AGSO Journal of Australian Geology & Geophysics, 14, 35–46

Application and extension of the ML earthquake magnitude scale in the Victoria region

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A new function for –logAo has been deduced, and parameters determined using nonlinear regression analysis of data from the Victorian seismograph network. The formula for local magnitude:

$$ML = \log A - \log S - \log Ao$$

where $-\log Ao = 0.7 + \log R + 0.0056Re^{-0.0013R}$

S = site amplification

has been adopted for the Victoria region. The values of –logAo closely follow the trend of Richter's values at medium hypocentral distances. The features of Bakun & Joyner's (1984) formula at close range, which were found to be applicable in Victoria, have been retained. The formula is applicable for distances from a few kilometers, and the maximum distance has been extended from 600 to 1000 km.

The value of logS is closely related to the seismometer foundation, varying from about 0.0 at a bedrock site to more than 0.7 at soft sedimentary sites. The determination and application of site corrections is examined in detail.

Introduction

Magnitude is one of several measures of the earthquake source. The local earthquake magnitude is a single scalar value determined from the peak recorded body wave (P or S) ground motion, corrected for attenuation by a simple function of distance from the source. Ground motion displacement, velocity or acceleration may be used.

The original scale of local earthquake magnitude implemented by Richter (1935, 1958) was based on the maximum amplitude recorded on a standard displacement seismograph. The magnitude ML is related to the log of this amplitude (A) by

$$ML = \log(A/Ao) = \log A - \log Ao \qquad (1)$$

where Ao includes an arbitary reference amplitude chosen to set the zero point on the ML magnitude scale. Sites where surface motion has been amplified, for example by soft sediments, require the application of a site correction.

Richter's data were acquired using Wood–Anderson torsion seismometers. Ao was defined as 10^{-6}m at a distance of 100 km from the epicentre; i.e. an earthquake registering a trace amplitude of 1 mm at a distance of 100 km from the epicentre would be assigned an ML magnitude of 3.0. The magnitude was determined independently for each of the horizontal components and the mean was taken.

Richter defined distance corrections empirically for southern California, and these are not necessarily valid for other regions. The applicability of the scale elsewhere depends upon the establishment of standard values of –logAo as a function of epicentral distance in each region. Richter's values of –logAo for southern California (Richter, 1958) enable the determination of an ML magnitude for earthquakes to an epicentral distance of 600 km. The mean depth of southern Californian earthquakes studied by Richter was thought to be 16 km (Richter, 1958). Richter points out that his –logAo corrections, because of the variation of recorded amplitude with crustal structure and distance, cannot be applied to deep-focus earthquakes.

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At the Seismology Research Centre, Victoria, where the research was carried out, ML magnitudes are obtained from measurements of peak seismogram amplitude and the frequency at this peak, and are computed by an earthquake location program. The response of each seismograph is parametrically defined by transducer output, damping and natural frequency, the recording system gain and filter orders and frequencies. This information is stored on a file, and is automatically accessed using the earthquake date. System response can be checked by curve fitting a calibrating pulse. A calibration pulse at the start and end of each record is used to detect changes in system response.

The Victorian network of seismographs is essentially of two types:

- Sprengnether MEQ–800 single component analogue recorders, and
- triggered digital three-component recorders developed by the Seismology Research Centre.

These recorders are coupled to either Sprengnether S6000, S7000 or Mark Products L4C seismometers. All systems are optimised to record local micro-earthquakes which have dominant frequencies in the 4 to 20 Hertz range. Earthquakes can be located with uncertainties from less than 2 km for events within the network up to tens of kilometers for distant events outside the network. The trigger algorithm on the digital seismographs is designed to record nearby earthquakes, so it is not common for events at a distance greater than a few hundred kilometers to be recorded on these instruments. Figure 1 shows the geographical distribution of the Victorian seismograph sites.

The measured zero-to-peak amplitude is in millimeters from an analogue record, or counts from a digital record, for the larger of P or S motion. For triaxial instruments this is from the component which gives the highest peak value. The frequency corresponding to this peak is measured or estimated and the corresponding ground displacement is then computed. It is assumed that this is the displacement that would give peak response on the standard Wood Anderson seismograph used in the Richter ML definition (gain 2800, period 0.8s, damping 0.8), and this Wood Anderson seismograph response in millimeters and its logarithm (logA) are computed. The gain value of 2800 is a design value and there is evidence that the effective gain of Wood Anderson seismographs is actually about 2000

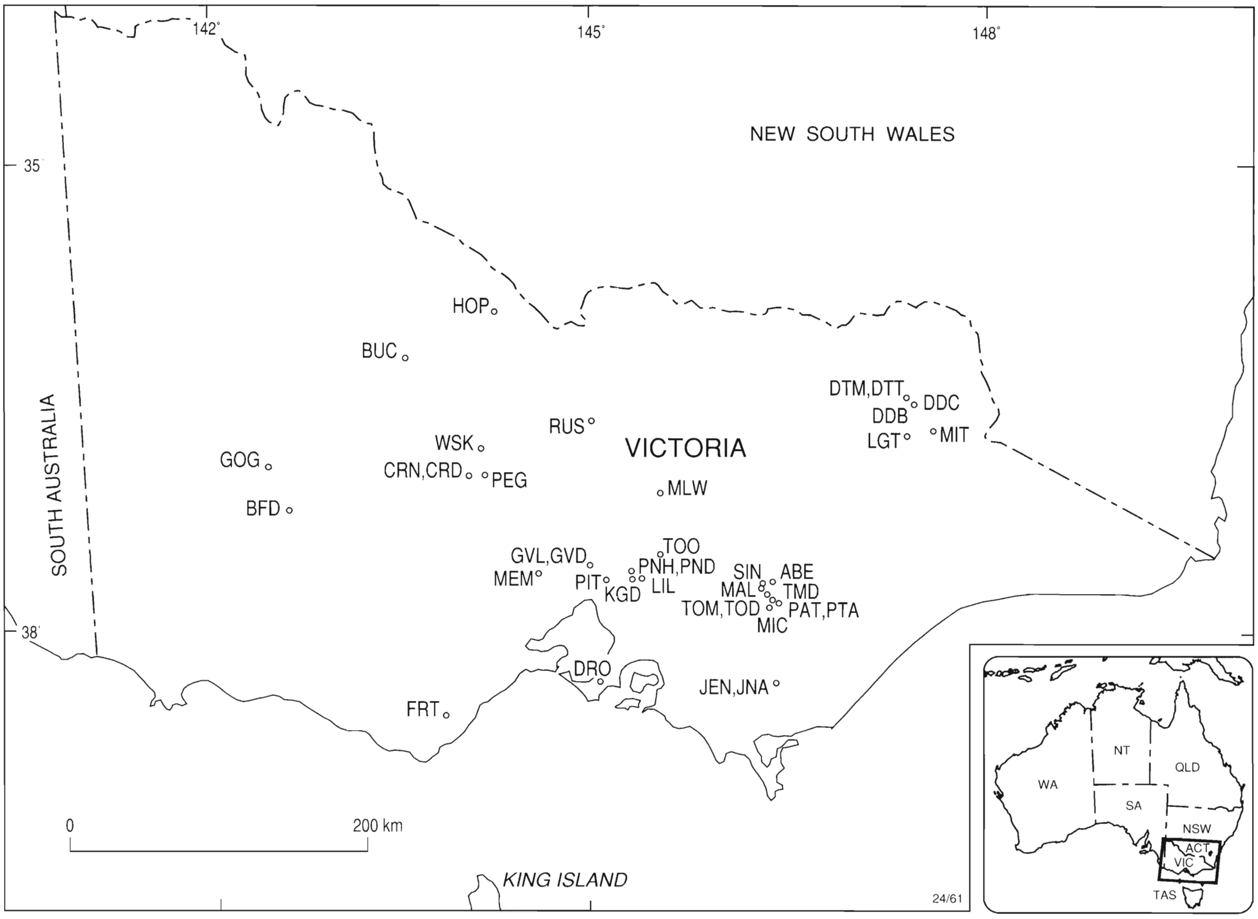

Figure 1. Victorian Seismograph Network.

(Boore, 1989; and Gaull & Gregson, 1991). There appears to be no reason to assume that Richter's instruments had the accepted standard gain of 2800 and standardization to this gain; for example using a multiplier of 1.346 (Gaull & Gregson, 1991) would introduce an error of 0.1 in the assigned magnitudes.

Prior to 1985 at the Seismology Research Centre, the Richter attenuation terms were approximated by a function based on a numerical fit to the Richter values by McGregor & Ripper (1976), but corrected for use with hypocentral distance:

$$-\log Ao = 2.26 + 0.00746R - 0.0000051R^2 \quad (2)$$

R is the hypocentral distance given by $\sqrt{\Delta^2 + h^2}$, where Δ and h are, respectively, the epicentral distance and depth in kilometres. This was valid only for distances up to 600 km; and the R^2 term gave significant errors if the function was used at greater distances.

Cuthbertson (1977), in a study of earthquakes in central Victoria, found no significant variation of ML with epicentral distance, suggesting that the variation in attenuation of seismic waves is similar to that of southern California.

In a study of earthquakes of central California, Bakun & Joyner (1984) found the Richter values of –logAo generally applied, that is, the attenuation characteristics of the crust and upper mantle were similar to those of southern California. Bakun & Joyner found that for hypocentral distances from a few tens of kilometers to over 400 km the values of –logAo were consistent with Richter's values. However, for distances less than 30 km their values of –logAo were significantly greater than those of Richter.

Considering geometrical spreading and anelastic attenuation terms, Bakun & Joyner (1984) derived, by regression analysis, a parametric expression for –logAo:

$$-\log Ao = 0.7 + \log R + 0.00301R \quad (3)$$

Figure 2(a) shows the relation between Richter's values of –logAo and –logAo calculated from Bakun's expression. It is obvious from Figure 2(a) that Bakun's expression is only consistent to about 475 km and beyond that distance deviates from the Richter values.

Figure 2(b) illustrates the deviation of Bakun & Joyner's (1984) values of –logAo from Richter's values at small values of R. Because Richter's values of –logAo are applicable to earthquakes of mean depth 16 km, the minimum value of R for which a Richter value of logAo exists is 16 km. However, earthquakes in California are in general much shallower than 16 km; for example, the earthquakes used in the study by Bakun & Joyner (1984) had a mean depth of approximately 7 km. If this value is used there is a closer fit between Bakun & Joyner and Richter's values of –logAo [Figure 2(c)] indicating that Richter's estimate of average depth was not accurate.

To provide more consistent magnitude values from nearby seismographs, the expression (3) for –logAo for the central

Californian region was adopted at the beginning of 1985 for the calculation of ML magnitudes in Victoria. This reduced the standard deviation of the calculated ML magnitude values for earthquakes, which included epicentral distances less than 30 km and generally increased the magnitude assigned to these earthquakes.

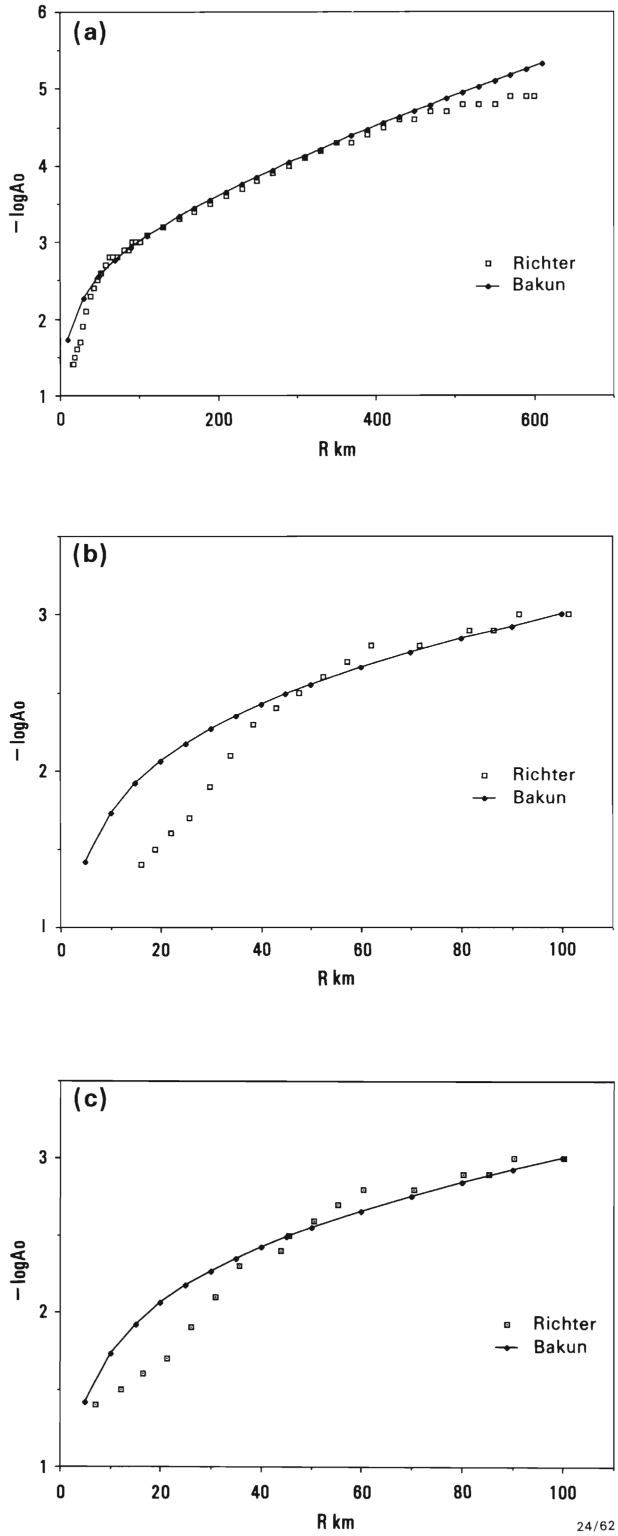

Figure 2(a). Comparison of –logAo from Bakun & Joyner's (1984) expression (3) with Richter's values of –logAo.
Figure 2(b). Comparison of –logAo from Bakun & Joyner's expression (3) with Richter's values (average depth 16 km) at close range.
Figure 2(c). Comparison of –logAo from Bakun & Joyner's expression (3) with Richter's values (average depth 7 km) at close range.

The major seismological recording centres and networks in Australia are for geographic reasons separated by large distances, in many cases of the order of 1000 km. Various organizations, including governments and universities, contribute to the over-all pattern of recording sites (Fig. 3). The recorded seismicity of Australia and the derived seismic risk has in the past been strongly influenced by this distribution (Denham, 1979). In order to have overlap between networks in the assignment of ML magnitudes, thus unifying the scale, it is highly desirable to extend the equivalent of Richter's –logAo values to distances of at least 1000 km.

The length of time for which the Seismology Research Centre Victorian seismographs have been installed varies considerably. The earliest seismographs GVL, PNH, LIL, KGD and TOM were installed in 1976–77 and it is on these seismographs that most of the data relating to earthquakes at ranges greater than 600 km have been recorded. The most recently installed (triggered digital) seismographs have been triggered by few distant earthquakes. Several of the original analogue seismographs PEG, LIL and KGD are no longer operational.

The aims of the following analysis were:

- to extend the use of the Bakun-type parametric magnitude expression (3) to a range of 1000 km
- to derive parameters for the Bakun-type expression which are based on Australian earthquake data, and
- to determine site corrections.

The magnitude function

Examining Bakun & Joyner's (1984) expression for –logAo, the term which significantly contributes to the deviation between Bakun & Joyner and Richter values for large epicentral distances is the term related to the anelastic attenuation, 0.00301R. If the trend followed by Richter's values at large epicentral distances is extrapolated, the term above would have to reduce to approximately 0.0015R at 1000 km.

The relation between the recorded amplitude A of ground motion at a range R from an earthquake hypocentre can be expressed as

$$A = \frac{ESe^{-\gamma R}}{R^{n}} \qquad (4)$$

where E is a parameter related to the earthquake size, S is site amplification, γ is the coefficient of anelastic attenuation and n is a geometrical spreading coefficient (Greenhalgh & Singh, 1986; Nuttli, 1973; Bakun & Joyner, 1984).

$$\gamma = \frac{\pi f}{uQ} \qquad (5)$$

where u is the wave speed, f is the frequency of the wave and Q is the specific quality factor (Bullen & Bolt, 1985, p101).

Taking the logarithm of A, we obtain an expression of the form:

Figure 3. Australian Seismographic Stations, 1989.

$$\log A = \log E + \log S - n\log R - \frac{\gamma R}{\ln 10}$$

Defining M = logE + C will give a logarithmic magnitude scale, where C is a scaling term adjusting the magnitude to the Richter magnitude values.

$$M = \log A - \log S + C + n\log R + \frac{\gamma R}{\ln 10}$$

$$M = \log A - \log S + C + n\log R + KR \qquad (6)$$

$$\text{where } K = \frac{\gamma}{\ln 10} = \frac{\pi f}{\ln 10 uQ} \qquad (7)$$

From (6) and considering the Richter magnitude scale (1), Richter's attenuation term –logAo is in the form used by Bakun & Joyner (1984)

$$-\log Ao = C + n\log R + KR \qquad (8)$$

In this paper we regard the site term, logS, as a correction to ground surface amplitude to give the equivalent motion for an ideal seismograph site. This means that the attenuation term –logAo is simply a function of distance, and does not involve a site correction.

The geometrical spreading coefficient n equals 1 for the spherical spreading of body waves through a homogeneous medium. Regression analysis by Bakun & Joyner (1984) determined n to be close to 1 and they adopted this value. Greenhalgh & Singh (1986), in a study of South Australian earthquakes, determined a value for n of 1.09. In the present study, to avoid a proliferation of parameters, a value of 1 for n was adopted. The other terms then give the difference from spherical spreading.

Using expression (6) and regression analysis Bakun & Joyner (1984) derived the parametric expression (3) for –logAo. Greenhalgh & Singh (1986) determined values of n and K for the South Australian region and obtained the following expression for –logAo

$$-\log Ao = 0.7 + 1.1\log\Delta + 0.0013\Delta \qquad (9)$$

In the studies by Greenhalgh & Singh (1986) and Bakun &

Joyner (1984), K, the parameter in (6) related to anelastic attenuation, was considered to be a constant. However, it is seen from (7) that K is a function of both frequency and wave speed. As R increases, the higher frequency waves are attenuated most, so that the waves determining magnitude decrease in frequency with R. Also, as R increases the waves penetrate to a greater depth near or into the mantle, and consequently the mean wave speed for the wave path increases with R. Both these factors decrease γ and possibly account for the change in K needed to generate Richter's values of –logAo beyond 475 km using Bakun's expression. Other factors, such as guided waves, may also be involved.

Q values depend upon frequency and radial displacement in the earth, varying from the order of 10,000 in the core to a few hundred in the aesthenosphere. Considerable variation in Q even within the lithosphere occurs, varying, for example, from approximately 1000 in the eastern United States to 200 in western United States (Aki, 1980). The frequency dependence of Q also varies from region to region. For seismically active regions there is a peak in Q^{-1} between 0.5 and 1 Hz, but for seismically stable areas, such as eastern and central United States, Q^{-1} is a constant or decreases monotonically with frequency (Aki, 1980). Rautian & Khalturin (1978) experimentally determined $Q = 360\sqrt{f}$. In other studies, Q proportional to f^m has been used, where m is between 0 and 1 (Bullen & Bolt, 1985, p.451). It appears that a reasonable assumption would be that either Q can be taken as independent of frequency or Q varies as some fractional power of frequency. In either case, since frequency is a term in the numerator in expression (5), γ will decrease with decreasing frequency which is the required trend.

Thus, we can anticipate that K will decrease with increasing R and also depend upon the regional attenuation characteristics. The variation of K with R is evident when the values of K from the various parametric expressions for –logAo are examined with respect to the maximum values of R for which the expressions were derived:

K	**Maximum R**	
0.00301	475 km	Bakun & Joyner (1984)
0.0013	600 km	Greenhalgh & Singh (1986)
0.00189	700 km	Hutton & Boore (1987)
0.000657	2000 km	Gaull & Gregson (1991)

In accordance with our aim to extend the use of the parametric expression to 1000 km, the 0.00301R of (3) was replaced by an exponent term giving the new expression:

$$-\log Ao = p1 + \log R + p2Re^{-p_3R} \qquad (10)$$

with parameters p_1, p_2 and p_3.

The choice of the form of the term $p_2Re^{-p_3R}$ was made to give the minimum and simplest change to the term KR, yet accommodate the trend of the decreasing proportional contribution of the term with R shown in the above values of K and the trend of the Richter values with distance beyond 500 km (Fig. 2a).

Assuming the parameters p_2 and p_3 are related to the seismic wave path, p_1 includes the site term logS which adjusts the value of logA to accommodate the site characteristics, and the constant C , from (8), adjusting the magnitude so that it is numerically equivalent to the original Richter magnitude.

ML magnitudes were obtained using measurements of peak seismogram amplitude and the frequency at this peak, and were computed using

$$ML = \log A + p1 + \log R + p2Re^{-p_3R} \qquad (11)$$

where A is the amplitude which would have been registered by Richter's standard Wood–Anderson seismograph and

$$p1 = -\log S + C \qquad (12)$$

Evaluation of parameters

Non-linear regression analysis was applied to the earthquake data for each seismograph site, giving values of the parameters p_1, p_2 and p_3 which minimise the standard deviation of the assigned and calculated values of ML magnitude. The magnitude assigned to an earthquake was the mean of the values available from the Victorian network, calculated using the Bakun & Joyner (1984) expression (3) for –logAo, and those determined by other seismograph networks.

Table 1 gives the values of the parameters resulting from the regression analysis of the data for each seismograph with the standard deviation of the values of ML magnitude calculated using expression (11) from the values of ML magnitude assigned to the earthquakes used. This analysis included all data with epicentral distances ranging from a few kilometers to over 1000 km. For the seismograph stations MEM, BUC, HOP, and TMD, no data for earthquakes with epicentral distances greater than 475 km were available. The seismograph station MIC had no data for earthquakes beyond 295 km and this accounts for the negative value for p_3, and station MAL, which had a very small negative value for p_3, had only one earthquake in its data set beyond 400 km; hence application beyond this distance is invalid.

When Bakun & Joyner's (1984) expression in the form

$$ML = \log A + p1 + 0.7 + \log R + 0.00301R \qquad (13)$$

(where p_1 can be regarded as a statistical station correction) was applied to the data from the analogue, stations which included significant numbers of earthquakes with epicentral distances greater than 475 km, the average standard deviation of the Bakun & Joyner ML values from (13) with respect to the assigned ML value was approximately 0.55, emphasizing the inappropriateness of (3) for values of R greater than 475 km. Also, when regression analysis was used to find a value of K appropriate for data to 1000 km range, a value of K less than 0.00301 was obtained, but the standard deviation for data with R less than 475 km then significantly increased.

Table 2 shows the results of regression analysis of the application of Bakun & Joyner's expression (13) to the data for all seismographs restricted to only those earthquakes whose epicentral distance from the seismograph was less than 475 km, i.e. selecting the range of epicentral distances over which the Bakun expression should apply.

Table 1. Parameter values and standard deviations derived using nonlinear regression analysis with expression (11).

SITE CODE	*p1*	*p2*	*p3*	*SD*	*N*
GVL	0.538	0.00563	0.00128	0.20	51
PNH	0.488	0.00710	0.00153	0.26	52
TOM	0.685	0.00491	0.00114	0.29	50
LIL	0.417	0.00747	0.00166	0.26	35
KGD	0.223	0.00834	0.00167	0.20	29
JEN	0.748	0.00456	0.00117	0.28	31
PEG	0.431	0.00503	0.00121	0.29	49
FRT	0.420	0.00453	0.00103	0.27	29
ABE	0.500	0.00369	0.00117	0.28	100
TOD	0.216	0.00426	0.00064	0.35	107
PAT	0.271	0.00386	0.00049	0.38	94
MEM	0.268	0.00520	0.00131	0.23	13
BUC	0.582	0.00637	0.00234	0.32	22
HOP	0.553	0.00765	0.00168	0.27	50
MIC	0.140	0.00083	−0.00383	0.36	63
MAL	0.860	0.00087	−0.00062	0.31	41
TMD	0.104	0.01450	0.01633	0.26	29

(i) SD is the standard deviation of the calculated values of ML magnitude and the assigned ML values for each earthquake.

(ii) N is the number of earthquakes used for each site analysis.

(iii) Epicentral distance range, 0 to 1000 km.

(iv) The first eight seismographs are analogue instruments, the others digital.

Table 3 allows a direct comparison of the standard deviations achieved with the revised expression (11) (henceforth for clarity called the Wilkie expression) from Table 1 for all data , with the standard deviations resulting from the application of Bakun & Joyner's expression (13) to the restricted (less than 475 km) data set (Table 2).

Table 2. Values of parameter and standard deviation resulting from regression analysis using Bakun & Joyner's expression (13) with R<475 km.

SITE CODE	*p1*	*SD*	*N*
GVL	0.070	0.19	30
PNH	0.133	0.28	40
TOM	0.079	0.32	41
LIL	0.079	0.30	28
KGD	0.017	0.19	23
JEN	0.066	0.28	24
PEG	−0.105	0.22	30
FRT	−0.184	0.25	22
ABE	−0.185	0.29	98
TOD	−0.401	0.35	105
PAT	−0.383	0.38	93
MEM	−0.293	0.24	13
BUC	−0.024	0.33	22
HOP	−0.011	0.30	50
MIC	−0.682	0.36	63
MAL	−0.031	0.37	40
TMD	−0.535	0.30	29

For the analogue seismographs, where from 20 to 40% of the data for each site were for earthquakes with epicentral distances from 475 to 1000 km, the standard deviations in most cases are less for the Wilkie expression applied to all data compared to the Bakun & Joyner expression applied to the restricted data. In the case of the digital seismographs, where almost 100% of the data were for earthquakes whose epicentral distance was less than 475 km, for which the Bakun & Joyner expression is applicable, the Wilkie expression gave a lower standard deviation in all cases compared to the Bakun & Joyner expression standard deviation.

Attenuation for Victoria

In Table 1, the positive correlation between p_2 and p_3 is obvious for the analogue stations and if the term $p_2Re^{-p_3R}$ in (11) is to be a general attenuation term for the Victorian or southeastern Australian region, constant values of p_2 and p_3 need to be adopted. The mean values of p_2 and p_3 were approximately 0.0056 and 0.0013, respectively, and coincide with the values computed for the seismograph station GVL, which is the seismograph with the greatest percentage of earthquakes with epicentral distances greater than 475 km.

The above values for p_2 and p_3 were adopted, and further regression analysis of the data was computed using

$$ML = \log A + p1 + \log R + 0.0056Re^{-0.0013R} \quad (14)$$

Table 4 shows the computed values of the parameter p_1 and the standard deviations of the calculated ML values with respect to the assigned ML values for each site. The adoption of the values of p_2 and p_3 resulted in all cases in a minimal increase in the standard deviation relative to the values in Table 3.

Table 3. Comparison of the standard deviations achieved with the Wilkie expression (11) for R from a few km to 1000 km, with the standard deviations resulting from the application of the Bakun & Joyner expression (13) to data with R less than 475 km.

SITE CODE	*WILKIE FORMULA* *SD from Table 1 (all data)*	*Bakun & Joyner FORMULA* *SD from Table 2 (data <475 km)*
GVL	0.20	0.19
PNH	0.26	0.28
TOM	0.29	0.32
LIL	0.26	0.30
KGD	0.20	0.19
JEN	0.28	0.28
PEG	0.29	0.22
FRT	0.27	0.25
ABE	0.28	0.29
TOD	0.35	0.35
PAT	0.38	0.38
MEM	0.23	0.24
BUC	0.32	0.33
HOP	0.27	0.30
MIC	0.36	0.36
MAL	0.31	0.37
TMD	0.26	0.30

The Bakun standard deviations from Table 2 have been included in Table 4 enabling a rough comparison of the performance of the two expressions: Wilkie applied to all

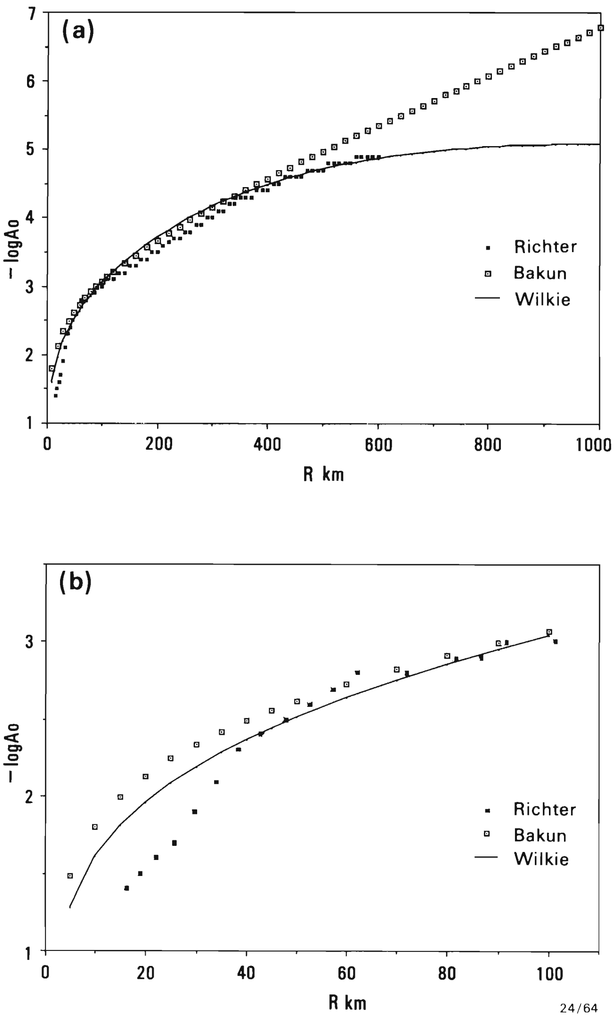

Figure 4(a). Comparison of Richter (1958), Bakun & Joyner (1984) and Wilkie (present study) expressions to a range of 1000 km.
Figure 4(b). Comparison of Richter, Bakun & Joyner and Wilkie expressions at close range.

data to 1000 km and Bakun & Joyner applied to data restricted to epicentral distances less than 475 km. The mean of the standard deviations for the former was 0.30 and for the latter 0.29. As described above, if the Bakun & Joyner formula was used with all data to 1000 km, the standard deviation was 0.55.

Figures 4(a) and 4(b) show plots, for the GVL seismograph, of the three estimates of –logAo considered, including the site corrections (GVL site correction 0.07, for Bakun & Joyner, is taken from Table 2):

–logAo empirical values Richter, 1958

$$-\log S - \log Ao = 0.07 + 0.7 + \log R + 0.00301R$$ Bakun& Joyner (modified)

$$-\log S - \log Ao = 0.55 + \log R + 0.0056Re^{-0.0013R}$$ Wilkie (present study)

The Wilkie expression retains the features of Bakun & Joyner's expression at short epicentral distances giving higher values of –logAo than Richter. It agrees closely with Richter (1958) and Bakun & Joyner (1984) to approximately 450 km, but then follows the required trend of the Richter values out to 600 km. The Wilkie expression then extends the estimate of –logAo to 1000 km, achieving over the whole range of epicentral distance the same standard deviation for computed ML magnitudes with respect to the assigned ML magnitude as the Bakun & Joyner expression gave for the data restricted to epicentral distances less than 475 km.

Table 4. Values of p_1 and standard deviations resulting from the application of expression (14). Standard deviations from the application of Bakun & Joyner's expression (13) with R <475 km has been included for comparison.

WILKIE FORMULA (p_2 = 0.0056, p_3 = 0.0013) (applied to all data to 1000 km)				*Bakun & Joyner FORMULA* (restricted data <475 km)
SITE	p_1	*ERROR*	*SD*	*SD*
GVL	0.55	0.05	0.20	0.19
PNH	0.66	0.07	0.26	0.28
TOM	0.62	0.08	0.29	0.32
LIL	0.58	0.09	0.27	0.30
KGD	0.53	0.08	0.22	0.19
JEN	0.59	0.10	0.29	0.28
PEG	0.36	0.08	0.29	0.22
FRT	0.33	0.10	0.28	0.25
ABE	0.36	0.06	0.29	0.29
TOD	0.17	0.07	0.36	0.35
PAT	0.19	0.08	0.38	0.38
MEM	0.21	0.13	0.23	0.24
BUC	0.58	0.14	0.33	0.33
HOP	0.62	0.08	0.27	0.30
MIC	–0.11	0.10	0.38	0.36
MAL	0.52	0.12	0.38	0.37
TMD	0.04	0.12	0.34	0.30
		Mean	0.30	0.29

ERROR = 2* standard error in p_1

Site corrections

In determining magnitudes, Richter (1958) applied station corrections which were determined statistically from the systematic deviation of the magnitude determined by a particular seismograph from the mean magnitude. Richter associated this correction with the local ground and installation conditions. Likewise associated with their parametric expression for –logAo, Bakun & Joyner (1984) applied station corrections which ranged from –0.6 to +0.4 and closely associated these corrections with local geology, rock sites giving positive corrections and sedimentary sites giving negative corrections.

ML magnitudes calculated for individual sites and recorded in the earthquake location files at the Seismology Research Centre, were used to calculate a site correction with respect to the adopted ML magnitude. The initial analysis used data for 1984–86. Only earthquakes whose magnitude was computed at three or more sites were included.

The range of magnitude (approximately 0 to 3) for which the corrections were calculated for Victoria varied from site to site, depending on the seismic activity in the vicinity and the proximity of other recording sites to enable an estimate of earthquake magnitude. However, plots of site correction against magnitude for the sites TOD, TMD, GVL and FRT, respectively, showed no statistically justifiable variation in the correction with respect to magnitude.

This conclusion is also supported by evidence from Bougainville Island, New Guinea, where Seismology Research Centre seismographs were operated at several sites. The range of ML magnitude, 3 to 6, and depth range, 0 to 500 km, associated with plate subduction in one of the most seismically active regions of the world, are in strong contrast to the intraplate Victorian micro-earthquakes. Plots of site corrections, which were of the order of –1.0, against magnitude showed in all cases corrections independent of magnitude.

Table 5. Mean ML magnitude site corrections 1984–86

SITE CODE	*CORRECTION*	*SD*	*N*	
MLW	0.14	0.28	207	
PNH	0.27	0.26	262	
TMD	–0.61	0.28	60	
GVL	0.13	0.18	251	
FRT	–0.52	0.18	45	
TOD	–0.26	0.25	96	
TOM	–0.17	0.22	222	Jan'84–Nov'85
TOM	0.05	0.21	123	Nov'85–Dec'86
PEG	–0.22	0.23	154	
JEN	0.19	0.30	188	
MEM	–0.43	0.15	7	
HOP	0.43	0.12	14	Jan'84–Sept'84
HOP	0.28	0.25	33	Oct'84–Dec'86
BUC	–0.01	0.23	31	
MAL	0.28	0.27	41	
PAT	–0.41	0.25	87	
ABE	–0.04	0.20	77	
MIC	–0.50	0.21	45	

Over the range of the first few tens of kilometres there is a rapid change in the frequencies recorded during an earthquake and a special investigation of the possibility of variation of site correction with R at small values of R was made; however, no evidence of variation was found.

Therefore, considering the above, it appears that a site correction, independent of magnitude, can be applied in the computation of ML magnitude for each seismograph. There is considerable evidence that ground motion is amplified at sedimentary foundation sites, especially the horizontal components (Phillips & Aki, 1986). On a logarithmic magnitude scale any amplification will appear as a constant correction and site amplification appears to be the main contribution to site corrections.

The site corrections with the number of earthquakes used and standard deviations for 1984–86 data are shown in Table 5. In order to confirm these corrections, the 1987–89 Victorian earthquake ML magnitude data were analysed for site corrections. The results are shown in Table 6, which includes the 1984–86 site corrections for comparison. In most cases, the corrections are closely confirmed. The change at MAL is due to the conversion in January 1988 from a vertical component to a triaxial seismograph, the change at HOP is due to the installation of some nearby seismographs thereby influencing the magnitudes assigned to earthquakes. However, no reason can be found for the change in site correction at PEG and FRT.

Further investigation of mean ML site corrections was carried out to try to eliminate the effects of site groupings; for example, where most nearby sites record only the vertical component or nearby sites are mainly on sediment and consequently register higher ML magnitudes due to amplification. Only earthquakes for which at least eight values of ML magnitude had been computed were used. This gave, for each earthquake, an assigned magnitude derived from seismographs with a wide variety of foundations, thus minimising local effects.

Table 6. Mean ML magnitude site corrections 1984–86 and 1987–89.

SITE	*1984–86*	*1987–89*
MAL	0.28	0.08
HOP	0.28	0.11
PNH	0.27	0.25
JEN	0.19	0.12
GVL	0.13	0.15
TOM	0.05	0.00
BUC	0.00	–0.05
ABE	–0.04	–0.09
PEG	–0.22	–0.46
TOD	–0.26	–0.30
PAT	–0.41	–0.50
MIC	–0.50	–0.51
FRT	–0.52	–0.14
TMD	–0.61	–0.66

The mean ML site corrections 1987–89 can be compared with the corrections for 1987–89 using only earthquakes with at least 8 computed ML magnitudes in Table 7. The sites with analogue recorders, detecting only the vertical component, have had their mean ML correction increased by approximately 0.1, whereas the corrections for sites with triaxial seismographs have generally remained constant.

An interpretation of this is that the smaller earthquakes, normally recorded at fewer than eight sites, can be detected by the analogue seismographs, but do not trigger the triaxial digital instruments. When the triaxial seismographs are triggered by the larger earthquakes, the horizontal components are used to determine the ML magnitude. Since the amplitude of the vertical component is generally less than the horizontals, the triggering of the triaxial instruments results in a higher magnitude being assigned to the earthquake and as a consequence the mean ML site correction for each analogue site will be increased. Implications of this will be discussed in a later paper.

Likewise when the triaxial sites are considered, both HOP and WSK have the largest increase in site correction. Often these seismographs are triggered by nearby earthquakes which are usually recorded only by the analogue seismographs. When larger earthquakes are considered, the increase in mean ML site correction can be attributed to the triggering of most of the triaxial seismographs and a consequent increase in the ML magnitude assigned to the earthquake.

Considering the above, the mean ML site corrections adopted were those indicated by using more than 8 ML magnitude values.

Table 7. Comparison of site corrections (1987–89) determined using three or more magnitude values with site corrections calculated when eight or more magnitude values were available.

SITE	*>=8 ML values*	*>=3 ML values*	*site foundation*	*components*
GVL	0.22	0.15	granite	Z
TOM	0.07	0.00	weathered granite	Z
TOD	–0.30	–0.30	weathered granite	ENZ
ABE	–0.07	–0.09	Palaeozoic sediment	ENZ
BEL	–0.23	–0.31	Palaeozoic sediment	ENZ
JEN	0.17	0.12	Cretaceous sediment	ENZ
WSK	0.02	–0.10	Palaeozoic sediment	ENZ
MLW	0.33	0.19	granite	Z
HOP	0.23	0.11	granite	ENZ
PAT	–0.53	–0.50	Palaeozoic sediment	ENZ
DRO	–0.02	–0.07	weathered granite	Z
PNH	0.37	0.25	Silurian sediment	Z
FRT	–0.12	–0.14	Cretaceous sediment	Z
BUC	0.01	–0.05	granite	ENZ
MIC	–0.53	–0.51	weathered granite	ENZ
TMD	–0.67	–0.66	rock fill dam	ENZ
CRN	0.35	0.11	granite	Z
RUS	–0.30	–0.32	Palaeozoic sediment	ENZ
MAL	0.16	0.08	hornfels	ENZ
PEG	–0.35	–0.46	Tertiary sediment	Z

E East–West component

N North–South component

Z Vertical component

The mean ML magnitude site corrections with their corresponding geological foundation are shown in Table 7. Phillips & Aki (1986) found an inverse relationship between site amplification and the age of sediment. There is no evidence of such a relationship in Table 7, apart from granite bedrock sites being in general the sites corresponding to the least amplification and a rock fill dam, representing very recent sediment, giving the greatest site amplification.

Figure 5 shows the mean ML site correction plotted against the corresponding value of p_1 from Table 4. The approximate linear nature of this plot indicates a direct relationship between the parameter p_1 and the mean ML site correction. It was previously assumed that p_2 and p_3 in expression (11) were related to path and p_1 to seismograph foundation. Figure 5 confirms the validity of this assumption.

It appears that the maximum value of p_1 is about 0.7. The triaxial sites which have a value of p_1 close to 0.7 are the rock foundation sites (Table 7); therefore, a value of 0.7 for p_1 can be thought of as the value corresponding to the ideal rock seismograph site. Since $p_1 = -\log S + C$ (12) and defining logS for an ideal site to be 0.0, the value of C is 0.7.

$$ML = \log A - \log S + 0.7 + \log R + 0.0056Re^{-0.0013R} \quad (15)$$

The attenuation function for Victoria is

$$-\log Ao = 0.7 + \log R + 0.0056Re^{-0.0013R} \quad (16)$$

The site term, logS, is a correction relative to the ideal hard rock site and is related to the site foundation amplification used in many earthquake building codes.

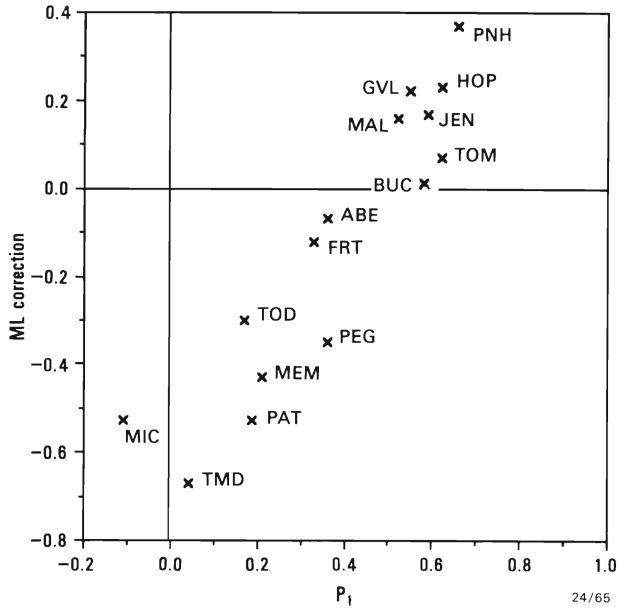

Figure 5. Plot of seismograph site correction versus p_1 from (14). Corrections for each site are the average differences between the magnitudes computed using the original Bakun & Joyner expression (13) and the assigned magnitude for each earthquake.

The site term can be determined for new sites as soon as a statistically reliable mean ML magnitude site correction can be determined. The site terms for the seismograph sites in this study are listed in Table 8.

The expressions of Greenhalgh & Singh (1986), Gaull & Gregson (1991), and Wilkie (this study) for –logAo are shown below for comparison:

$-\log Ao = 0.7 + 1.1\log\Delta + 0.0013\Delta$ Greenhalgh & Singh (1986)

$-\log Ao = 0.66 + 1.137\log R + 0.000657R$ Gaull & Gregson (1991)

$-\log Ao = 0.7 + \log R + 0.0056Re^{-0.0013R}$ Wilkie (present study)

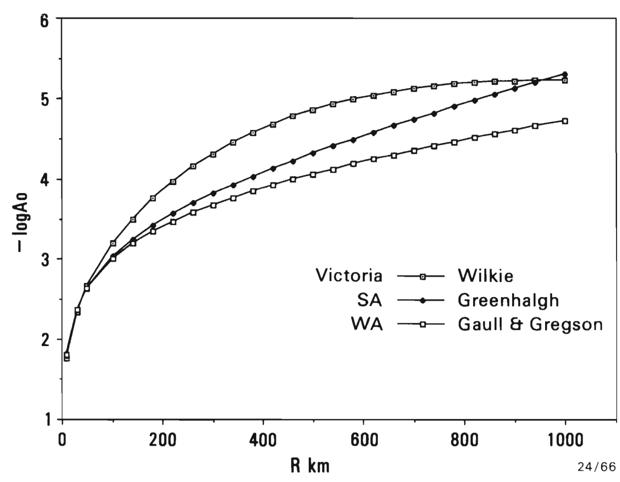

Figure 6. Comparison of Australian attenuation expressions.

Table 8. Site terms, logS, to be applied in expression (15) for the calculation of ML magnitudes.

SITE	*SITE TERM (logS)*
GVL	0.15
PNH	0.04
TOM	0.08
LIL	0.12
KGD	0.17
JEN	0.11
PEG	0.34
FRT	0.37
ABE	0.34
TOD	0.53
PAT	0.51
MEM	0.49
BUC	0.12
HOP	0.08
MIC	0.81
MAL	0.18
TMD	0.66

Figure 6 shows a comparison of the Australian expressions for –logAo, emphasising the lower attenuation for South Australia and Western Australia compared with that for Victoria. Part of the difference is due to the different definition of the site correction. Both Greenhalgh & Singh and Gaull & Gregson relate the site correction to an 'average' site, while the Wilkie expression relates it to a typical bedrock site, giving a difference of about 0.2, depending on the nature of the 'average' site in South Australia or Western Australia. The near-linear variation of –logAo with R at large distances for the South Australian and Western Australian expressions shows the dominance of the KR term in (6).

In order to confirm the correctness of the above formula and corrections, magnitudes were recalculated for a fresh sample of 35 earthquakes, most of which had a magnitude of 2 and above to ensure that a reasonable number of seismographs recorded each event. The results were:

- Comparing the old and new values of mean magnitude for each earthquake, it was found that the mean difference over all earthquakes in the sample was less than 0.04, the new values being less than the old. This result would be expected, because by choosing the larger events many were recorded at the high amplification sites in the Thomson Reservoir area and hence had their mean magnitude reduced.

- Those earthquakes recorded at a set of sites with low magnification had their magnitude increased, and those recorded at a set of sites including some high magnification sites had their magnitude decreased. Some events had a change of –0.2, when high amplification sites such as MIC and TMD were involved. Remembering that overall the old magnitudes assigned depend upon the subset of seismographs recording a particular event, but the site corrections are with respect to the total set of Victorian seismographs with a range of site amplifications involved, the above result would be expected

- The standard deviation of the magnitude values for the sites recording a particular earthquake was on average reduced by a factor of 0.7, and in many cases where the high amplification sites were involved the standard deviation was halved.

Table 9 shows two examples of the reassessment of magnitude described above, one for an event at Mt Selma close to the Thomson Reservoir higher amplification sites, and the other at Benambra in eastern Victoria. In both cases, the standard deviation of the individual magnitude values was substantially reduced. In the case of the Benambra event, the new mean magnitude is greater than the old, and for the Mt Selma event the new magnitude is less than the old, consistent with the application of site corrections adopted with respect to the total set of Victorian seismograph sites.

Table 9. Reassessment of magnitudes for two Victorian earthquakes showing substantial reduction in the standard deviation of individual magnitude values.

	Mt Selma		*Benambra*	
SITE	*ML old*	*ML new*	*ML old*	*ML new*
GVL	1.8	1.9	2.3	2.4
PNH	1.6	1.8	2.1	2.4
TOM	2.0	1.9	2.2	2.3
TOD	1.9	1.5		
MIC	2.5	1.8		
PAT	2.3	1.9		
ABE	2.1	1.9		
MAL	1.8	1.7		
TMD	2.3	1.7		
JEN	1.4	1.5	2.3	2.5
PEG	1.9	1.9	3.0	2.9
MLW			2.3	2.5
DRO			2.2	2.3
mean	1.96	1.77	2.34	2.47
stand. dev.	0.32	0.16	0.30	0.20

The extended range of the formula was tested on two well-documented earthquakes:

- The Lithgow earthquake on 13th February 1985, magnitude 4.3 (Michael-Leiba & Denham, 1987).
  It was possible to measure the magnitude of this earthquake at six Victorian network sites with ranges extending from 586 to 667 km.
  The mean magnitude was 4.4 (standard deviation 0.19) compared with a value of 4.3±0.2 assigned to the earthquake.

- The Newcastle earthquake on 28th December 1989, magnitude 5.6 (McCue & others, 1990).
  This earthquake was offscale on most of the Victorian network analogue seismographs, but eight magnitude values could be computed, with site ranges extending from 708 to 940 km. The mean magnitude was 5.9 (standard deviation 0.32) compared with a value of 5.6 adopted from a variety of sources (mainly conversions from other magnitude scales and indirect measures such as duration and isoseismal radii) with no estimate of error. The direction of the fault was northwest–southeast, giving a maximum of shear-wave radiation to the southwest in the direction of the Victorian seismograph sites.

One would expect that the Victorian network with its wide variety of site foundations, dictated to some extent by logistics associated with specialized projects, would give higher values of magnitude compared with those from bedrock sites normally selected for seismic observatories, when more flexible site location is possible. This is an example of one of the features of the Richter scale which make its world wide portability difficult.

It must be noted that this study does not define the new Victorian scale to be consistent with that in southern California. Use of magnitudes as previously computed in the regression for p_1, p_2 and p_3 means that the Victorian datum remains essentially unchanged.

Discussion

The assignment of a magnitude to an earthquake is a simple concept: the magnitude is a number representing a measure of the earthquake 'size' determined from a seismogram according to a prescribed procedure. Complexity arises from the many factors influencing the propagation of seismic waves which are used to measure magnitude. These factors include asymmetry in the source radiation pattern, frequency dependent attenuation, variation in attenuation depending on the propagation path which varies with R, and seismograph site amplification.

Ideally, each seismograph recording of a particular earthquake should give the same magnitude irrespective of seismograph site foundation or R. This consistency will not be achieved in practice because of the many variables involved. Some of these variables have been studied in this investigation. By the separation of parameters which represent path and site, combined with a knowledge of the influence of the components used in the magnitude measurement, a reduction in the standard deviation of the computed magnitudes can be achieved, and a magnitude can be assigned keeping in mind the overall quality of the network sites used in the assessment.

The new expression for attenuation is:

$$-\log Ao = 0.7 + \log R + 0.0056Re^{-0.0013R}$$

This is a simple arbitary function used to fit the variation of amplitude with distance, and it is possible that other more complex functions will give a better fit. The constants 0.0056 and 0.0013 are appropriate for southeast Australian earthquakes, and may differ in other regions. The constant 0.7 is a scaling term, used to adjust magnitude values to the original Victorian magnitude values. Unification to the original Richter magnitude values depends on the difference in attenuation between California and Victoria, and on the difference in site amplification at average seismograph sites in California (1935) and Victoria (1987–89).

Extension of the parametric expression for –logAo to a range of 1000 km opens the possibility of other networks doing a similar analysis; thus, with the extended range, several networks can assign an ML magnitude to an earthquake giving a unification of the local magnitude scale Australia-wide.

We have seen that the seismograph sites have a major influence on ML magnitude assignment. At most sedimentary foundation sites there is amplification of the horizontal components, and a different magnitude will be determined for an earthquake depending on the combination of foundation conditions at the recording sites. For example, an ML magnitude assigned from seismographs all located on bedrock sites would be of the order of 0.5 less than that assigned by a network of seismographs on sedimentary sites. This difference can be very significant when site corrections are of the order of –1.0, as experienced in Bougainville.

The relationship in Figure 5 shows that the site term logS, which we define as a correction with respect to an 'ideal' site, could partially solve this problem. On the assumption that bedrock sites are normally sought by seismologists, then the local magnitude scale needs to be defined so that the assigned magnitude is that from the mean of equivalent bedrock sites in order to eliminate the lack of definition with respect to site combination choice.

The definition of the site term relative to a rock site, rather than an 'average' site, links this correction to site amplification as used in earthquake building codes.

Although the Richter local magnitude scale has been adopted world wide, it is not a portable scale and is only defined for southern California. The problem lies in the definition of the zero magnitude earthquake in terms of an earthquake at a distance of 100 km from the recording site. This immediately involves the southern Californian attenuation factors and therefore makes the portability of the scale difficult.

The result of using the new attenuation function and the site corrections defined is to give negligible change in the average magnitude for most Victorian earthquakes, a reduction in the standard deviation of magnitudes computed from different seismographs for each earthquake and the ability to compute magnitudes to a distance of 1000 km rather than 600 km.

Acknowledgments

The authors thank S. Greenhalgh and D. Denham for their detailed and helpful reviews of the paper, and AGSO for the supply of seismic information used in the project. J. Wilkie wishes to thank the Victoria University of Technology for supporting the research with a grant of PEP leave.

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