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MAGNITUDES OF GREAT SHALLOW EARTHQUAKES FROM 1904 TO 1952

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ABSTRACT

The "revised magnitudes", *M*, converted from Gutenberg's unified magnitude, *m*, and listed by Richter (1958) and Duda (1965) are systematically higher than the magnitudes listed by Gutenberg and Richter (1954) in *Seismicity of the Earth*. This difference is examined on the basis of Gutenberg and Richter's unpublished original worksheets for *Seismicity of the Earth*. It is concluded that (1) the magnitudes of most shallow "class a" earthquakes in *Seismicity of the Earth* are essentially equivalent to the 20-sec surface-wave magnitude, M_S; (2) the revised magnitudes, *M*, of most great shallow (less than 40 km) earthquakes listed in Richter (1958) (also used in Duda, 1965) heavily emphasize body-wave magnitudes, m_b, and are given by $M = \frac{1}{4}M_S + \frac{3}{4}(1.59\ m_b - 3.97)$. For earthquakes at depths of 40 to 60 km, *M* is given by $M = (1.59\ m_b - 3.97)$. *M* and M_S are thus distinct and should not be confused. Because of the saturation of the surface-wave magnitude scale at $M_S \simeq 8.0$, use of empirical moment versus magnitude relations for estimating the seismic moment results in large errors. Use of the fault area, *S*, is suggested for estimating the moment.

INTRODUCTION

In spite of its imperfections, magnitude is still the most commonly used parameter in describing the "size" of an earthquake. M_S values have been used with various empirical relations to estimate the energy and the seismic moment of earthquakes. Earthquake energy and seismic moment are important in the discussion of various global problems, such as heat flow, the Chandler Wobble, and plate motion. For earthquakes from 1904 to 1952, three magnitude catalogs are most commonly used: Gutenberg and Richter (1954), Richter (1958) and Duda (1965). However, there are significant differences between the magnitude values listed in these catalogs. In view of the fundamental importance of the earthquake magnitude in various geophysical problems, we examine these differences and the meaning of the magnitude scale adopted in each of these catalogs.

MAGNITUDE SCALES

The magnitude of an earthquake was the first source parameter to be defined and is still the most directly measurable. As originally defined by Richter (1935), magnitudes for local earthquakes, M_L, were calculated from amplitudes on Wood-Anderson torsion instruments. Gutenberg and Richter (1936, 1941, 1942) published several intermediate reports on amplitudes and magnitudes. Gutenberg (1945a, b, c) defined surface-wave magnitudes, M_S, and body-wave magnitudes, m_b. The final versions of the body-wave and surface-wave scales were given by Gutenberg and Richter (1956). The details of Gutenberg and Richter's body-wave and surface-wave magnitudes, as well as later definitions, are discussed in the Appendix.

Although M_S and m_b are measured at different periods, Gutenberg and Richter viewed M_S and m_b as parameters representing the same quantity, namely, energy (Gutenberg, 1945c). This view led Gutenberg and Richter (1956) and Gutenberg (1957) to the concept of "unified magnitude". To facilitate the construction of a "unified magnitude" scale, they obtained empirical relations between m_b and M_S by least squares.

$$m_b = 0.63\, M_S + 2.5 \tag{1a}$$

$$M_S = 1.59\, m_b - 3.97 \tag{1b}$$

These relations were then used to define the body-wave basis and surface-wave basis for magnitudes. Magnitudes are converted by using the relations

$$m(M) = 0.63\, M + 2.5 \tag{2a}$$

$$M(m) = 1.59\, m - 3.97 \tag{2b}$$

where M is a magnitude on the surface-wave basis and $m(M)$ is the corresponding magnitude on the body-wave basis. Similarly, if m is a magnitude on the body-wave basis then $M(m)$ is the computed magnitude on the surface-wave basis. $m_s \equiv m(M_S)$ is the magnitude on the body-wave basis calculated from the observed surface-wave magnitude, M_S. Also $M_b \equiv M(m_b)$ is the magnitude on the surface-wave basis calculated from the observed body-wave magnitude.

The unified magnitude, m, was obtained by taking a weighted average of m_b and m_s (Gutenberg and Richter, 1956; Gutenberg, 1957)

$$m = \alpha m_b + \beta m_s \tag{3}$$

with $\alpha + \beta = 1$. It is equally possible to define the unified magnitude on the surface-wave basis

$$M = \alpha M_b + \beta M_S. \tag{4}$$

Richter prefers this to m. In his book (Richter, 1958), he converted Gutenberg's unified magnitudes, m, to M by using equation (2b). (As a result of roundoff the M values differ slightly from those obtained directly from equation (4).)

GREAT EARTHQUAKE MAGNITUDES FROM 1904 TO 1952

Four primary data sets for magnitudes of large shallow earthquakes from 1904 to 1952 are displayed in Table 1. Gutenberg and Richter (1954) listed all of the 109 events in Table 1 in their Table 13, "class *a* shallow shocks." (Their Table 13 contained events having $M \geq 7.75$.) The earthquake locations and origin times are also from Gutenberg and Richter. Richter (1958) listed "revised magnitudes" for the class *a* shocks with magnitudes greater than $7\frac{3}{4}$ in his Table XIV-2. Duda (1965) listed magnitudes for all of the events in Table 1. Each of these references lists "magnitudes" without any description of the scales used to derive them. The revised magnitudes denoted by M given by Richter (1958) are on the average 0.22 higher than the magnitudes in *Seismicity of the Earth.* The largest difference is 0.6. The magnitudes listed by Duda (1965) are taken from Richter's catalog if an event is listed there—otherwise the value from *Seismicity of the Earth* is used. Thus the differences between Duda's magnitudes and the Gutenberg-Richter (G-R) catalog reflect only the differences between Richter's catalog and the G-R values. We will explore the difference between the Richter (1958) magnitudes and the G-R (1954) magnitudes, to clarify the differences between the magnitude scales.

The best source of data for re-examining the magnitudes is the original work of Gutenberg and Richter. Fortunately, most of their original worksheets for *Seismicity of the Earth* are still on file at Caltech. We found copies of their worksheets for 91 of the 109 events in Table 1. The surface-wave magnitudes (M_S) for these 91 events (and five others, from other sources) are listed in Table 1. (Sources for the other five events are given in footnotes.) The surface-wave magnitudes were derived from the worksheets in a straightforward manner. Gutenberg and Richter's original single station M_S (often labeled $M_{\max}$, for maximum amplitude, on their worksheets) values were numerically averaged for each event. On the whole, the surface-wave magnitudes from the notes differ only slightly from those in the Gutenberg-Richter catalog.

Magnitudes in *Seismicity of the Earth* were given to the nearest tenth when Gutenberg and Richter considered the value accurate to the nearest tenth, e.g., 8.0, 7.7; values which they considered to be less accurate are given only to the nearest quarter, e.g. 8, $7\frac{3}{4}$. The magnitudes in *Seismicity of the Earth* are an average of 0.06 higher than those from the notepads. Furthermore, the magnitudes of 74 of the 96 events differ by 0.1 or less. We therefore conclude that the magnitudes in *Seismicity of the Earth* are essentially equivalent to M_S for the events we have checked. Probably for nearly all the shallow events in the G-R catalog it is safe to treat their "magnitude" as being M_S.

We also obtained body-wave magnitudes from the notes. Because there were several different definitions of the body-wave magnitude, many of the worksheets have several different calculations in which a body-wave magnitude is given. We list in Table 1 the value which appeared to us to be calculated according to the method in Gutenberg and Richter (1956). Although in some cases the value we have listed may be slightly in error, it seems important to list these previously unpublished m_b values. m_b values were given in the worksheets for 90 events, and are listed in Table 1, together with two from other sources. Apparently the station corrections given by Gutenberg (1945c) were used in making these m_b determinations.

Two other items are listed in Table 1. $\bar{T}$ is the average period used in determination of m_b from equation (A5). Also, Gutenberg and Richter considered most of the events in Table 1 to be at normal depth, but some earthquakes were considered to be at depths of 40 to 60 km. The deeper events are indicated by the reference to footnote *a* to the right of the date.

UNIFIED MAGNITUDES

Gutenberg and Richter never published the details of their methods of determining the unified magnitudes. However, Gutenberg (1957) stated that the unified magnitude was found primarily from body-wave magnitudes, with only supplemental use of surface-wave magnitudes. This suggests that m_b was emphasized in the weighted average of m_b and m_s to find m described by Gutenberg and Richter (1956). Our analysis, described below, supports this suggestion.

A preliminary examination of the data in Table 1 suggested that in most cases the weights used by Gutenberg and Richter in finding the unified magnitudes were $\alpha = \frac{3}{4}$ and $\beta = \frac{1}{4}$ (in equations 3 and 4). In finding m they apparently used the magnitudes in *Seismicity of the Earth* as M_S. Therefore we have used the magnitudes from *Seismicity of the Earth*, rather than the M_S values we list in Table 1, in testing these weights. Also, for the deeper events (40 to 60 km) in Table 1 the weights apparently

TABLE 1

Earthquake Data

				Published Magnitudes			Gutenberg-Richter Notes		
No.	Date	Time	Location	Seism. of Earth (1954)	Duda (1965)	Richter (1958)	M_S	m_b	$\bar{T}$
1	1904, Jan. 20	14:52.1	7N 79W	7¾	7.9	7.9	7.7	7.6	12
2	June 25	14:45.6	52N 159E	8.0	8.3	8.3	7.9	7.8	8
3	June 25	21:00.5	52N 159E	8.1	8.1	8.1	8.0	7.7	6
4	June 27	00:09.0	52N 159E	7.9	7.9	7.9	7.9	7.5	7
5	Aug. 24	20:59.9	30N 130E	7¾	7.9	7.9	7.7	7.7	9
6	Aug. 27	21:56.1	64N 151W	7¾	8.3	8.3	7.7	7.8	7
7	Dec. 20^a	05:44.3	8½N 83W	7¾	8.3	8.3	7.6	7.8	11
8	1905, Feb. 14	08:46.6	53N 178W	7¾	7.9	7.9	7.9	7.5	12
9	Apr. 4	00:50.0	33N 76E	8	8.6	8.6	—	—	—
10	July 6	16:21.0	39½N 142½E	7¾	7.9	7.9	7.8	7.5	—
11	July 9	09:40.4	49N 99E	8¼	8.4	8.4	7.9^b	—	—
12	July 23	02:46.2	49N 98E	8¼	8.7	8.7	8.2^b	—	—
13	1906, Jan. 31	15:36.0	1N 81½W	8.6	8.9	8.9	8.7	8.2	9
14	Apr. 18	13:12.0	38N 123W	8¼	8.3	8.3	8.3	7.4	13
15	Aug. 17	00:10.7	51N 179E	8.0	8.3	8.3	8.2	7.8	7
16	Aug. 17	00:40.0	33S 72W	8.4	8.6	8.6	8.4	—	—
17	Sep. 14	16:04.3	7S 149E	8.1	8.4	8.4	—	—	—
18	Nov. 19^a	07:18.3	22S 109E	7¾	7¾	—	7.5	7.5	10
19	Dec. 22	18:21.0	43½N 85E	7.9	8.3	8.3	7.7	7.5	9
20	1907, Apr. 15	06:08.1	17N 100W	8.1	8.3	8.3	8.0	7.9	14
21	Sep. 2	16:01.5	52N 173E	7¾	7¾	—	7.8	7.3	13
22	Oct. 21	04:23.6	38N 69E	8.0	8.1	8.1	7.6	7.6	11
23	1909, July 30^a	10:51.9	17N 100½W	7¾	7¾	—	7.4	7.4	10
24	1911, Jan. 3	23:25:45	43½N 77½E	8.4	8.7	8.7	8.4	8.1	14
25	Feb. 18	18:41:03	40N 73E	7¾	7¾	—	7.6	7.3	8
26	June 7^a	11:02.7	17½N 102½W	7¾	7.9	7.9	7.7	7.5	8
27	July 12^a	04:07.6	9N 126E	7¾	7¾	—	7.7	7.6	8
28	Aug. 16	22:41.3	7N 137E	7.9	8.1	8.1	7.8	7.6	9
29	1912, May 23	02:24.1	21N 97E	8.0	7.9	7.9	8.0	7.3	13
30	Aug. 9	01:29.0	40½N 27E	7¾	7¾	—	7.7	7.0	10
31	1913, Mar. 14^a	08:45:00	4½N 126½E	7.9	8.3	8.3	7.9	7.7	4
32	Aug. 6	22:14.4	17S 74W	7¾	7.9	7.9	—	—	—
33	1914, May 26	14:22.7	2S 137E	7.9	7.9	—	8.0	7.3	6
34	1915, May 1	05:00:0	47N 155E	7.9	8.1	8.1	8.0	7.7	11
35	July 31	01:31.4	54N 162E	7¾	7¾	—	7.6	7.5	7
36	Oct. 3	06:52.8	40½N 117½W	7¾	7¾	—	7.7	7.3	7
37	1916, Jan. 1	13:20.6	4S 154E	7¾	7.9	7.9	—	—	—
38	Jan. 13	08:20.8	3S 135½E	7.8	8.1	8.1	7.7	7.6	7
39	1917, Jan. 30	02:45.6	56½N 163E	7¾	8.1	8.1	7.8	7.7	9
40	May 1^a	18:26.5	29S 177W	8	8.6	8.6	7.9	7.9	8
41	June 26	05:49.7	15½S 173W	8.3	8.7	8.7	8.4	8.0	11
42	1918, Aug. 15	12:18.2	5½N 123E	8¼	8.3	8.3	8.0	7.6	7
43	Sep. 7	17:16:13	45½N 151½E	8¼	8.3	8.3	—	—	—
44	Nov. 8	04:38.0	44½N 151½E	7¾	7.9	7.9	7.7	7.5	6
45	Dec. 4^a	11:47.8	26S 71W	7¾	7¾	—	7.6	7.3	9
46	1919, Apr. 30	07:17:05	19S 172½W	8.3	8.4	8.4	—	—	—
47	May 6	19:41:12	5S 154E	7.9	8.1	8.1	—	—	—
48	1920, June 5	04:21:28	23½N 122E	8	8.3	8.3	—	—	—
49	Sep. 20	14:39:00	20S 168E	8	8.3	8.3	7.9	7.8	7
50	Dec. 16	12:05:48	36N 105E	8½	8.6	8.6	—	—	—
51	1922, Nov. 11	04:32.6	28½S 70W	8.3	8.4	8.4	—	—	—
52	1923, Feb. 3	16:01:41	54N 161E	8.3	8.4	8.4	8.3	7.7	7
53	Sep. 1	02:58:36	35¼N 139½E	8.2	8.3	8.3	8.2^c	7.7	—
54	1924, Apr. 14	16:20:23	6½N 126½E	8.3	8.3	8.3	8.3	7.7	5
55	June 26	01:37:34	56S 157½E	7.8	8.3	8.3	7.7	7.9	8
56	1927, Mar. 7	09:27:36	35¾N 134¾E	7¾	7.9	7.9	7.6	7.6	4

Table 1—*Continued*

No.	Date	Time	Location	Published Magnitudes: Seism. of Earth (1954)	Published Magnitudes: Duda (1965)	Published Magnitudes: Richter (1958)	Gutenberg-Richter Notes: M_S	Gutenberg-Richter Notes: m_b	Gutenberg-Richter Notes: $\bar{T}$
57	1927, May 22	22:32:42	36¾N 102E	8.0	8.3	8.3	7.9	7.9	7
58	1928, June 17	03:19:27	16¼N 98W	7.8	7.9	7.9	7.8	7.6	9
59	Dec. 1	04:06:10	35S 72W	8.0	8.3	8.3	8.0	7.7	8
60	1929, Mar. 7	01:34:39	51N 170W	8.1	8.6	8.6	7.7[d]	7.7[d]	9[d]
61	June 27	12:47:05	54S 29½W	7.8	8.3	8.3	—	—	—
62	1931, Jan. 15	01:50:41	16N 96¾W	7.8	7.9	7.9	7.8	7.6	13
63	Feb. 2	22:46:42	39½S 177E	7¾	7.9	7.9	7.8	7.6	10
64	Aug. 10	21:18:40	47N 90E	8.0	7.9	7.9	7.9	7.6	9
65	Oct. 3	19:13:13	10½S 161¾E	7.9	8.1	8.1	7.9	7.7	7
66	1932, May 14	13:11:00	½N 126E	8.0	8.3	8.3	8.0	7.8	13
67	June 3	10:36:50	19½N 104¼W	8.1	8.1	8.1	8.2	7.6	12
68	June 18	10:12:10	19½N 103½W	7.8	7.9	7.9	7.8	7.4	11
69	1933, Mar. 2	17:30:54	39¼N 144½E	8.5	8.9	8.9	8.3[e]	8.2[e]	11[e]
70	1934, Jan. 15	08:43:18	26½N 86½E	8.3	8.4	8.4	8.3	7.8	10
71	July 18	19:40:15	11¾S 166½E	8.2	8.1	8.1	8.1	6.8	10
72	1935, Sep. 20	01:46:33	3½S 141¾E	7.9	7.9	7.9	—	—	—
73	Dec. 28	02:35:22	0N 98¼E	7.9	8.1	8.1	7.7	7.7	8
74	1938, Feb. 1	19:04:18	5¼S 130½E	8.2	8.6	8.6	8.2	8.0	6
75	Nov. 10	20:18:43	55½N 158W	8.3	8.7	8.7	8.3	8.2	13
76	1939, Jan. 25	03:32:14	36¼S 72¼W	7¾	8.3	8.3	—	—	—
77	Jan. 30	02:18:27	6½S 155½E	7.8	7.9	7.9	7.8	—	—
78	Apr. 30[a]	02:55:30	10½S 158½E	8.0	8.1	8.1	8.0	7.4	7
79	Dec. 26	23:57:21	39½N 38½E	8.0	7.9	7.9	7.8	7.7	8
80	1940, May 24[a]	16:33:57	10½S 77W	8	8.4	8.4	7.9	7.9	8
81	1941, June 26[a]	11:52:03	12½N 92½E	8.1	8.7	8.7	7.7	8.0	8
82	Nov. 18	16:46:22	32N 132E	7.8	7.9	7.9	7.8	7.5	8
83	Nov. 25	18:03:55	37½N 18½W	8.3	8.4	8.4	8.2	7.8	8
84	1942, May 14	02:13:18	¾S 81½W	7.9	8.3	8.3	7.9	7.7	8
85	Aug. 6[a]	23:36:59	14N 91W	7.9	8.3	8.3	7.9	7.7	5
86	Aug. 24[a]	22:50:27	15S 76W	8.1	8.6	8.6	8.2	7.9	11
87	Nov. 10	11:41:27	49½S 32E	7.9	8.3	8.3	7.9	7.7	11
88	1943, Apr. 6[a]	16:07:15	30¾S 72W	7.9	8.3	8.3	7.9	7.6	9
89	May 25	23:07:36	7½N 128E	7.9	8.1	8.1	7.7	7.8	7
90	July 29	03:02:16	19¼N 67½W	7¾	7.9	7.9	7.7	7.5	8
91	Sep. 6	03:41:30	53S 159E	7.8	7.9	7.9	7.7	7.5	11
92	1944, Dec. 7	04:35:42	33¾N 136E	8.0	8.3	8.3	8.0	7.8	15
93	1945, Nov. 27	21:56:50	24½N 63E	8¼	8.3	8.3	8.0	7.7	9
94	Dec. 28	17:48:45	6S 150E	7.8	7.8	—	7.7	7.3	9
95	1946, Aug. 4	17:51:05	19¼N 69W	8.1	8.1	8.1	8.0	7.6	10
96	Sep. 12	15:20;20	23½N 96E	7¾	7¾	—	7.8	7.4	8
97	Sep. 29	03:01:55	4½S 153½E	7¾	7¾	—	7.7	7.4	8
98	Dec. 20	19:19:05	32½N 134½E	8.2	8.4	8.4	8.2	7.8	9
99	1948, Jan. 24	17:46:40	10½N 122E	8.2	8.3	8.3	8.2	7.7	13
100	Sep. 8	15:09:11	21S 174W	7.8	7.9	7.9	7.8	7.5	6
101	1949, Aug. 22	04:01:11	53¾N 133¼W	8.1	8.1	8.1	8.1	7.5	8
102	Dec. 17	06:53:30	54S 71W	7¾	7¾	—	7.7	7.4	7
103	Dec. 17	15:07:55	54S 71W	7¾	7¾	—	7.7	7.4	6
104	1950, Aug. 15	14:09:30	28½N 96½E	8.6	8.7	8.7	8.6	8.0	9
105	Dec. 2[a]	19:51:49	18¼S 167½E	7¾	8.1	8.1	7.2	7.6	7
106	1951, Nov. 18	09:35:47	30½N 91E	8.0	7.9	7.9	8.0	7.3	10
107	1952, Mar. 4	01:22:43	42½N 143E	8.3	8.6	8.6	8.3	8.0	9
108	Mar. 19	10:57:12	9½N 127¼E	7¾	7.9	7.9	7.6	7.6	8
109	Nov. 4	16:58:26	52¾N 159½E	8¼	8.4	8.4	8.2	7.9	8

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[a] Hypocentral depth 40–60 km.

[b] Okal (1977).

[c] Kanamori and Miyamura (1970).

[d] Kanamori (1972).

[e] Kanamori (1971).

are $\alpha = 1$ and $\beta = 0$, i.e. only the body-wave magnitude was used in finding the unified magnitude of these events.

We have the m_b values from the worksheets for 77 events for which Richter (1958) gives a revised magnitude. Of these, 66 are at normal depth and 11 at depths of 40 to 60 km. We tested the relations

$$M = \tfrac{1}{4} M_S + \tfrac{3}{4} (1.59 \, m_b - 3.97) \tag{5}$$

for events at normal depth and

$$M = (1.59 \, m_b - 3.97) \tag{6}$$

for events at depths of 40 to 60 km. We then rounded the M value from equation (5) or (6) to the nearest tenth. 53 of our 66 M values for shallow earthquake were within 0.1 of the revised magnitude given by Richter, as were 8 of the 11 deep earthquake magnitudes. Furthermore, the scatter was basically symmetric about zero. We therefore conclude that equations (5) and (6) give the revised magnitude, M, of Richter (1958).

Thus the revised magnitudes, M, in Richter's catalog are distinctly different from M_S in *Seismicity of the Earth.* The magnitudes given in these catalogs are on different scales. Errors have resulted from treating the revised magnitudes, M, as M_S. For illustration we now examine several earthquakes for which the magnitude is significantly larger in Richter's catalog than in *Seismicity of the Earth.*

The Tokachi-Oki earthquake of March 4, 1952 is a simple case. Gutenberg and Richter (unpublished notes) found $m_b = 8.0$ and $M_S = 8.3$. The "magnitude" in *Seismicity of the Earth* is given as 8.3. For $M_S = 8.3$, equation (2a) yields $m_s = 7.7$. The weighted average, from equation (3) of m_s and m_b (with $\alpha = \frac{3}{4}$ and $\beta = \frac{1}{4}$) gives $m = 7.9$, or through equation (2b), $M = 8.6$, which is the value given by Richter (1958).

Richter (1958, p. 350) gives some examples of calculating the unified magnitude in his Table 22–5. This table is misleadingly labeled. The column labeled "m from surface waves" is not an m_s value from equation (2a). Rather, it is the average of m_s and m_b. This may have resulted from the manner in which the table was constructed. Perhaps the M value had already been found and the other columns were added later. In any case, the unified magnitude found by taking an unweighted average of the "m from body waves" and the "m from surface waves" still has the effect of weighting m_b three times as heavily.

The Aleutian earthquake of March 7, 1929 is a notable example of a large difference between M_S, from the G-R catalog, and M, from the Richter catalog. Kanamori (1972) found $m_b = 7.67$ and $M_S = 7.68$. The G-R catalog gives $M = 8.1$. Their magnitude may have been increased to compensate for the apparent focal depth of 50 to 60 km which was noted by Richter (1958); this is unclear, because we did not find the worksheet for this event. Richter (1958) gave $m_b = 7.9$ and $M = 8.6$; apparently his unified magnitude was derived completely from m_b, using equation (6).

Despite its various imperfections, the magnitude scale provides important information concerning the source spectrum at the period where the magnitude is determined. In the light of recent earthquake source theories (e.g. Aki, 1967), the differences between the source spectra of different events are very important for understanding various source characteristics, such as source dimension, stress drop and ambient stress. As shown in Table 1, most body-wave magnitudes for large earthquakes from 1904 to 1952 were determined at periods of 6 to 12 sec. However, the determinations of m_b used in the *PDE Catalog* are made at periods of 1 to 3 sec. Thus the classical and modern m_b determinations represent different parts of the spectrum and should not be directly compared. It is important to note not only the magnitude but also the period at which the magnitude is determined. This point is discussed further in the appendix.

ESTIMATES OF SEISMIC MOMENT

Besides being intrinsically significant, the magnitudes are frequently used to estimate other source parameters. For example, Gutenberg and Richter (1956) gave an empirical relation between log E, seismic energy, and m, unified magnitude. Later, Brune (1968), Davies and Brune (1971) and O'Connell and Dziewonski (1976) used the magnitudes from Duda's catalog, together with empirical relations between log M_o and M_S (treating Duda's magnitudes as M_S) to estimate seismic moment, M_o. The first two papers used the moment estimates to estimate the seismic slip rates between plates, while the last used the estimated moments to study the excitation of the Chandler Wobble by earthquakes.

Moment estimates from the magnitude of great earthquakes are very unreliable. Several recent papers (Kanamori and Anderson, 1975; Chinnery and North, 1975; Geller, 1976) point out that for any earthquake with $M_o \gtrsim 10^{28}$ dyne cm, M_S will be 8.3 ± 0.3. Thus for great earthquakes M_S is essentially constant, independent of further increase in M_o. Once the maximum magnitude is reached, estimates of M_o from M_S are extremely unreliable and almost meaningless.

More reliable estimates of M_o may be made by using the fault area S. Several studies have shown (Aki, 1972, Kanamori and Anderson, 1975; Abe, 1975) that a remarkably linear relation exists between log S and log M_o for very large earthquakes. In terms of a crack model, this relation suggests a constant stress drop, $\Delta\sigma$. For a circular crack,

$$M_o = (16/7)\Delta\sigma(S/\pi)^{3/2}.$$

The fault area, S, can be reliably estimated from the locations of aftershocks. Even for earthquakes in the early part of the century, S can be fairly reliably estimated from ISS data (e.g., Sykes, 1971). Abe (1975) proposed a relation

$$M_o = 1.23 \times 10^{22}\, S^{3/2} \text{ dyne-cm} \qquad (S \text{ in km}^2) \quad (7)$$

for determining the moment from the fault area. This relation corresponds to a nearly circular geometry and a stress drop of about 30 bars. Although this relation does not apply to earthquakes having a stress drop very different from 30 bars, it should give much more reliable estimates of M_o for most large earthquakes than empirical moment-magnitude relations.

One of the most remarkable examples is the March 7, 1929 Aleutian Islands earthquake. Kanamori (1972) obtained a moment of 6.7×10^{27} dyne-cm. Although the aftershock area for this event is not very well determined, Sykes (1971) suggests that S is no greater than 8×10^3 km^2. Relation (7) then gives $M_o = 8.8 \times 10^{27}$ dyne-cm, which is in good agreement with the measured moment. On the other hand Richter (1958) gave $M = 8.6$ for this event. If this value is considered as M_S and is used to estimate the moment through an empirical relation between M_o and M_S (e.g., $\log M_o = 8.8 + 2.5\, M_S$; O'Connell and Dziewonski, 1976), $M_o = 2 \times 10^{30}$ dyne-cm is obtained. This value is more than 200 times too large and is equal to the largest seismic moment ever reliably determined (2×10^{30} dyne-cm for the 1960 Chilean earthquake; Kanamori and Cipar, 1974).

CONCLUSION

We have given M_S values (for 96) and m_b values (for 92) of the 109 "class *a*" shallow earthquakes in Gutenberg and Richter's (1954) *Seismicity of the Earth.* Our values of M_S, taken from Gutenberg and Richter's unpublished notes, differ only slightly from the Gutenberg-Richter magnitudes, which are significantly lower than the "revised magnitudes" of Richter (1958) and Duda (1965). This difference results from the fact that the Gutenberg-Richter magnitudes are basically M_S, while the revised magnitudes are "unified magnitudes" which heavily emphasize m_b.

For most shallow earthquakes Richter's (1958) M is related to the 20-sec surface-wave magnitude, M_S, and the body-wave magnitude m_b by

$$M = \tfrac{1}{4} M_S + \tfrac{3}{4}[1.59\, m_b - 3.97].$$

For events at depths of 40 to 60 km the revised magnitude, M, is calculated only from m_b.

$$M = 1.59\, m_b - 3.97.$$

Revised magnitude, M and surface-wave magnitude M_S are distinct magnitude scales and should not be confused.

APPENDIX

Surface-Wave Magnitudes

Gutenberg (1945a) presented an empirical formula for surface-wave magnitudes. His formula was derived from a least-squares fit to amplitude data from mostly Pacific earthquakes. For shallow earthquakes at distances $15° < \Delta < 130°$, Gutenberg found the formula

$$M_S = \log A_H + 1.656 \log \Delta + 1.818 + C. \qquad \text{(A1)}$$

C is the (empirically determined) station correction and A_H is the horizontal component of the maximum ground movement (in microns) during the surface waves having a period of about 20 sec. This formula was derived for oceanic paths and for teleseismic distances. (The problems which result from magnitude determination at short distances or along continental paths have been discussed by Alewine (1972) and Marshall and Basham (1972) and will not be covered here.)

The amplitude, A_H, in equation (A1) is a somewhat ill-defined quantity. Gutenberg intended A_H to be the "total" horizontal amplitude (zero to peak). By this he meant that A_H was the "vector sum"

$$A_H = (A_N^2 + A_E^2)^{1/2} \qquad \text{(A2)}$$

where A_N is the maximum amplitude on the N-S component and A_E the maximum on the E-W component. The "vector sum" probably leads to an amplitude which is larger than the amplitude one would measure from the (rotated) Rayleigh wave or Love wave. The maxima on the N-S and E-W components will rarely occur at the same time; thus the amplitude derived from equation (A2) must always be at least as large as the true maximum amplitude, both because A_N and A_E may be measured at different times and because Love and Rayleigh waves may overlap. Gutenberg (1945a) clearly recognized that use of the vector sum leads to increased amplitudes. He recommended that if only one component is available for magnitude determination, its amplitude should be multiplied by 1.4 (i.e., $\sqrt{2}$) for use in equation (A1).

Many investigators after Gutenberg and Richter proposed their own versions of the surface-wave magnitude scale. The results of their research were summarized by Vanek *et al.* (1962) who proposed the formula

$$M_S = \log (A/T)_{\max} + 1.66 \log \Delta + 3.3 \tag{A3}$$

which has been adopted officially by the International Association for Seismology and Physics of the Earth's Interior (IASPEI). In equation (A3) $(A/T)_{\max}$ is the maximum of all A/T (amplitude/period) values of the wave groups on a record. For $T = 20$ sec, equation (A3) reduces to

$$M_S = \log A_{20} + 1.66 \log \Delta + 2.0. \tag{A4}$$

Equation (A4) is nearly identical to Gutenberg's equation (A1); the only significant difference is that the additive constant in equation (A4) is 0.18 larger. The method for measuring A_{20} or $(A/T)_{\max}$ is not precisely defined. If the horizontal components are combined "vectorially" then the magnitudes from equation (A3) or (A4) will be systematically higher than Gutenberg's by 0.18. On the other hand, if each horizontal component is used separately, and the two independent horizontal M_S values are averaged, then magnitudes from the IASPEI formula would be virtually identical to Gutenberg's. There does not seem to be a precise definition of how $(A/T)_{\max}$ should be measured, although the usual method seems to be vectorial summation. Perhaps an international standard should be developed by the IASPEI.

Since the more widespread use of vertical broad-band instruments, and particularly since the advent of the WWSSN, M_S has frequently been determined from the amplitude on the vertical component, using equation (A3). The relation between the vertical and horizontal amplitudes is not clear. The spectral ratio of horizontal to vertical Rayleigh-wave components (ellipticity) probably is a good approximation for the ratio of $(A/T)_{\text{horiz.}}$ to $(A/T)_{\text{vert.}}$, even though the amplitudes are measured in the time domain. If the ellipticity is used to approximate the time-domain ratio, then one expects the vertical Rayleigh-wave amplitude to be about 1.4 times the horizontal. Thus $\log (A/T)_{\text{vert.}}$ might be 0.15 larger than $\log (A/T)_{\text{horiz.}}$ for Rayleigh waves. This increase may be offset by the tendency for Love waves, vector summing and higher modes to increase $(A/T)_{\text{horiz.}}$.

We have discussed only a small fraction of the research on surface-wave magnitudes following Gutenberg and Richter. In spite of some later revisions in the procedures for determining magnitudes, the modern definition is essentially equivalent to Gutenberg and Richter's M_S. Their M_S values probably can be compared to modern measurements without appreciable difficulties.

BODY-WAVE MAGNITUDES

Gutenberg (1945b, c) gave formulas for body-wave magnitudes of shallow and deep earthquakes, respectively. Later, Gutenberg and Richter (1956) published their final version of the body-wave magnitude formula

$$m_b = \log (A/T) + Q. \tag{A5}$$

Q is an empirically determined term which accounts for the source-receiver distance and the source depth. (A/T) is the maximum in the wave group of either P, PP or SH, with separate tables and charts of Q for each phase. (A is either the center-to-peak or half of the peak-to-peak ground displacement.)

Although later authors, e.g., Vanek *et al.* (1962) have proposed revisions of the m_b formula, the Gutenberg-Richter formula continues in wide use. There are two main differences between the original method for implementing equation (A5) and the current practice of the USGS. These differences, discussed below, result in substantially different m_b values from Gutenberg and Richter's.

One radical change in m_b determination is the different type of instrument used for modern determinations. Most of the P waves used by Gutenberg and Richter, particularly for larger events, were all measured on broad-band instruments at periods of about 6 to 12 sec, with longer periods for the larger events. The m_b measurements currently made by the USGS use amplitudes and periods from the short-period WWSSN instruments, which are sharply peaked at about $\frac{1}{2}$ sec. In practice, the period at which the peak amplitude occurs is nearly always about 1 sec. Furthermore, the USGS instructions ask that T be restricted to less than 3 sec. Another change in the way magnitudes are determined is the USGS requirement that (A/T) must be measured in the first 5 sec of the record. The previous practice had been that the peak (A/T) might be measured longer into the record, to allow for an earthquake with a gradual onset (Båth, 1966). Richter (personal communication) notes that using the first P instead of the maximum leads to representing major earthquakes (about 7 or more) by magnitudes around 5 which are those of minor immediate foreshocks.

The discrepancy between the narrow-band m_b values determined by the USGS and the broad-band m_b values obtained by seismologists in the eastern hemisphere is well known to observational seismologists (e.g., SIPRI, 1968). Although many factors enter into the problem, the main cause of the discrepancy appears to be the different passbands of the instruments. Because the P-wave spectrum eventually saturates at any given frequency as the seismic moment increases, the time-domain amplitude at 1 sec reaches a constant upper limit; thus m_b values measured on short-period narrow-band instruments are saturated for smaller earthquakes than the broad-band instruments (Geller, 1976).

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