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A new local magnitude scale for southeastern Australia

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Measurements of maximum trace amplitudes from 181 short-period vertical seismograms recorded at hypocentral distances of 3—1500 km from 36 earthquakes in the magnitude range 0.8—4.3 were used to derive a new preliminary ML scale for southeastern Australia ML = log A + (1.34±0.09)log(R/100) + (0.00055±0.00012)(R-100) + 3.13 + S where ML is local magnitude, A (mm) is equivalent Wood-Anderson trace amplitude not corrected for the measurement having been made on a vertical component, R (km) the hypocentral distance and S the station correction.

Introduction

Richter (1935, 31) defined the magnitude of an earthquake as 'the logarithm of the calculated maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer (T_0=0.8, V=2800, h=0.8) would register that shock at an epicentral distance of 100 kilometers'. T_0 is the undamped free period of the seismometer, V is the static or geometric magnification, and h is the coefficient of damping (Anderson & Wood, 1925). Thus a magnitude ML 3.0 earthquake would have a maximum trace amplitude of 1 mm (1000 µm) on a Wood-Anderson seismograph at a distance of 100 km from its epicentre. The corresponding amplitude of a magnitude ML 0.0 shock would be 0.001 mm (1 µm).

Clearly not all earthquakes are conveniently located 100 km from a seismograph, so Richter (1935) drew up an attenuation curve for Southern California based on a group of 11 events which occurred in January 1932. He plotted the logarithm of the observed amplitude against the epicentral distance. A single curve, representing the attenuation for an arbitrary event, was drawn parallel to the individual attenuation curves. From this he constructed a table of the logarithms of the maximum trace amplitudes (mm) with which a magnitude zero event would be recorded on a standard Wood-Anderson seismograph at epicentral distances in the range 0—600 km (Richter, 1958). He called these values log A_0, and defined the magnitude, ML, as

$$ML = \log A - \log A_0 \quad (1)$$

where A (mm) is the maximum trace amplitude of an event, measured on a standard Wood-Anderson seismograph at a certain distance, and A_0 is the corresponding amplitude which would have been recorded for a zero magnitude shock at that distance. The amplitudes are measured zero to peak.

Richter (1935, 1958) also applied empirical corrections, S, to the ML determination from each station or preferably from each instrument (each station consisting of a pair of horizontal seismographs) to give

$$ML = \log A - \log A_0 + S \quad (2)$$

Richter (1958) pointed out two limitations of his scale. One was its dependence on the Wood-Anderson seismograph. The other was that the table of log A_0 values cannot be assumed to apply outside the Californian area because of possible differences in mean focal depth, geology and crustal structure.

Despite Richter's warnings, his local magnitude scale was widely applied with little or no modification for many years in various parts of the world. Recently, Hutton & Boore (1987) redetermined the attenuation function in Southern California using thousands of observations and modern computing methods. Similar work has been done in other parts of the United States (e.g. Bakun & Joyner, 1984), Japan (e.g. Takeo & Abe, 1981), Greece (Kiratzi & Papazachos, 1984), South Australia (Greenhalgh & Singh, 1986) and Western Australia (Gaull & Gregson, 1991). Our paper gives a new preliminary attenuation function and station corrections for the Australian Geological Survey Organisation's (AGSO) short-period vertical seismographs in southeastern Australia.

Method

The seismograph stations used in the study (Fig. 1) were Canberra (CNB), Australian Capital Territory; Cobar (CMS), Cooney (COO), Stephens Creek (STK), Riverview (RIV) and Dalton (34.726°S,149.177°E) in New South Wales; Roma (RMQ) in southern Queensland; and Bellfield (BFD) and Toolangi (TOO) in Victoria. In May 1985, the Toolangi photographic recorder (designated TO1 in this study) was converted to hot stylus recording (TO2).

The maximum trace amplitude and corresponding period on the AGSO seismograms were measured wherever possible for 36 events in southeastern Queensland, New South Wales, Victoria and Tasmania (Table 1). This gave a total of 181 observations at hypocentral distances of 3—1484 km. The earthquakes were chosen to give a range of magnitudes, geographic localities and hypocentral distances. The number of measurements for each event varied from two to nine with a mean of five. Those earthquakes with only two measurements were selected because one of the hypocentral distances was less than 50 km. This was to give definition to the attenuation curve at short distances. The amplitudes were converted to Wood-Anderson trace amplitudes, A (mm), making no correction for the measurements having been made on a vertical component, and assuming a maximum Wood-Anderson magnification of 2800. Because the formula which would result from this study was intended for routine use, it was not considered practical to try to decide which oscillation on the seismogram would actually represent the maximum trace amplitude on a Wood-Anderson.

Gaull & Gregson (1991) found that maximum trace amplitudes read from a horizontal component seismograph were a mean of 1.34±0.05 times those read from the vertical component. This is equivalent to applying a correction of +0.13 to the magnitude determined from the vertical component, because the magnitude is proportional to the logarithm of the amplitude (log 1.34 is 0.13).

Following Hutton & Boore (1987),

$$-\log A_0 = n \log(R/100) + K(R-100) + 3.0 \quad (3)$$

where R is hypocentral distance (km), n is the geometric spreading coefficient and K the attenuation coefficient. Combining (2) and (3),

$$ML = \log A + n \log(R/100) + K(R-100) + 3.0 + S \quad (4)$$

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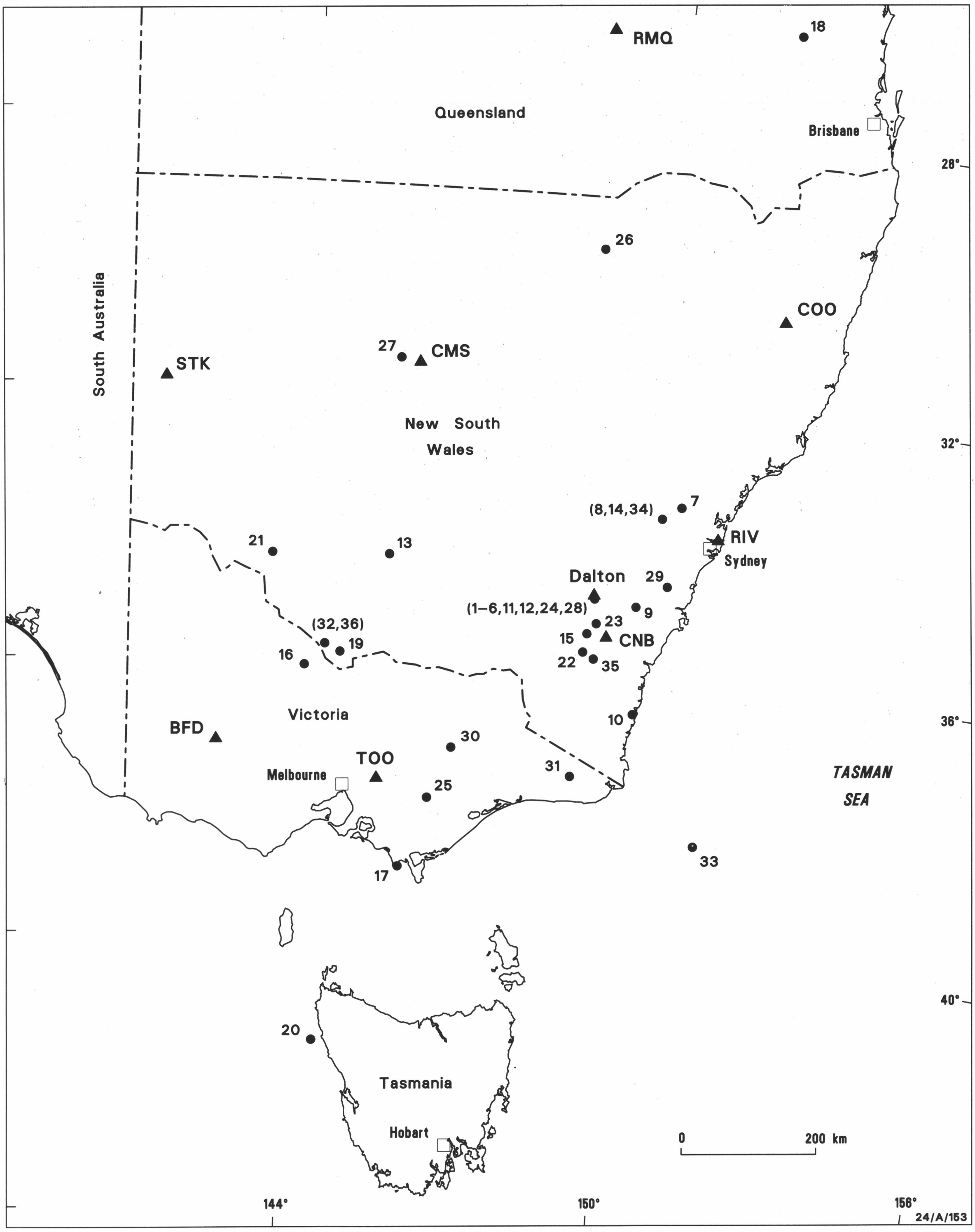

Figure 1. Seismograph stations (triangles) and epicentres (dots) of earthquakes used in the southeastern Australian magnitude study. The numbers are the Id numbers in Table I.

Equation (4) reflects the assertion that a magnitude ML 3.0 earthquake has a maximum trace amplitude of 1 mm on a Wood-Anderson seismograph 100 km distant. Because our measurements were made on vertical component instruments,

$$ML = \log A + n \log(R/100) + K(R-100) + 3.13 + S \quad (5)$$

where the 0.13 added to the 3.0 from equation (4) is the correction mentioned above. Gaull & Gregson's (1991) value was adopted because it was very similar to the ad hoc correction of 0.15 which had been used traditionally by the Australian Seismological Centre in Canberra. As magnitudes are routinely rounded to one decimal place, the difference is immaterial.

Rearranging (5), the model fitted to the data was

$$-3.13 - \log A = n \log(R/100) + K(R-100) - M_i + S_j \quad (6)$$

Table 1. Earthquakes used in the southeastern Australian magnitude study.

Id no.	*locality*	*year*	*month*	*day*	*hour*	*min*	*lat. (°S)*	*long. (°E)*	*new ML*
1	Oolong NSW	1984	08	09	06	30	34.82	149.19	4.0
2	Oolong NSW	1984	08	09	10	01	34.82	149.19	3.1
3	Oolong NSW	1984	08	09	10	33	34.82	149.19	2.9
4	Oolong NSW	1984	08	09	14	01	34.82	149.19	2.9
5	Oolong NSW	1984	08	10	01	29	34.82	148.19	3.0
6	Dalton NSW	1984	01	07	10	06	34.76	149.18	2.8
7	Upper Colo NSW	1986	02	20	21	43	33.33	150.60	3.6
8	Lithgow NSW	1985	02	13	08	01	33.49	150.18	4.0
9	Inveralochy NSW	1986	06	23	06	29	34.92	149.86	2.5
10	Bermagui NSW	1986	08	01	07	57	36.43	149.99	2.5
11	Oolong NSW	1986	07	18	03	28	34.79	149.16	1.4
12	Oolong NSW	1986	07	29	14	42	34.78	149.16	1.7
13	Griffith NSW	1986	09	22	14	21	34.31	145.55	3.6
14	Lithgow NSW	1986	10	19	15	52	33.53	150.16	2.5
15	Canberra ACT	1985	11	28	20	51	35.28	149.11	2.3
16	Pyramid Hill Vic	1986	07	14	10	36	36.05	144.16	3.1
17	Cape Liptrap Vic	1984	10	20	05	16	38.94	146.00	4.3
18	Murgon Qld	1984	10	30	06	29	26.34	151.82	3.8
19	Mathoura NSW	1986	04	10	18	53	35.78	144.85	3.7
20	Off W coast Tas	1986	03	16	01	53	41.45	144.63	3.8
21	Balranald, NSW	1986	08	03	05	47	34.36	143.55	2.9
22	Tharwa ACT	1987	04	04	03	20	35.62	149.05	2.2
23	Sutton NSW	1987	04	29	17	05	35.21	149.25	1.2
24	Oolong NSW	1987	05	17	01	57	34.77	149.19	1.2
25	Deep Creek Vic	1987	05	30	14	44	37.88	146.52	3.7
26	Moree NSW	1988	01	15	10	25	29.72	148.91	2.9
27	Cobar, NSW	1988	02	23	21	56	31.47	145.60	2.8
28	Oolong NSW	1988	03	10	04	51	34.75	149.17	0.8
29	Mittagong NSW	1988	03	21	13	40	34.53	150.45	2.1
30	Bonnie Doon Vic	1988	04	07	22	57	37.06	145.90	2.9
31	Mt Ellery Vic	1988	04	19	06	24	37.41	149.00	3.1
32	Caldwell NSW	1988	04	21	16	45	35.72	144.52	3.1
33	West Tasman Sea	1988	04	24	04	21	38.22	151.35	3.5
34	Lithgow NSW	1988	04	30	17	00	33.50	150.15	2.8
35	Williamsdale NSW	1988	05	15	00	48	35.65	149.17	2.1
36	Bunnaloo NSW	1988	07	03	08	23	35.73	144.49	3.8

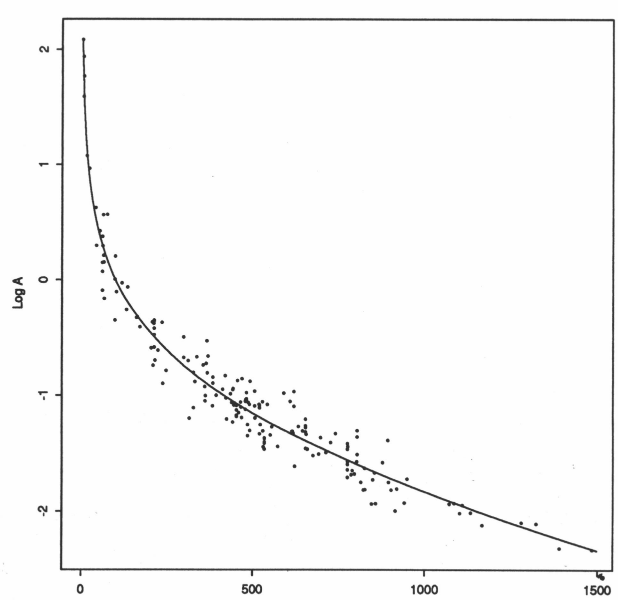

Figure 2. Amplitude, A (mm), normalised to ML 3.0, with the vertical component and station corrections included, plotted against hypocentral distance, R (km).

where M_i is the individual earthquake magnitude and S_j are the station corrections. The model was fitted using the GLIM package (Baker & Nelder, 1978) as a linear (in the parameters) regression with normal error distribution. The earthquake and station corrections were treated as qualitative variables or factors, while the variables log(R/100), (R-100) and (-3.13 - log A) were treated as quantitative variables (McCullagh & Nelder, 1983). The goodness of fit and significance of each parameter can be estimated using a Student t statistic for each parameter and a multiple-correlation coefficient for overall goodness of fit.

Results

The model fits extremely well, accounting for 94% of the variation in the data - the square of the multiple-correlation coefficient being 0.94. All variables give a highly significant reduction in deviance (sums of squares) with the parameter, n, being highly significant. Analysis of variance indicates significant ($P<0.001$) earthquake and station adjustments as well as attenuation effects.

The estimate of n is 1.34 with a standard error of 0.09. The estimate of K is 0.00055 with a standard error of 0.00012. The station correction which should be added to a single station ML estimate to approximate the mean ML is -0.3 for RIV, -0.1 for CNB, 0.0 for CMS, TOO, BFD and Dalton, +0.1 for COO and RMQ, and +0.2 for STK. The mean magnitudes, determined by regression, for the 36 earthquakes are given in Table 1. The

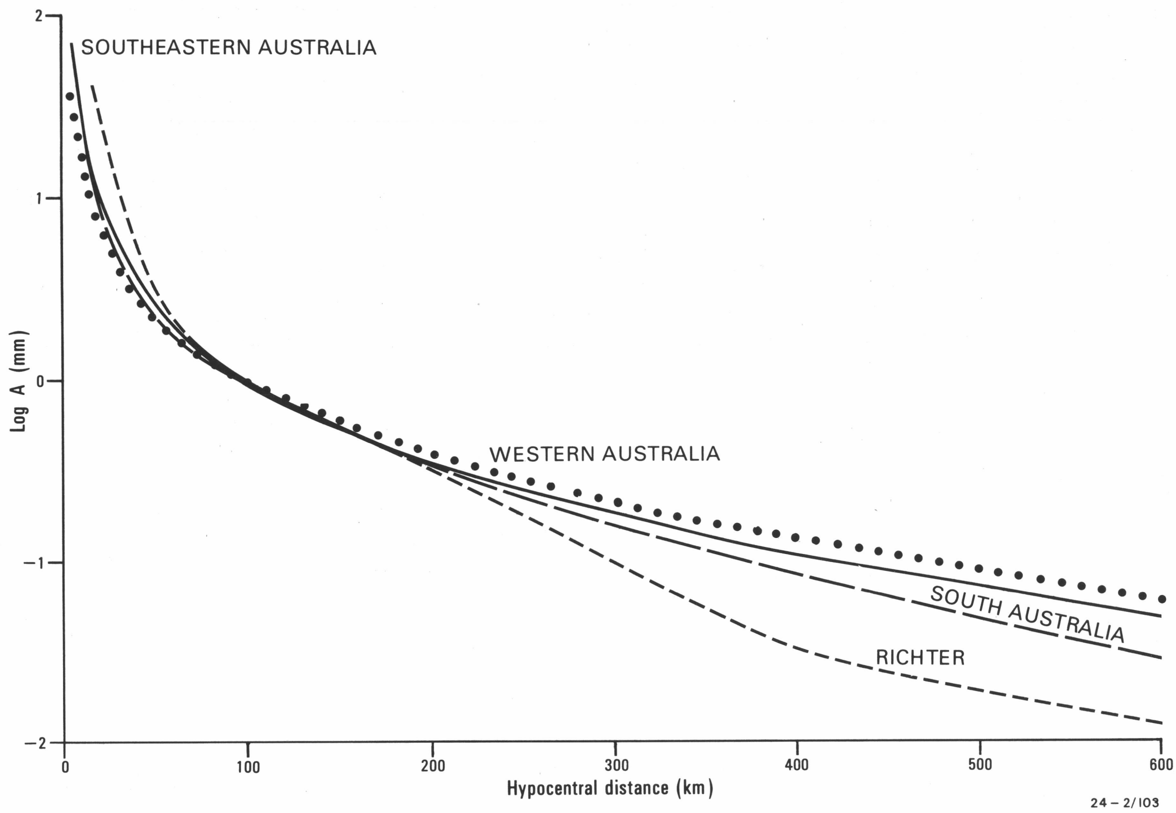

Figure 3. Theoretical maximum trace amplitude from a magnitude ML 3.0 earthquake on a Wood-Anderson seismograph at hypocentral distances up to 600 km according to Richter (1958), and the attenuation functions for South Australia, Western Australia and southeastern Australia.

amplitude data normalised to ML 3.0 (with the vertical component and station corrections included) are plotted against hypocentral distance in Figure 2.

Discussion

Because this study is based on a relatively small number of observations (181 measurements on 36 earthquakes), the results should be regarded as preliminary. Table 1 shows that 10 of the 36 events have epicentres in the Oolong-Dalton area. Four of these events (numbers 11, 12, 24 and 28) were included because they were the only ones which were recorded on two of the stations at distances of less than 10 km from one of them (Dalton). Their distances from the other (CNB) were 60—65 km and they were not recorded on any of the other stations. Consequently, they provided important information on the attenuation at small hypocentral distances.

To see whether the inclusion of a high proportion of larger Oolong-Dalton events in the analysis had biassed the results unduly, four of them (numbers 2, 3, 4 and 5) were eliminated and the analysis redone. The values of n and K (1.34 and 0.00056 respectively) were again highly significant, but did not differ significantly from those obtained previously. The station corrections remained unchanged except for TO1 and COO which became -0.2 and 0.0 respectively. As eliminating the four events reduced the number of observations at TO1 to only two, the 0.0 station correction based on six measurements is preferred. The change at COO was actually from +0.07 to +0.03, and it is probably preferable to adopt a zero station correction for COO.

The value of 1.34 for n, the geometric spreading coefficient, is higher than for most other studies. For example, in Gaull & Gregson (1991) an n of 1.14 was obtained. However, Kiratzi & Papazachos (1984) derived attenuation functions for Greece with n equal to 2.00 for ML exceeding 3.7, and 1.58 for smaller magnitudes. The theoretical value of the geometric spreading coefficient in a semi-infinite, vertically stratified medium, is 1.00 for body waves, 2.00 for head waves, and 0.50 for surface waves (Brekhovskikh, 1960). The n of 1.34 obtained in our study may be attributed to head waves, as well as body waves, giving rise on occasion to the greatest amplitude on the records. Deviation of the geology from the theoretical model may also be a contributing factor.

Figure 3 shows the theoretical maximum trace amplitude from a magnitude ML 3.0 earthquake on a Wood-Anderson seismograph at hypocentral distances up to 600 km according to Richter (1958), Greenhalgh & Singh (1986), Gaull & Gregson (1991) and this study. Both Richter and Greenhalgh & Singh used epicentral distance, so focal depths of 16 and 10 km were assumed for Southern California (Richter, 1958) and South Australia (Gaull & others, 1990) respectively in converting epicentral to hypocentral distances. The four attenuation functions are very similar in the range 52—210 km. However, taking the mean focal depth of earthquakes in California to be 16 km, as stated in Richter (1958), then at distances less than 52 km, use of Richter's attenuation will cause southeastern, Western and South Australian magnitudes to be underestimated. This discrepancy is probably an artefact of the assumed 16 km focal depth. Most of the106 central Californian earthquakes used in Bakun & Joyner's (1984) study had depths in the range 5—10 km. If these depths are applicable to Richter's data, his attenuation at hypocentral distances less than 52 km is similar to the Australian functions. However, at distances greater than 210 km, Richter's attenuation deviates increasingly from the Australian results, and use of it will cause local magnitudes of Australian events to be overestimated.

Conclusions

The new preliminary ML scale adopted by the Australian Seismological Centre for southeastern Australia is

$$ML = \log A + (1.34\pm0.09)\log(R/100) + (0.00055\pm0.00012)(R-100) + 3.13 + S$$

where A (mm) is equivalent Wood-Anderson trace amplitude, 0.13 is the vertical component correction, R (km) is hypocentral distance (3—1500 km) and S the station correction. The attenuation is very similar to Richter's (1958) over distances of 52—210 km and probably also when closer to the focus, but lower over longer distances. At a hypocentral distance of 600 km, Richter's attenuation will overestimate ML by 0.6.

The station correction which should be added to a single station ML to approximate the mean ML is -0.3 for RIV, -0.1 for CNB, 0.0 for COO, CMS, TOO, BFD and Dalton, +0.1 for RMQ, and +0.2 for STK.

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