Bulletin of the Seismological Society of America, Vol. 95, No. 6, pp. 2517–2524, December 2005, doi: 10.1785/0120050043

# Revised $M_L$ Determination for Crustal Earthquakes in Taiwan

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**Abstract** The local magnitude scale $M_L$ is an empirically derived scale anchored to a zero magnitude reference event. Richter defined the amplitude of ground shaking at an epicentral distance of 100 km for a zero magnitude earthquake in southern California. The crustal attenuation characteristics of Taiwan result in a relatively high $M_L$ when compared to moment magnitude, $M_w$. We therefore define a revised $M_L$ scale for crustal earthquakes in the Taiwan region that is more consistent with $M_w$. Using observed peak ground shaking and $M_w$, we determine a new log $A_0$ curve of ground shaking versus hypocentral distance, $R$, for a zero magnitude earthquake, and station correction factors. The log $A_0$ curve determined in this study is,

$$\log A_0(R) = 0.332 - 1.568 \cdot \log(R) \pm 0.280.$$

Using this new log $A_0$ curve and station corrections, the new $M_L$ is more consistent with $M_w$, with a 0.2 magnitude unit uncertainty. The new log $A_0$ curve has a value of $-2.80$ at the distance of 100 km compared to the anchor point of $\log A_0 = -3$ at the same distance as defined by Richter for southern California. This means that the current $M_L$ estimates in Taiwan (which use Richter's definition) average 0.2 magnitude units larger than their $M_w$. The station correction factors also determined are large, from $-0.40$ to 0.52 magnitude units. The use of station corrections in routine seismic network operation in Taiwan will improve magnitude estimates. This is particularly important for smaller events when recording stations may be predominantly on either hard rock or soft soil sites, which could lead to under- or overestimates of the magnitude by up to half a magnitude unit.

## Introduction

There are many magnitude scales in current use. Local magnitude, $M_L$, introduced by Richter (1935) is still popular with earthquake monitoring agencies (Alsaker *et al.*, 1991; Shin, 1993; Spallarossa *et al.*, 2002; Wu *et al.*, 1997) because of the relative ease of measurement and its direct relation to the strength of shaking at the period range of most importance to the built environment (Kanamori and Jennings, 1978). However, $M_L$ is an empirically derived scale based on the observed strength of shaking for earthquakes in southern California. Other magnitude scales provide better representations of some important event characteristics. In particular, moment magnitude, $M_w$, is related to the seismic moment released during an event.

Determination of $M_L$ is based on the amplitude recorded by a Wood–Anderson torsion seismograph with a natural period of 0.8 sec, a damping constant 0.8, and a static magnification of 2800. By definition, in a zero magnitude earthquake in southern California a Wood–Anderson instrument 100 km from the epicenter would record ground shaking with a peak amplitude of 0.001 mm. The relative size of an event can then be calculated by comparison to the zero magnitude reference event:

$$M_L = \log A(\Delta) - \log A_0(\Delta) \quad (1)$$

Where $A$ and $A_0$ are the maximum amplitude in millimeters of the earthquake and the reference event at a prescribed epicentral distance, $\Delta$, respectively. According to this definition $\log A_0 = -3$ at 100 km from the epicenter.

$M_L$ in its original form is rarely used because Wood–Anderson torsion instruments are uncommon. However, a large number of modern digital instruments are in operation worldwide, and digital seismic waveforms can easily be used to simulate a Wood–Anderson seismogram (Kanamori *et al.*, 1999). Thus, $M_L$ is now widely used by many seismic networks outside of southern California, including by the Central Weather Bureau Seismic Network (CWBSN) of Taiwan (Shin, 1993) and others (Gibowicz, 1972; Ebel, 1982; Bakun and Joyner, 1984; Alsaker *et al.*, 1991; Spallarossa *et al.*, 2002; Kim, 1998). Most applications of $M_L$ by regional seismic networks use the definition $\log A_0 = -3$ at a distance 100 km for a zero magnitude earthquake (Bakun and Joyner, 1984; Kiratzi and Papazerchos, 1984; Chavez and Priestley, 1985; Greenhalgh and Singh, 1986; Hutton and Boore, 1987; Shin, 1993). However, variations in regional attenuation characteristics, due to different crustal structure, lead to a discrepancy in the meaning of an $M_L = 0$ earthquake when the same $\log A_0 = -3$ at 100 km definition is applied in different regions.

$M_w$, derived from moment tensor analysis, provides the most robust estimate of the magnitude of earthquakes. Kanamori *et al.* (1993) show that events of $M_L$ less than 6.5 have a linear relationship with log(energy) radiated by the earthquakes. Clinton *et al.* (2004) also show that $M_L$ is correlated 1:1 to $M_w$ in the magnitude range from 4.5 to 6.5 in southern California. Therefore, $M_w$ values for events of $4.5 < \mathbf{M} < 6.5$ can be used to calibrate regional $M_L$ scales so that they provide magnitudes that are more consistent with $M_w$ (Ristau *et al.*, 2003) and therefore with $M_L$ for southern California. By rearranging equation (1) and replacing $M_L$ with $M_w$, $\log A_0$ as a function of hypocentral distance ($R$) can be obtained as follows,

$$\log A_0(R) = \log A(R) - M_w$$

In this study, we use the $M_w$ of crustal earthquakes in the Taiwan region to determine the $\log A_0$ curve and station corrections. A revised $M_L$ determination for Taiwan earthquakes is then possible that is more consistent with the $M_w$ and $M_L$ scales for southern California earthquakes.

## Data

Waveform data were provided by the Central Weather Bureau (CWB) earthquake Rapid Reporting System (RRS) (Wu *et al.*, 1997, 2000, 2002, 2004), which consists of about 90 telemetered strong-motion stations in Taiwan (Fig. 1). Waveforms from three-component force-balanced accelerometers (FBA) are continuously telemetered at the headquarters of the CWB in Taipei via leased telephone lines. Ground-motion recordings are digitized at 50 samples per second with a 16-bit resolution. The full recording range is $\pm 2g$. A total of 79 RRS stations were used in this study; each recorded a minimum of eight events.

Fifty-six shallow earthquakes with $M_w \leq 6.2$ in Taiwan were used for this study (Fig. 1 and Table 1). The events all had $M_w$ between 4.7 and 6.2 as reported in the Harvard Moment Tensor Catalog and focal depths less than 35 km. Owing to the $M_L$ saturation problem, we do not use events with $M_w$ larger than 6.2. All events were well recorded by the CWB RRS from 1995 to 2004 and were widely felt in Taiwan. The earthquakes have been relocated using a joint inversion for three-dimensional velocity structures and location (Thurber and Eberhart-Phillips, 1999; Wu *et al.*, 2003) using both the $P$ and $S$ arrival times of the CWBSN and S–P times from the records of the Taiwan Strong Motion Instrumental Program (TSMIP) (Wu *et al.*, 1998). A total of 1898 RRS system records were used for this magnitude study.

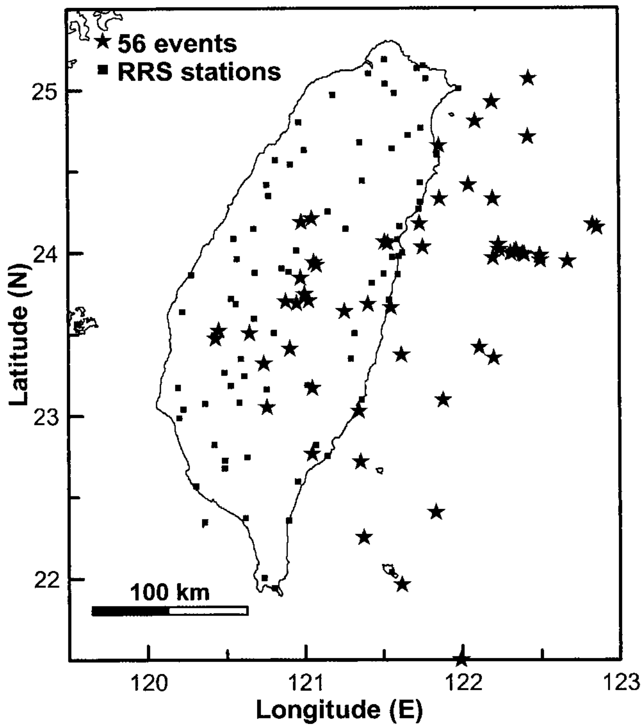



Figure 1. Distribution of stations (squares) participating in the Central Weather Bureau earthquake rapid reporting system (RRS) and the epicenters of the 56 events (stars) used in this study.

## Method and Results

Wood–Anderson seismograms were simulated from the recorded accelerograms (Kanamori *et al.*, 1999), and the peak ground motion was measured on the two horizontal components. Although there is some question about the magnification of the standard Wood–Anderson instrument (Uhrhammer and Collins, 1990), we used the standard magnification, 2800. The average of $\log A$ was determined from two horizontal components providing one peak ground motion observation per event–station pair. Using equation (2) and the Harvard $M_w$, $\log A_0$ could then be determined.

We determined a best-fit relation between $\log A_0$ and hypocentral distance. The decrease in the amplitude, *Amp*, of seismic waves with distance from the hypocenter, $R$, can be represented using the functional form $Amp \sim e^{-\gamma R}/R^n$, where $n$ is the geometrical spreading coefficient, and $\gamma$ can be related to the anelastic attenuation coefficient $Q$. Taking the logarithm, we obtain $\log(Amp) = C_s - (\gamma/\ln 10)R - n \log(R)$, where $C_s$ is a constant. Therefore, in this study we consider the linear regression model,

$$\log A_0 = A + B \cdot R + C \cdot \log(R) - S_i, \quad (3)$$

Table 1
Fifty-Six Events Used in This Study

| Origin Time (UTC) | | Lat. (N) | Long. (E) | Depth (km) | $M_L$ CWB | $M_W$ Harvard | $M_L$ New | Readings | Gap* (deg.) |
|---|---|---|---|---|---|---|---|---|---|
| 1995/01/10 | 07:55:19 | 23.683 | 121.407 | 13.79 | 5.12 | 5.1 | 5.04 | 11 | 26 |
| 1995/02/23 | 05:19:02 | 24.176 | 121.737 | 29.72 | 5.76 | 6.2 | 6.06 | 23 | 180 |
| 1995/04/03 | 11:54:40 | 24.001 | 122.335 | 15.4 | 5.89 | 5.6 | 5.59 | 22 | 206 |
| 1995/04/03 | 22:33:25 | 23.994 | 122.312 | 19.47 | 5.36 | 5.3 | 4.98 | 11 | 203 |
| 1995/05/27 | 18:11:11 | 23.029 | 121.347 | 20.67 | 5.25 | 5.7 | 5.43 | 28 | 139 |
| 1996/03/05 | 17:32:08 | 23.966 | 122.200 | 5.87 | 5.96 | 5.8 | 5.77 | 33 | 196 |
| 1996/03/29 | 03:28:52 | 24.047 | 122.234 | 14.14 | 5.62 | 5.7 | 5.48 | 25 | 197 |
| 1996/08/10 | 06:23:05 | 23.944 | 122.671 | 23.6 | 5.78 | 5.6 | 5.57 | 14 | 237 |
| 1997/01/05 | 10:34:16 | 24.708 | 122.423 | 5.00 | 5.82 | 5.2 | 5.40 | 23 | 248 |
| 1997/07/04 | 18:37:29 | 23.052 | 120.759 | 4.45 | 5.18 | 5.1 | 5.00 | 23 | 24 |
| 1998/01/18 | 19:56:51 | 22.766 | 121.047 | 7.22 | 5.03 | 5.2 | 5.06 | 24 | 49 |
| 1998/07/17 | 04:51:14 | 23.506 | 120.649 | 5.75 | 6.28 | 5.7 | 5.75 | 20 | 52 |
| 1998/07/24 | 18:44:02 | 21.501 | 121.99 | 5.00 | 5.99 | 6.1 | 5.82 | 30 | 278 |
| 1999/09/10 | 14:18:21 | 22.406 | 121.835 | 23.52 | 5.41 | 5.4 | 5.35 | 26 | 207 |
| 1999/09/21 | 18:18:37 | 24.186 | 120.981 | 2.13 | 5.23 | 5.2 | 4.89 | 19 | 28 |
| 1999/09/22 | 12:17:20 | 23.744 | 121.000 | 24.99 | 6.02 | 5.2 | 5.50 | 28 | 70 |
| 1999/09/23 | 12:44:34 | 23.940 | 121.060 | 16.12 | 5.6 | 5.2 | 5.28 | 30 | 36 |
| 1999/09/25 | 08:43:30 | 23.689 | 120.950 | 13.04 | 5.11 | 5.1 | 5.41 | 32 | 25 |
| 1999/10/01 | 12:54:10 | 23.700 | 120.880 | 6.07 | 5.12 | 5.2 | 5.19 | 31 | 57 |
| 1999/10/02 | 17:14:16 | 23.978 | 122.494 | 18.85 | 5.30 | 5.1 | 5.19 | 14 | 235 |
| 1999/10/18 | 16:00:45 | 23.706 | 121.027 | 29.65 | 5.16 | 5.3 | 5.30 | 35 | 79 |
| 1999/10/22 | 02:18:57 | 23.474 | 120.433 | 20.72 | 6.31 | 5.8 | 5.99 | 36 | 26 |
| 1999/10/22 | 03:10:17 | 23.523 | 120.453 | 16.16 | 5.87 | 5.5 | 5.78 | 42 | 34 |
| 2000/02/15 | 21:33:18 | 23.321 | 120.739 | 20.16 | 5.59 | 5.2 | 5.41 | 44 | 37 |
| 2000/05/17 | 03:25:46 | 24.208 | 121.047 | 2.00 | 5.59 | 5.4 | 5.23 | 47 | 29 |
| 2000/06/19 | 21:56:24 | 23.924 | 121.077 | 30.43 | 5.18 | 5.2 | 5.28 | 34 | 27 |
| 2000/07/14 | 00:07:32 | 24.032 | 121.756 | 3.72 | 5.67 | 5.4 | 5.38 | 29 | 166 |
| 2000/07/28 | 20:28:07 | 23.412 | 120.906 | 2.00 | 5.99 | 5.6 | 5.71 | 38 | 19 |
| 2000/08/23 | 00:49:16 | 23.662 | 121.554 | 30.76 | 5.56 | 5.3 | 5.36 | 25 | 156 |
| 2000/09/10 | 08:54:46 | 24.057 | 121.535 | 19.7 | 6.28 | 5.8 | 5.74 | 39 | 28 |
| 2001/03/01 | 16:37:50 | 23.845 | 120.975 | 14.67 | 5.70 | 5.2 | 5.39 | 47 | 51 |
| 2001/06/19 | 05:16:15 | 23.170 | 121.049 | 11.03 | 5.49 | 5.3 | 5.09 | 28 | 33 |
| 2001/12/22 | 21:40:27 | 24.171 | 122.831 | 5.00 | 5.46 | 5.1 | 5.20 | 8 | 251 |
| 2002/04/03 | 18:06:10 | 24.329 | 121.864 | 19.05 | 5.34 | 5.3 | 5.08 | 42 | 165 |
| 2002/04/28 | 13:23:46 | 24.151 | 122.859 | 11.65 | 5.63 | 5.2 | 5.33 | 18 | 253 |
| 2002/05/15 | 03:46:06 | 24.656 | 121.861 | 12.08 | 6.15 | 6.1 | 5.81 | 60 | 156 |
| 2002/05/28 | 16:45:18 | 24.017 | 122.239 | 17.71 | 6.18 | 6.1 | 5.75 | 60 | 200 |
| 2002/06/13 | 20:40:28 | 24.806 | 122.091 | 12.18 | 5.08 | 5.2 | 4.83 | 20 | 177 |
| 2002/07/11 | 07:36:24 | 24.012 | 122.347 | 16.32 | 5.83 | 5.8 | 5.46 | 53 | 207 |
| 2002/07/17 | 19:14:42 | 23.354 | 122.204 | 21.34 | 5.19 | 5.2 | 4.88 | 15 | 206 |
| 2002/08/28 | 17:05:34 | 22.253 | 121.376 | 17.74 | 6.04 | 5.5 | 5.64 | 45 | 112 |
| 2002/09/01 | 05:56:23 | 23.990 | 122.388 | 18.75 | 5.56 | 5.4 | 5.21 | 32 | 221 |
| 2002/09/01 | 07:07:36 | 23.986 | 122.399 | 20.34 | 5.60 | 5.3 | 5.25 | 25 | 221 |
| 2002/09/15 | 01:06:55 | 23.979 | 122.498 | 15.75 | 5.31 | 5.1 | 5.17 | 28 | 226 |
| 2003/05/15 | 01:17:42 | 25.068 | 122.43 | 16.56 | 5.22 | 5.1 | 5.05 | 21 | 223 |
| 2003/06/09 | 01:52:50 | 24.413 | 122.047 | 34.41 | 6.20 | 5.8 | 5.90 | 57 | 187 |
| 2003/07/30 | 18:36:32 | 23.951 | 122.499 | 20.43 | 5.20 | 5.2 | 5.03 | 16 | 226 |
| 2004/01/01 | 03:15:18 | 23.373 | 121.619 | 30.66 | 5.67 | 5.2 | 5.55 | 65 | 184 |
| 2004/02/04 | 03:23:59 | 23.419 | 122.113 | 27.72 | 5.95 | 5.4 | 5.68 | 66 | 202 |
| 2004/05/01 | 07:56:11 | 24.064 | 121.514 | 23.81 | 5.77 | 5.2 | 5.36 | 62 | 20 |
| 2004/05/08 | 08:02:46 | 21.962 | 121.618 | 10.72 | 5.61 | 5.5 | 5.36 | 23 | 249 |
| 2004/05/16 | 06:04:08 | 23.096 | 121.883 | 20.79 | 5.67 | 5.5 | 5.54 | 64 | 194 |
| 2004/05/19 | 07:04:12 | 22.717 | 121.357 | 19.77 | 6.31 | 6.2 | 6.06 | 66 | 129 |
| 2004/06/02 | 16:56:29 | 23.639 | 121.257 | 10.12 | 5.15 | 4.7 | 4.89 | 52 | 23 |
| 2004/07/06 | 07:32:02 | 24.924 | 122.197 | 4.87 | 5.25 | 5.2 | 5.08 | 25 | 193 |
| 2004/11/11 | 02:16:44 | 24.328 | 122.200 | 29.97 | 6.12 | 5.6 | 5.73 | 64 | 199 |

*Station coverage gap in the hypocenter location process.

where $A$, $B$, and $C$ are constants to be determined from the regression analysis. $S_i$ is the correction factor for station $i$. Correction factors of the RRS stations have not been well determined. However, those stations have recorded many earthquakes. Thus, we determined the factors empirically by averaging the residuals between the observed and predicted values.

Our data set included some offshore events. Their locations are more uncertain than those of onshore earthquakes, as are the inferred values of $R$. We therefore down weight data values associated with events with station coverage gaps (Lee and Lahr, 1975) large than 180° by a factor of 2 in the regression analysis. With a total of 1898 RRS records as the input, the resulting best-fit attenuation relationship for log $A_0$ ($R$) is given by

$$\log A_0(R) = 0.247 - 0.000281 \cdot R - 1.509 \cdot \log(R) \pm 0.279 \quad (4)$$

Residuals between the observed and predicted values are approximately normally distributed with zero mean. We found a small linear term, 0.000281$R$, in equation (4). Thus, we conducted an $F$ test for this term and found it has an $F$ value 1.002, indicating that this term is not statistically significant and can be dispensed with. The new relationship for log $A_0$ ($R$) is given by

$$\log A_0(R) = 0.332 - 1.568 \cdot \log(R) \pm 0.280 \quad (5)$$

Figure 2 shows the 1898 readings of log $A_0$ after the station corrections were applied and the regression curve. The station correction factors and their standard deviations, also determined in the regression analysis, are listed in the Table 2.

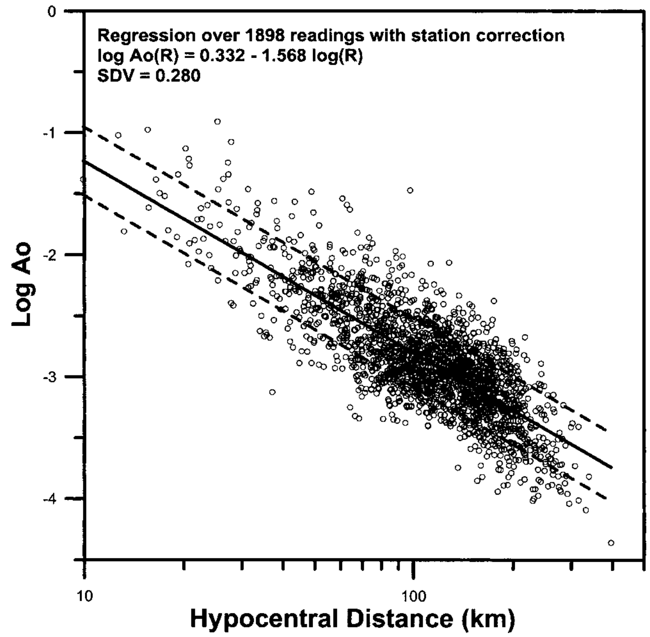



Figure 2. Relationship between log $A_0$ and hypocentral distance for all 56 events. The log $A_0$ values have had station corrections applied, which were determined simultaneously with the least-squares best-fit relation shown by the solid line. One standard deviation is shown by the dashed lines.

## Discussion and Conclusion

Figure 3 shows the log $A_0$ curve determined in this study and that currently used by the CWB (Shin, 1993). Shin (1993) anchored the log $A_0$ curve at a hypocentral distance of 100 km, where it was set equal to $-3$ as in southern California. Our log $A_0$ curve at the same distance has a value of $-2.80$. Thus, the $M_L$ determined in this study should be approximately 0.20 units lower than the current CWB $M_L$ ($M_{L\_CWB}$). Similarly, if $M_L$ remains anchored by setting the log $A_0$ curve to $-3$ at a distance of 100 km, then the differences between $M_L$ and $M_w$ will average 0.20 units in the Taiwan region, consistent with our previous study (Wu *et al.*, 2001).

Figure 4a compares $M_{L\_CWB}$ with $M_W$ for the 56 events used in this study. $M_{L\_CWB}$ is generally larger than $M_w$. The differences between $M_{L\_CWB}$ and $M_w$ for the 56 events are distributed in a large range from $-0.45$ to 0.82, with an average of 0.20 and a standard deviation of 0.26. The 0.20 unit difference is from the log $A_0$ curve to $-3$ at a distance of 100 km. It is clear from Figure 4a that $M_{L\_CWB}$ does not correlate well with $M_w$. However, the $M_L$ determined in this study ($M_{L\_new}$) is well correlated with $M_w$. $M_{L\_new}$ was determined by using the new log $A_0$ curve and by applying station corrections (Table 2). Figure 4b shows $M_{L\_new}$ versus $M_w$. $M_{L\_new}$ exhibits an almost 1:1 correlation with $M_w$. The differences between $M_{L\_new}$ and $M_w$ are distributed in a small range from $-0.37$ to 0.35, with an average of $-0.02$ and a standard deviation 0.19. This improved correlation between $M_{L\_new}$ and $M_w$ is due to both the new definition of log $A_0$ and the use of stations corrections. The effect of anchoring log $A_0$ at $-2.8$ rather than $-3.0$ is a downward shift in all magnitude estimates, while the application of station corrections reduces the variance in magnitude estimates from individual station records. The standard deviation of 0.19 between $M_{L\_new}$ and $M_w$ is due to the differences between these two scales but also includes uncertainty in hypocentral distance, which affects the log $A_0$ analysis and causes some error in $M_w$ estimation.

The use of station corrections is a major difference in the calculation of $M_{L\_new}$ and $M_{L\_CWB}$, as they are not currently applied by the CWB in their magnitude determination. We find the station correction factors to be large, from $-0.40$ to 0.52 magnitude units, with an average of 0.01 and a standard deviation 0.23 (Table 2). Table 2 also shows the standard deviations of station correction factors for each station.

It is difficult to justify the statistical significance of the station correction terms (using an $F$-test for example) given

Table 2
Parameters of 79 Stations Used in This Study

| Station Code | Lat. (N) | Long. (E) | Elevation (m) | Readings | Station Correction | S.D. of Station Correction |
|---|---|---|---|---|---|---|
| TAP | 25.039 | 121.522 | 5.5 | 43 | −0.311 | 0.236 |
| HSN | 24.802 | 120.969 | — | 32 | −0.261 | 0.211 |
| TCU | 24.147 | 120.676 | −66.0 | 32 | −0.029 | 0.216 |
| CHY | 23.498 | 120.424 | −173.0 | 42 | −0.305 | 0.269 |
| ALS | 23.510 | 120.805 | 2413.4 | 36 | −0.064 | 0.278 |
| PNG | 23.567 | 119.555 | 10.8 | 25 | −0.041 | 0.284 |
| KAU | 22.568 | 120.308 | −183.0 | 28 | −0.256 | 0.212 |
| HEN | 22.006 | 120.738 | −128.0 | 17 | −0.251 | 0.244 |
| ILA | 24.765 | 121.748 | 7.2 | 45 | −0.257 | 0.316 |
| HWA | 23.977 | 121.605 | −119.0 | 52 | −0.167 | 0.348 |
| CHK | 23.099 | 121.365 | 33.5 | 44 | 0.116 | 0.339 |
| TTN | 22.754 | 121.146 | 9.0 | 18 | −0.070 | 0.281 |
| TAW | 22.358 | 120.896 | 8.1 | 11 | 0.380 | 0.279 |
| LAY | 22.039 | 121.551 | 324.0 | 19 | 0.043 | 0.271 |
| NCU | 24.970 | 121.187 | 133.5 | 31 | −0.239 | 0.237 |
| SML | 23.883 | 120.900 | 1014.8 | 34 | −0.190 | 0.267 |
| NST | 24.631 | 121.001 | 164.3 | 34 | −0.008 | 0.257 |
| WSF | 23.638 | 120.222 | 5.9 | 29 | −0.304 | 0.277 |
| WTC | 23.864 | 120.281 | 4.2 | 16 | −0.284 | 0.235 |
| SCL | 23.175 | 120.194 | 7.4 | 27 | −0.314 | 0.343 |
| SGS | 23.082 | 120.583 | 277.5 | 14 | 0.140 | 0.200 |
| SGL | 22.725 | 120.491 | 29.9 | 25 | −0.240 | 0.244 |
| ENA | 24.428 | 121.741 | 113.0 | 38 | 0.040 | 0.285 |
| ESL | 23.814 | 121.433 | 177.8 | 32 | 0.330 | 0.376 |
| ENT | 24.639 | 121.565 | 279.9 | 31 | 0.091 | 0.331 |
| NSY | 24.416 | 120.761 | 311.0 | 37 | −0.105 | 0.259 |
| EHY | 23.506 | 121.322 | 237.2 | 24 | 0.516 | 0.274 |
| WNT | 23.878 | 120.684 | 109.8 | 38 | 0.003 | 0.302 |
| WGK | 23.686 | 120.562 | 75.2 | 40 | −0.239 | 0.232 |
| WTP | 23.246 | 120.614 | 560.3 | 14 | 0.110 | 0.262 |
| STY | 23.163 | 120.757 | 639.7 | 21 | 0.196 | 0.242 |
| NSK | 24.676 | 121.358 | 682.3 | 29 | 0.158 | 0.337 |
| SSD | 22.746 | 120.632 | 148.3 | 19 | 0.206 | 0.209 |
| WHF | 24.145 | 121.265 | 3394.7 | 19 | −0.034 | 0.290 |
| EHC | 24.267 | 121.732 | 10.9 | 8 | 0.311 | 0.149 |
| SCZ | 22.372 | 120.620 | 73.6 | 10 | 0.292 | 0.201 |
| ANP | 25.187 | 121.520 | 825.7 | 25 | 0.069 | 0.262 |
| TAI1 | 23.040 | 120.228 | −190.0 | 29 | −0.279 | 0.223 |
| CHN1 | 23.185 | 120.528 | 360.0 | 22 | 0.165 | 0.246 |
| CHN3 | 23.076 | 120.365 | 50.0 | 16 | −0.183 | 0.265 |
| CHN4 | 23.351 | 120.593 | 205.0 | 30 | −0.185 | 0.258 |
| CHN5 | 23.597 | 120.678 | 840.0 | 18 | −0.211 | 0.289 |
| TWA | 24.980 | 121.580 | 260.0 | 20 | −0.013 | 0.238 |
| TWB1 | 25.008 | 121.988 | 130.0 | 12 | 0.252 | 0.286 |
| TWC | 24.609 | 121.849 | 20.0 | 34 | 0.212 | 0.316 |
| TWD | 24.080 | 121.595 | 30.0 | 34 | 0.500 | 0.354 |
| TWE | 24.721 | 121.667 | 20.0 | 31 | 0.000 | 0.300 |
| TWF1 | 23.352 | 121.297 | 260.0 | 27 | 0.490 | 0.319 |
| TWG | 22.821 | 121.072 | 195.0 | 14 | 0.246 | 0.450 |
| TWK1 | 21.943 | 120.805 | 90.0 | 8 | 0.142 | 0.234 |
| TWL | 23.267 | 120.488 | 590.0 | 32 | 0.082 | 0.216 |
| TWM1 | 22.823 | 120.423 | 340.0 | 16 | −0.081 | 0.203 |
| TWQ1 | 24.348 | 120.773 | 260.0 | 35 | −0.046 | 0.217 |
| TWS1 | 25.101 | 121.418 | 60.0 | 34 | −0.066 | 0.230 |
| TWT | 24.251 | 121.153 | 1500.0 | 20 | 0.137 | 0.362 |
| TYC | 23.904 | 120.856 | 20.0 | 20 | 0.330 | 0.170 |
| WLC | 22.348 | 120.362 | 38.0 | 10 | 0.085 | 0.283 |
| NWF | 25.071 | 121.781 | 765.3 | 32 | −0.317 | 0.322 |
| NNS | 24.440 | 121.373 | 1140.0 | 34 | −0.150 | 0.276 |
| ELD | 23.189 | 121.017 | 1040.0 | 21 | 0.378 | 0.291 |
| ECL | 22.597 | 120.954 | 70.0 | 12 | 0.320 | 0.247 |

(*continued*)

Table 2
Continued

| Station Code | Lat. (N) | Long. (E) | Elevation (m) | Readings | Station Correction | S.D. of Station Correction |
|---|---|---|---|---|---|---|
| NOU | 25.151 | 121.766 | 10.0 | 13 | 0.225 | 0.199 |
| WCH | 24.086 | 120.549 | — | 24 | −0.271 | 0.216 |
| NML | 24.568 | 120.817 | — | 17 | −0.084 | 0.224 |
| SPT | 22.678 | 120.488 | — | 9 | −0.109 | 0.341 |
| TAI2 | 22.987 | 120.201 | — | 14 | −0.153 | 0.262 |
| WDL | 23.718 | 120.532 | — | 17 | −0.334 | 0.159 |
| EGC | 23.709 | 121.540 | — | 16 | 0.115 | 0.390 |
| ETL | 24.160 | 121.610 | — | 29 | 0.223 | 0.343 |
| EGA | 23.973 | 121.563 | — | 17 | 0.090 | 0.358 |
| ESF | 23.871 | 121.508 | — | 23 | 0.030 | 0.302 |
| EYL | 23.867 | 121.598 | — | 15 | 0.488 | 0.345 |
| WYL | 23.962 | 120.57 | — | 20 | −0.400 | 0.194 |
| NSD | 24.541 | 120.914 | — | 16 | 0.073 | 0.251 |
| WPL | 24.014 | 120.949 | — | 13 | 0.300 | 0.220 |
| KLUP | 25.133 | 121.728 | — | 15 | 0.007 | 0.270 |
| TWCP | 24.599 | 121.85 | — | 17 | −0.366 | 0.309 |
| HWAP | 23.998 | 121.627 | — | 12 | 0.046 | 0.236 |
| EHP | 24.309 | 121.741 | — | 17 | −0.170 | 0.286 |

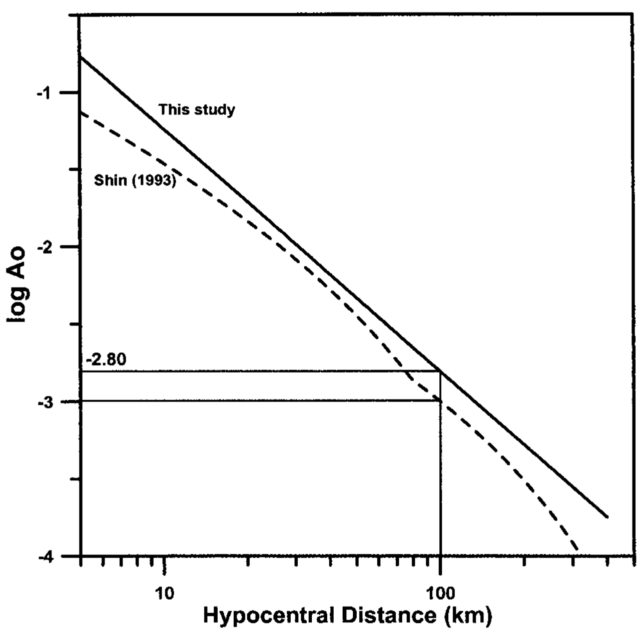



Figure 3. Plot of log $A_0$ versus hypocentral distance showing the amplitude of ground shaking for the zero magnitude reference earthquake. The log $A_0$ curve determined in this study (solid line) is higher than that currently used by the Central Weather Bureau, Taiwan (dashed line) (Shin, 1993).

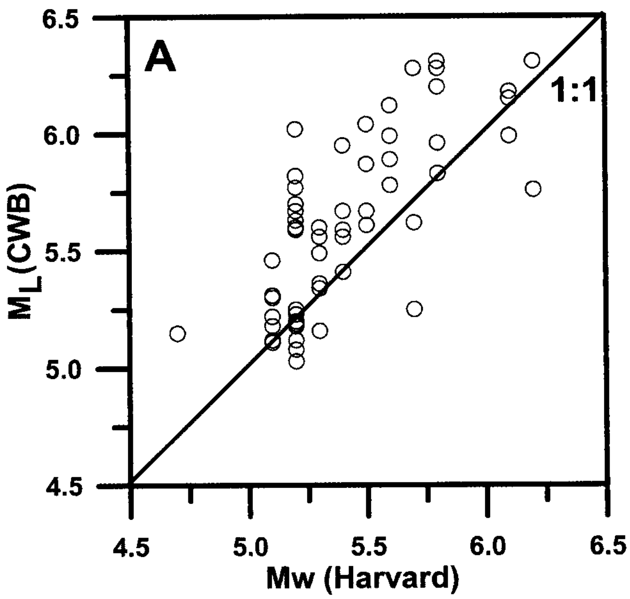
their standard deviations. However, there is a strong correlation between the station corrections and geology, which argues for their use. Figure 5 shows station correction factors on a map showing the geological context. The western coastal plain, Taipei basin, and Pingtung and Lanyang plains are places of high amplification with negative station correction factors, whereas the central mountain range and the more mountainous areas of eastern Taiwan are places of low amplification with positive station correction factors. The correction factors correlate reasonably well with the surface geology as determined from published maps.

Application of these correction factors in the determination of $M_{L\_new}$ reduces the standard deviation between the local and moment magnitudes determined for the events from $\pm 0.26$ for $M_{L\_CWB}$ to $\pm 0.19$ magnitude units for $M_{L\_new}$. These corrections are particularly important for smaller earthquakes, which are only recorded at stations close to the epicenter. In this case all the stations may be on either hard rock or soft soil sites, which could lead to under- or overestimates in the magnitude of up to half a magnitude unit.

Consistency in magnitude estimates determined by different seismic networks is important for study and comparison of seismicity and tectonic processes between global regions. Application of $M_{L\_new}$ in Taiwan will allow for improved seismotectonic studies in the region and more robust magnitude estimates for use in seismic hazard mitigation.

## Acknowledgments

We wish to thank Prof. Hiroo Kanamori and Dr. Egill Hauksson for their valuable comments. We also thank Prof. Euan Smith for his detailed review of this article and his valuable comments. This research was supported by the National Science Council and Central Weather Bureau of the Republic of China.



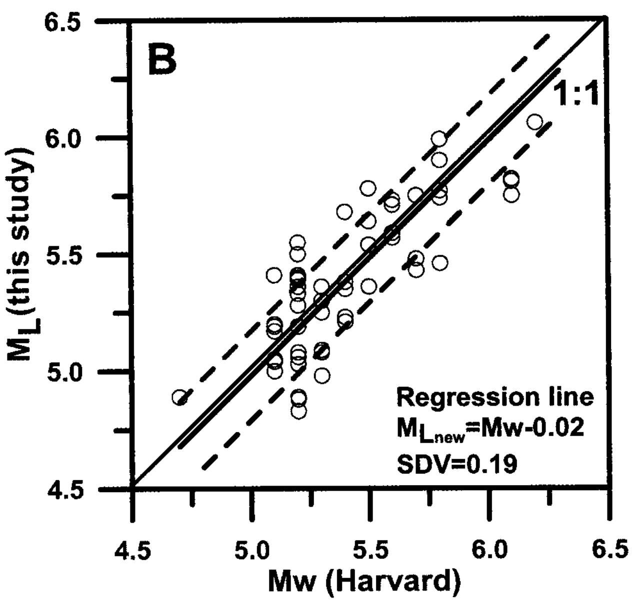




Figure 4. Comparison of $M_{L\_new}$, $M_{L\_CWB}$, and $M_w$ for the 56 events used in this study. (A) $M_{L\_CWB}$ versus $M_w$ showing the relatively high values of $M_{L\_CWB}$ when compared to $M_w$. Note also the wide variance in $M_{L\_CWB}$ estimates. (B) $M_{L\_new}$ versus $M_w$. The average offset between the two is low, 0.02 magnitude units, and the standard deviation is smaller than that in (A) at 0.19.

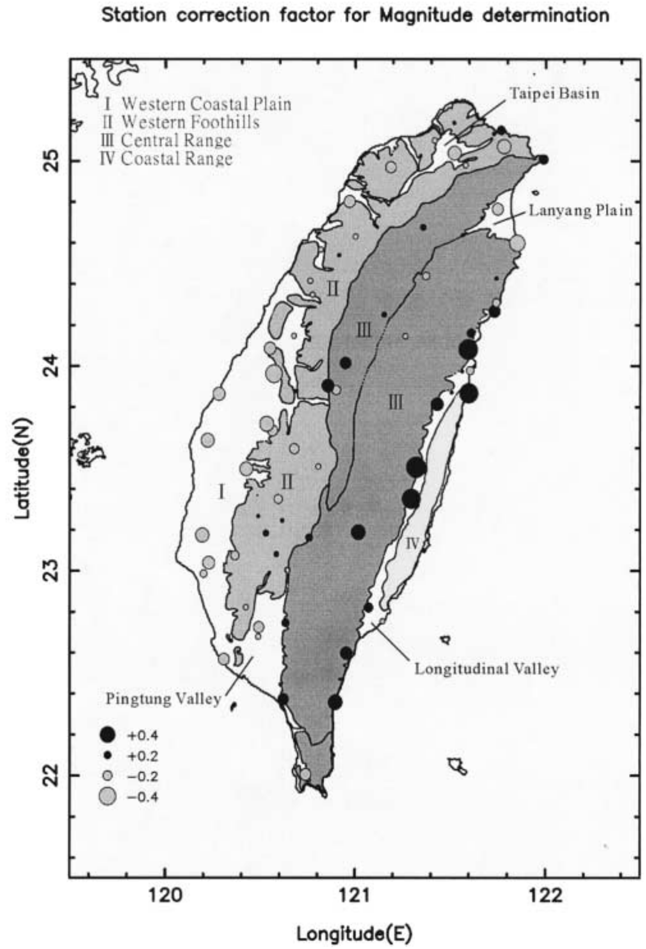



Figure 5. Map of station correction factors and major geological units. Large negative corrections are found at sedimentary sites, while positive corrections are necessary at rock sites.

## References

Alsaker, A., L. B. Kvamme, R. A. Hansen, A. Dahle, and H. Bungum (1991). The $M_L$ scale in Norway, *Bull. Seism. Soc. Am.* **81,** 379–398.

Bakun, W. H., and W. B. Joyner (1984). The $M_L$ scale in central California, *Bull. Seism. Soc. Am.* **74,** 1827–1843.

Centroid Moment Tensor (CMT) Catalog, www.seismology.harvard.edu/CMTsearch.html (last accessed January 2005).

Chavez, D. E., and K. R. Priestley (1985). $M_L$ observations in the Great Basin and $M_0$ versus $M_L$ relationships for the 1980 Mammoth Lakes, California, earthquake sequence, *Bull. Seism. Soc. Am.* **75,** 1583–1598.

Clinton, J. F., K. Solanki, and E. G. Hauksson (2004). An automated moment tensor solution for the Southern California Seismic Network (SCSN), the 2004 AGU fall meeting, 13–17 December 2004, San Francisco, California.

Ebel, J. E. (1982). $M_L$ measurements for northeastern United States earthquakes, *Bull. Seism. Soc. Am.* **72,** 1367–1378.

Gibowicz, S. J. (1972). The relationship between teleseismic body-wave magnitude *m* and local magnitude $M_L$ from New Zealand earthquakes, *Bull. Seism. Soc. Am.* **62,** 1–11.

Greenhalgh, S. A., and R. Singh (1986). A revised magnitude scale for South Australian earthquakes, *Bull. Seism. Soc. Am.* **76,** 757–769.

Hutton, L. K., and D. M. Boore (1987). The $M_L$ scale in southern California, *Bull. Seism. Soc. Am.* **77,** 2074–2094.

Kanamori, H., and P. C. Jennings (1978). Determination of local magnitude, $M_L$, from strong motion accelerograms, *Bull. Seism. Soc. Am.* **68,** 471–485.

Kanamori, H., P. Maechling, and E. Hauksson (1999). Continous monitoring of ground-motion parameters, *Bull. Seism. Soc. Am.* **89,** 311–316.

Kanamori, H., J. Mori, E. Hauksson, T. H. Heaton, L. K. Hutton, and L. M. Jones (1993). Determination of earthquake energy release and $M_L$ using TERRAscope, *Bull. Seism. Soc. Am.* **83,** 330–346.

Kim, W. Y. (1998). The $M_L$ scale in eastern North America, *Bull. Seism. Soc. Am.* **88,** 935–951.

Kiratzi, A. A., and B. C. Papazachos (1984). Magnitude scales for earthquakes in Greece, *Bull. Seism. Soc. Am.* **74,** 969–985.

Lee, W. H. K, and J. C. Lahr (1975). HYPO71 (Revised): a computer for determining hypocenter, magnitude, and first motion pattern of local earthquakes, *U.S. Geol. Surv. Open-File Rep. 75-311*, 114 pp.

Richter, C. F. (1935). An instrumental earthquake scale, *Bull. Seism. Soc. Am.* **25,** 1–32.

Ristau, J., G. C. Rogers, and J. F. Cassidy (2003). Moment magnitude–local magnitude calibration for earthquakes off Canada's West Coast, *Bull. Seism. Soc. Am.* **93,** 2296–2300.

Shin, T. C. (1993). The calculation of local magnitude from the simulated Wood–Anderson seismograms of the short-period seismograms, *TAO* **4,** 155–170.

Spallarossa, D., D. Bindi, P. Augliera, and M. Cattaneo (2002). An $M_L$ scale in northwestern Italy, *Bull. Seism. Soc. Am.* **92,** 2205–2216.

Thurber, C., and D. Eberhart-Phillips (1999). Local earthquake tomography with flexible gridding, *Comp. Geosci.* **25,** 809–818.

Uhrhammer, R. A., and E. R. Collins (1990). Synthesis of Wood–Anderson seismograms from broadband digital records, *Bull. Seism. Soc. Am.* **80,** 702–716.

Wu, Y. M., C. H. Chang, N. C. Hsiao, and F. T. Wu (2003). Relocation of the 1998 Rueyli, Taiwan, earthquake sequence using three-dimensions velocity structure with stations corrections. *TAO* **14,** 421–430.

Wu, Y. M., C. H. Chang, Y. B. Tsai, J. K. Chung, T. C. Shin, and C. Y. Wang (1998). Improvement on earthquake location by using near-source $P + S$ arrivals and $S - P$ time differences, *Proc. of the 7th Taiwan Symposium on Geophysics*, Chungli, Taiwan, 19–20 November 1998, 165–180.

Wu, Y. M., C. C. Chen, T. C. Shin, Y. B. Tsai, W. H. K. Lee, and T. L. Teng (1997). Taiwan Rapid Earthquake Information Release System, *Seism. Res. Lett.* **68,** 931–943.

Wu, Y. M., N. C. Hsiao, T. L. Teng, and T. C. Shin (2002). Near real-time seismic damage assessment of the rapid reporting system. *TAO* **13,** 313–324.

Wu, Y. M., W. H. K. Lee, C. C. Chen, T. C. Shin, T. L. Teng, and Y. B. Tsai (2000). Performance of the Taiwan Rapid Earthquake Information Release System (RTD) during the 1999 Chi-Chi (Taiwan) earthquake. *Seism. Res. Lett.* **71,** 338–343.

Wu, Y. M., T. C. Shin, and C. H. Chang (2001). Near realtime mapping of peak ground acceleration and peak ground velocity following a strong earthquake, *Bull. Seism. Soc. Am.* **91,** 1218–1228.

Wu, Y. M., T. L. Teng, N. C. Hsiao, T. C. Shin, W. H. K. Lee, and Y. B. Tsai (2004). Progress on earthquake rapid reporting and early warning systems in Taiwan, in *Earthquake Hazard, Risk, and Strong Ground Motion*, Y. T. Chen, G. F. Panza, and Z. L. Wu (Editors), Seismological Press, Beijing, 463–486.

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Manuscript received 10 March 2005.