and their standard deviation can be calculated from more station readings, with better azimuthal distribution, than m_B, and with smaller standard errors for the whole instrumental period.

Individual surface-wave station magnitudes, therefore, were calculated from the Prague formula which is valid for distances between 2° and 160°, provided that the periods used are appropriate for the distance, e.g. *Lg* and *Sg* at short distances.

The amplitude and period readings are those reported in various station bulletins available to me. In all, 1360 station readings for surface-wave magnitudes were culled from bulletins of which only 1244—those recorded by medium-period instruments—were used. For body-wave magnitudes, only 182 amplitude–period ratios are available.

Most estimates of M_S were made from long-period horizontal (LH) amplitudes on medium-period seismographs which constitute the bulk of the data. However, where long-period vertical (LV) amplitudes were available, a separate estimate of M_s was made. There is only a small difference between M_{LH} and M_{LV}, with magnitudes from horizontal components being systematically higher by 0.1(±0.1) units of magnitude. Event magnitudes were obtained, therefore, by averaging M_{LH} and M_{LV} values.

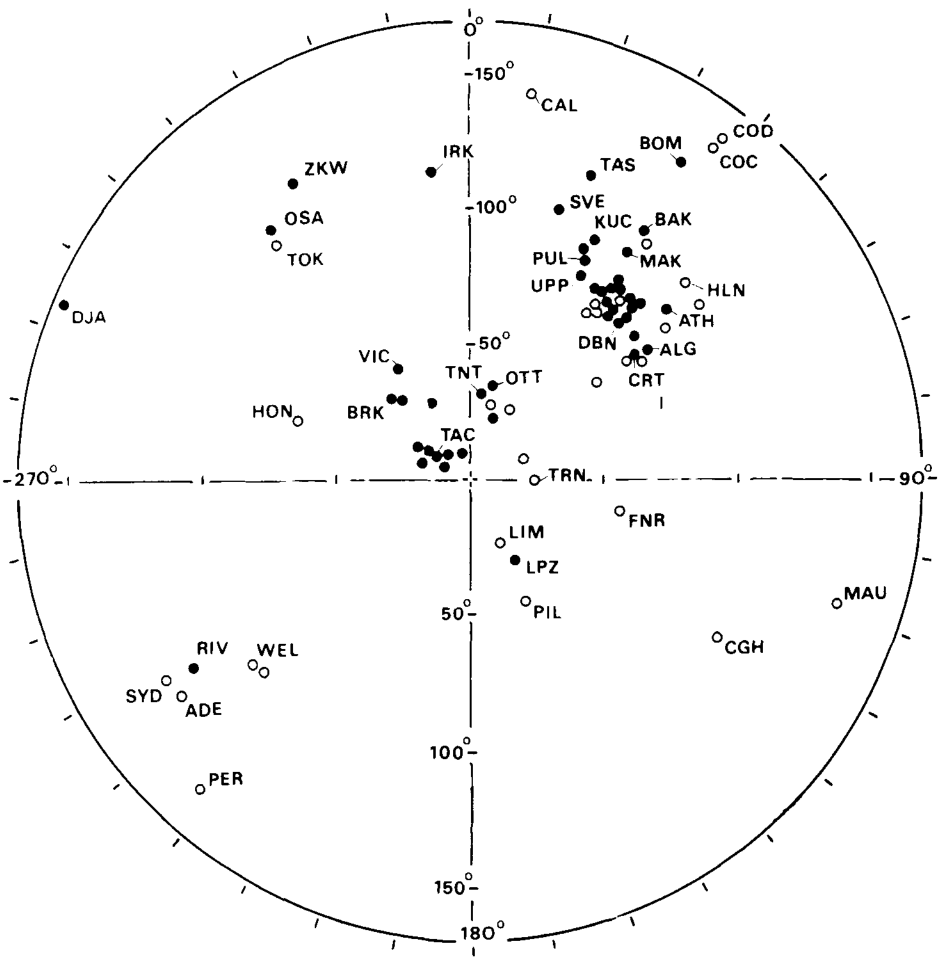

Figure 2. Azimuthal equidistant plot centred on Central America, showing the location of seismographic stations which operated undamped Milne recorders during the period 1898–1917 (open circles), and damped seismographs (solid circles) in the period 1903–30, used for the determination of magnitudes of earthquakes in Central America.

Station corrections

Station corrections have little effect on average magnitudes except when the number of stations is relatively small; less than five in our case. For some of the more important stations the available number of station readings is sufficiently large to allow the assessment of station corrections Δ_M. For De Bilt (DBN), for instance, which is a continuous source of data, Δ_M remains almost constant throughout the period with a mean value of -0.24. For La Paz (LPZ), Δ_M is zero for the period before 1917, remaining constant at $+0.30$ after that year. For some stations, particularly those in Mexico and North America, Δ_M varies erratically with time. Table 2 lists the values of Δ_M obtained in this study, which ignores path and azimuthal corrections.

In estimating M_S, the maximum value of the amplitude (A) period (T) ratio was restricted to stations at which T was clearly associated with surface waves. When periods differed from values that correspond to surface waves, the calculated magnitudes were treated separately and a second estimate of M_S was made irrespective of the value of T. A comparison of these two estimates shows that the application of the period restriction implicit in the Prague formula results in magnitude values which are larger by about 0.1–0.3 units than the values that can be obtained without this restriction; also that the standard deviation of M_S derived from 'period-restricted' values is systematically smaller than the M_S value obtained from 'unrestricted' station estimates. I observed the same effect found in the calculation of M_S from a much larger data set for European and Middle Eastern events. This seems to explain the distance dependence of the Prague formula suggested by Herak & Herak (1993) who disregarded this constraint in the application of the Prague formula.

Mean values of M_S calculated with and without period constraint were found to have almost the same standard deviations, which are on average 0.20(±0.07) and 0.28(±0.16) respectively.

Average surface-wave magnitudes, with station corrections, and the number (N) of the station magnitudes used to calculate M_S are listed in Table 1. These values have been calculated assuming a shallow focus.

Body-wave magnitudes

Body-wave magnitudes m_B from medium-period instruments were estimated on the assumption of shallow depth using the Gutenberg distance–depth factor $Q(D, h)$ for distances in excess of 16° and for whichever phase, *PZ, PH,* PPZ, PPH or *SH*, amplitude data were available. With body waves, because of the limited amount of data, we had little choice but to combine magnitude estimates from all *P* and *S* phases and take an average in which broad-band values (m_B) predominate. Again here m_B values were calculated assuming a shallow depth, and as a consequence m_B values for subcrustal events in Table 1 need correction.

Milne magnitudes

Trace amplitudes from undamped instruments are also available for the period before 1918. These were used to calculate an equivalent magnitude M_M for stations equipped with standard Milne instruments from

$$M_M = \log(2A_t) + 1.25\log(D°) + 4.06 \quad (1)$$

where $2A_t$ is the double trace amplitude (peak-to-peak) in millimetres on Milne seismograms and D is the epicentral distance in degrees.

Equation (1) was originally derived from 23 earthquakes in Iran for which both M_S and Milne trace amplitudes were available. Additional readings from another 95 shallow earthquakes in Eastern Europe, the Mediterranean region, Western Asia and Africa showed that the constant in eq. (1) was probably magnitude-dependent, its value increasing from 4.0 to 4.4 as the mean of the M values of the input sample increased from 6.0 to 7.0 (Ambraseys & Melville 1982).

For our Central American data set, which has a magnitude mode of less than 6.5, we used eq. (1), and M_M estimates from this formula are shown separately in Table 1.

DISCUSSION

I calculated magnitudes for 169 of the 340 earthquakes in the region for which instrumental data are available. At this stage our relocation programme shows that six of these events occurred outside the study area and 17 are subcrustal. The histogram in Fig. 3 shows the distribution with magnitude of the remaining 146 crustal earthquakes, some of which with further refinement may prove to be deeper.

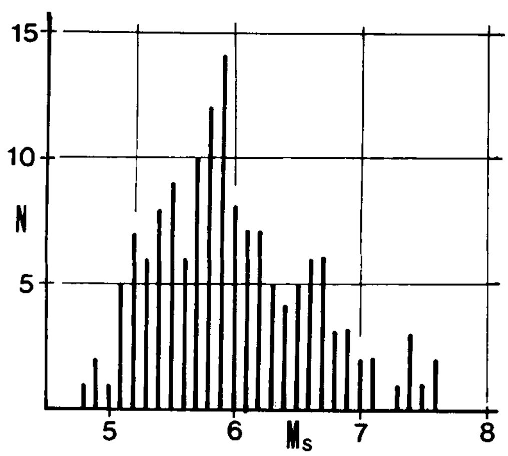

Figure 3. Number of shallow events N of magnitude M_s determined in this study.

For 17 of these earthquakes we also have magnitude estimates from Gutenberg & Richter (1965) and for two additional events estimates from Duda (1965).

Comparison between M_S and M_G

Gutenberg & Richter (1965) have assigned magnitudes to 26 Central American events of magnitude greater than 5.9. Gutenberg's unpublished worksheets suggest that in assessing magnitudes he exercised a considerable degree of personal judgement, not only in the selection of the data he used to determine magnitudes, but also in the way in which he combined the results from different phases to arrive at a final estimate. His worksheets (Gutenberg 1958) show that for most of his calculations he was systematically using fewer station readings than were available at the time. Our comparison of his data with the original station readings he used confirms that many of the amplitudes for surface waves to which he assigned a 20 s period were in fact associated with periods of 10–30 s. To understand Gutenberg's system one has to study his own interpretation of his worksheets, which is not easy. There is unlikely to be great improvement in M_S without adding the many available station readings which he omitted from his calculations.

The values of M_s calculated in this study for shallow events and the M_G values derived by Gutenberg & Richter (1965) are listed in Table 1.

Figure 4 shows a comparison between our estimates of M_s and those M_G values obtained by Gutenberg & Richter (1965) for shallow events (open circles). Open squares in Fig. 4 refer to subcrustal events and the comparison for this class of events is made here between our estimated m_B and

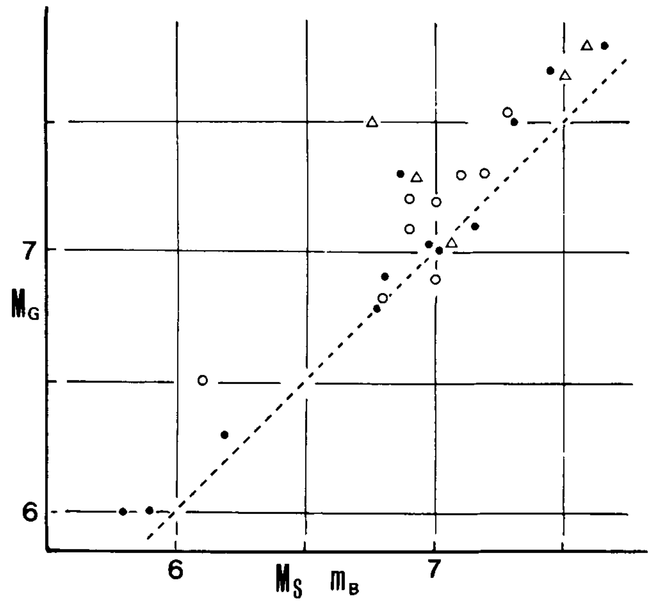

Figure 4. Comparison between estimated magnitudes M_s and those calculated by Gutenberg & Richter (1965), M_G, for shallow events (solid circles). Open circles refer to subcrustal events and the comparison is made between our estimated m_B and M_G calculated by Gutenberg & Richter (1965). For the period before 1904 (open triangles), we compare our M_M estimates and those made by Gutenberg & Richter (1965).

the values of M_G calculated by Gutenberg & Richter (1965), which are again overestimated confirming, however, that for deeper events M_G is in fact the broad-band body-wave magnitude m_B. Open triangles in Fig. 4 show the comparison between our M_M estimates and those made by Gutenberg & Richter (1965) for the period before 1904.

In all cases shown in Fig. 4, M_G values are larger than M_s, on average by 0.15 (±0.15). This bias implies that moment estimates made from M_G values, derived from, say, a global $M_s - M_o$ relation such as that of Kanamori & Anderson (1975), would be overestimated by a factor of 1.7.

The tendency of magnitude estimates made by Gutenberg from Milne amplitude readings to be exaggerated is partly due to the fact that he assumed too small an effective gain for the Milne instruments, an observation already made by Kanamori & Abe (1979). However, this is also partly because in a number of cases he calculated average magnitudes from Milne amplitudes belonging to two or more separate events closely spaced in time but reported together in the Shide Circulars. For instance:

(1) For the earthquake of 1900 November 9 he includes in his calculations readings from Batavia which in fact belong to a separate event 2 hr later in Japan (Utsu 1982).

(2) For the earthquake of 1901 October 8 he includes in his calculations readings from Mauritius that belong to a separate earthquake in the Indian Ocean in the same hour.

(3) Instrumental readings of maximum phases on Milne seismographs and body phases from European stations confirm the position of the earthquake of 1902 April 19 in Guatemala, provided it is recognized that readings at stations at epicentral distances beyond about 80° belong to two other separate events which occurred about the time: one in the Indian Ocean and the other in China, at 02.57 hours and 02.60 hours respectively. Gutenberg (1956, 1958) uses Milne amplitudes from all three earthquakes to calculate the M_M of the Guatemalan earthquake, the value of which he overestimates.

(4) For the earthquake of 1902 September 23, instrumental readings from stations world-wide agree well with its macroseismic position in Chiapas, provided it is recognized that some of the readings from distant stations in the Shide Circulars belong to an earthquake in the south of the Indian Ocean which occurred 13 min later.

(5) There is also one case where the difference between our estimate of M_s and that of Gutenberg's is due to his gross mislocation of the event. This is the case of the earthquake of 1900 June 21. Milne readings are very confused and cannot be used to locate the earthquake, other than to confirm that it is in the Central American region where macroseismic information places it in the Pacific, offshore from the Nicoya Peninsula in Costa Rica. This location is about 1300 km south-west of Gutenberg's (1956, 1958) position which is between Jamaica and Cuba, from where there is no corroborating evidence for the shock.

Comparison between M_s and M_M

This can be made only for the period 1903–17, for which we have values of both M_M and M_s for crustal events. Fig. 5 shows a comparison between estimated magnitudes M_s and those calculated from eq. (1). The mean residual of $M_s - M_M$ is only −0.02(±0.15), confirming the reliability of eq. (1).

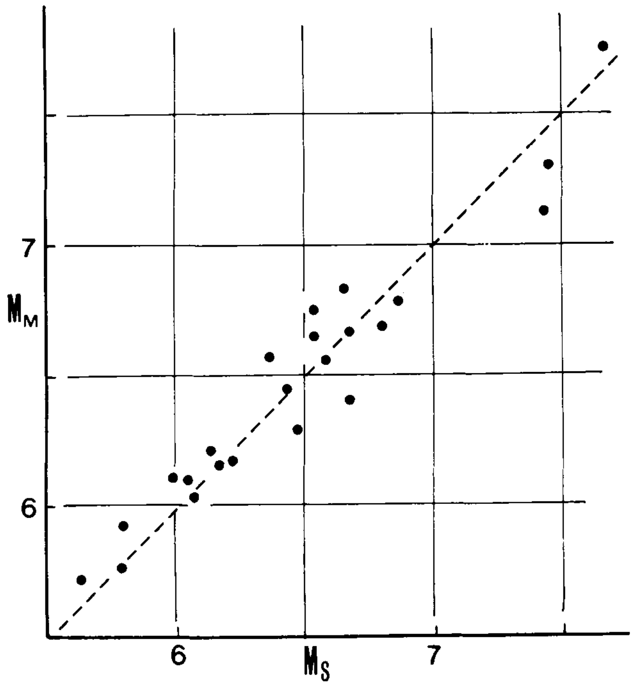

Figure 5. Comparison between estimated surface-wave magnitudes (M_s) and those (M_M) calculated from eq. (1) for shallow earthquakes.

Empirical assessment of M_s in terms of number of stations

An empirical way in which the magnitude of an earthquake can be assessed is by making use of the number of stations N_s that recorded the event (Ambraseys & Melville 1982). If we assume a world-wide network of uniformly distributed stations equipped with the same type of seismographs, M_s will be a function of N_s. Such a perfect distribution and uniformity of seismographs is hardly realistic. Nevertheless, as a first approximation M_s may be obtained from a region-specific relation between magnitude and the number of reporting stations N_s which is not necessarily equal to the number of stations contributing readings to BAAS or to ISS. During the period 1913–30, BAAS and ISS systematically used fewer stations than were available, and for this period N_s has to be derived by resorting to station bulletins. For instance, for the period of the First World War and for some years afterwards, BAAS and ISS did not make use of 80 per cent of the European stations that reported amplitudes and periods, while over the period 1913–30 and even later, many active stations were not included in the ISS listing, either because their readings were received too late to be included in the ISS bulletin or because they added little to the location of an event. In our case N_s is the number of stations that recorded an event and this is equal to or greater than the number of stations used by BAAS/ISS.

Because the world network of stations was changing continually, for the correlation of M_s with N_s it is necessary to normalize N_s with respect to the number of active stations

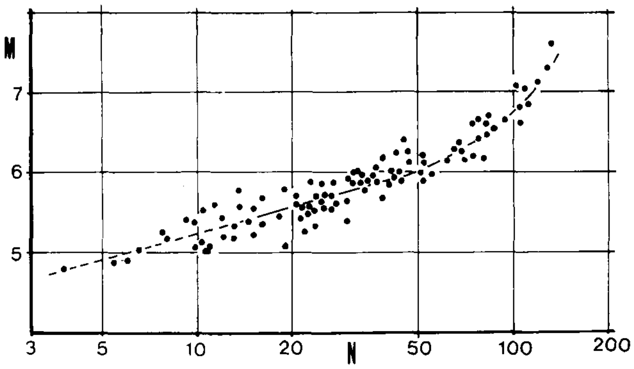

Figure 6. Graph of magnitude M_s of shallow earthquakes during the period 1913–30 against N, normalized to the number of stations active in 1930. Number of stations in operation in: 1913 73; 1914 64; 1915 65; 1916 61; 1917 68; 1918 84; 1919 81; 1920 90; 1921 82; 1922 102; 1923 102; 1924 98; 1925 108; 1926 117; 1927 131; 1928 135; 1929 140; 1930 131.

N during a reference year. Fig. 6 shows a graph of M_s for shallow earthquakes in Table 1 plotted against the number of reporting stations, normalized to the number of active stations in 1930, which we take as our reference year. For events for which teleseismic data are not available then, this plot may be used, with relatively small uncertainty, to estimate M_s from the number of stations N. I used this method to determine M_s only for five small events in our data set.

Moment rate

The cumulative moment was derived from Kanamori & Anderson's $M_s - M_o$ relation ($M_s = -10.7 + 2/3 \log M_o$, M_o in dyn cm). In summing the moments we only included crustal earthquakes (n and $n-$ in Table 1), the magnitudes of which were calculated in this study. The total moment is 1.63×10^{21} Nm, about 70 per cent of which is contributed by the six large earthquakes ($M_s > 7.2$) of the period 1902–16. The average moment rate is 4.9×10^{19} Nm yr^{-1}.

Using the magnitudes M_G of the 16 crustal earthquakes determined by Gutenberg & Richter (1965), the total moment becomes 2.42×10^{21} Nm. Thus the use of M_G overestimates the total moment by a factor of two. This is no surprise, as it could have been predicted by the overestimation of M_G by 0.15 magnitude units. Also the M_s values calculated by Abe & Noguchi (1983) and Duda (1965) overestimate the total moment by factors of four and nine, respectively.

CONCLUSIONS

Figure 1 shows the distribution of all the earthquakes known to us in the period 1898–1930 to which we have assigned magnitudes. The locations of some of these shocks are to some extent uncertain, and their focal position is still under investigation.

The data in Table 1 suggest that foreshocks and aftershocks of shallow earthquakes on average release about one-quarter of the moment (0.25 ± 0.22) associated with the main shock. This pattern of relatively large magnitude shocks preceding or following a seismic event is one of the factors contributing to the overall destructiveness and progressive damage caused by earthquakes in the region.

The original intention was not so much to discover new large-magnitude earthquakes because these, it was thought, had already been sought out by Gutenberg & Richter (1965), but rather to produce a uniform body of magnitude data for hazard assessment. It is of interest, however, that in the process of this reappraisal, 168 events, for which magnitudes can be calculated either on early Milne seismographs or later damped instruments, were identified, that is about six times as many as listed in regional or global catalogues, as well as 34 events of $M_s > 6.5$, which is twice as many as listed by Gutenberg & Richter (1965).

The results from this study confirm that the use of M_G results in an overestimation of the slip rate in Central America for the first half of the century by a factor of two. This is not a very serious error compared with the errors that arise from uncertainties in M_o of more recent events. What is important, however, is that the instrumental data of the early part of this century are invaluable in seismicity and hazard studies and that instrumental information for the uniform assessment of M_s and M_M deserves wider use.

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