Australian Earthquake Engineering Society 2010 Conference, Perth, Western Australia

# The influence of attenuation in earthquake ground-motion and magnitude estimation: implications for Australian earthquake hazard

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## Abstract

Geoscience Australia (GA) is currently undertaking the process to update the Australian National Earthquake Hazard Map using modern methods and an extended, more complete catalogue of Australian earthquakes. This map is a key component of Australia's earthquake loading code. The characterisation of strong ground-shaking using Ground-Motion Prediction Equations (GMPEs) underpins any earthquake hazard assessment. Recently there have been many advances in ground-motion modelling for active tectonic regions. However, the challenge for Australia – as it is for other stable continental regions – is that there are very few ground-motion recordings from large-magnitude earthquakes with which to develop empirically-based GMPEs. Consequently, there is a need to consider other numerical techniques to develop GMPEs in the absence of recorded data. Recently published Australian-specific GMPEs, which employ these numerical techniques, are now available and these will be integrated into GA's future hazard outputs.

This paper addresses several fundamental aspects related to ground-motion in Australia that are necessary to consider in the update of the National Earthquake Hazard Map, including: 1) a summary of recent advances in ground-motion modelling in Australia; 2) a comparison of Australian GMPEs against those commonly used in other stable continental regions; and 3) the impact of updated attenuation factors on local magnitudes in Australia. Specific regional and temporal aspects of magnitude calculation techniques across Australia and its affects on the earthquake catalogue will also be addressed.

**Keywords:** attenuation, ground-motion prediction equations, local magnitude

## INTRODUCTION

One of the key challenges in assessing earthquake hazard in Australia is in understanding the attenuation of ground-motion through the continental crust. Many earthquake scientists understand the importance of being able to calculate the attenuation of seismic energy at different periods for earthquake hazard assessments using ground-motion prediction equations (GMPEs). Selection of appropriate GMPEs is often considered one of the largest contributors to uncertainty in seismic hazard analyses (F. Scherbaum, pers comm., 2008). However, in contemporary earthquake hazard assessments, the role that attenuation plays for calculating earthquake magnitudes is often forgotten. A catalogue of earthquakes, where the local magnitudes were calculated by an inappropriate equation, is likely to have an equally important impact on hazard as the uncertainties associated with selecting GMPEs. Poor estimates of earthquake magnitude can significantly affect regional earthquake recurrence estimates used to assign the probability of a given sized earthquake occurring in the future. Furthermore, not knowing the correct magnitude creates a high level of uncertainty when tying recorded ground-motions to a given sized earthquake for empirically-derived GMPEs.

The number of seismic recording stations in the Australian continent is still quite sparse relative to other regions of the world, and our low level of seismicity means that it is difficult to obtain multiple quality ground-motion records from a single event. However, the number of records we can use to evaluate seismic attenuation throughout the continent has been steadily increasing and in some regions, we are able to develop a more accurate understanding of the way seismic energy attenuates as it propagates through the crust, based on recorded data. Furthermore, in some regions we now possess abundant ground-motion records from which to study attenuation, and I will use some of these data to evaluate existing studies on seismic attenuation in Australia for both ground-motion prediction and magnitude determination.

## PREVIOUS WORK

The first equations that were used to calculate earthquake ground-motion for Australian earthquakes were those produced by Gaull *et al.* (1990) for the development of the 1990 Australian Seismic Hazard Map. These relations, developed for multiple regions, were based on the determination of mean radii from isoseismal maps from Australian earthquakes, where macroseismic intensities are converted to peak ground acceleration (PGA) and peak ground velocity (PGV). Though simple, these relations were effective for evaluating potential ground-shaking levels for different magnitude and distance ranges.

Subsequent to the Gaull *et al.* (1990) study there has been a variety of work undertaken to obtain a better understanding of ground-motion attenuation in Australia. Wilkie and Gibson (1995) used high sample-rate data from Gippsland to determine the anelastic attenuation parameter, or quality factor, $Q$ for Victoria. Subsequent estimates of $Q$ have been determined for southeastern Australia (SEA) by Allen (2004) and Allen *et al*. (2007). The values of $Q$ from these respective studies are underpinned by different geometrical spreading models $G(R)$, and thus are not directly comparable. Owing to the sparse datasets from elsewhere in the country, only limited work has been undertaken to determine anelastic attenuation parameters in other regions of the country. For example Allen *et al*. (2006) calculated these parameters from data collected from the 2001-2002 Burakin, Western Australia (WA) earthquake sequence (Leonard, 2002).

Allen *et al*. (2007) also introduced a piecewise tri-linear $G(R)$ model for SEA which suggests higher attenuation in the near-source range than previously considered, in addition to a zone of little-to-no attenuation resulting from critical Moho reflections between approximately 90-150 km from the earthquake source. The observation of critical Moho reflections is similar with observations in eastern North America (Burger *et al.*, 1987; Atkinson, 2004). The Allen *et al.*

(2007) paper develops an empirical Fourier spectral model for the southeastern Australian dataset (moment magnitude $M_W$ 1.9-4.7). However, this model is limited to the magnitude range of the dataset. A comparison of Australian and eastern North American Fourier spectral amplitude data over comparable magnitude and distance ranges has also been undertaken by Allen and Atkinson (2007). They observed that the attenuation of Fourier spectral amplitudes was generally similar between the two stable continental regions for distances less than about 70 km. Beyond this distance range, SEA ground-motion attenuates at a faster rate than those from eastern North America.

As previously mentioned, there are very few ground-motion recordings from large-magnitude earthquakes with which to develop empirically-based GMPEs. Consequently, there is a need to consider other numerical techniques to develop GMPEs in the absence of recorded data. Parameters such as those described above are fundamental to the development of stochastic GMPEs in the absence of strong-motion data for large intraplate earthquakes. The development of non-intensity GMPEs for Australia has only really emerged in the last half of this decade, with a few Australian-specific models now being considered for use in the upcoming revision of the Australian National Earthquake Hazard Map (Burbidge *et al.*, 2010). Lam and others first introduced their Component Attenuation Model (CAM) about 10 years ago (Lam *et al.*, 2000). This model uses representative physical earthquake parameters and crustal properties for Australia to develop a stochastic ground-motion model. The CAM model has subsequently been updated through several studies (e.g., Lam and Wilson, 2008).

Other GMPEs that adopt properties from small-to-moderate sized magnitude events and use stochastic techniques to estimate ground-shaking for larger earthquakes have been developed in SEA (McPherson and Allen, 2006) and southwest WA (Liang *et al.*, 2008). The McPherson and Allen (2006) GMPE has not yet been finalised or peer reviewed. However, it is included herein for subsequent comparisons of GMPEs considered appropriate for eastern Australia.

Somerville *et al.* (2009) develop GMPEs for several regions across Australia using broadband simulation of accelerograms combined with regional crustal velocity models and earthquake source scaling relations. The work of Somerville *et al.* (2009) is the most comprehensive work to date in the field of attenuation modelling in Australia, and sets the benchmark for future work in this space.

## COMPARISON OF GROUND-MOTION PREDICTION EQUATIONS

As noted above, there now a handful of GMPEs that have been developed specifically to estimate ground-motions from Australian earthquakes. In this section we indicate several GMPEs which are under consideration for use in eastern Australia only. Figure 1 shows a comparison of 5% damped response spectra for a moment magnitude $M_W$ 6.5 earthquake at a range of rupture distances for several GMPEs: three GMPEs from eastern North America (Atkinson and Boore, 1995; Toro *et al.*, 1997; Atkinson and Boore, 2006), one from western North America (Chiou and Youngs, 2008), and two aforementioned models developed for SEA (McPherson and Allen, 2006; Somerville *et al.*, 2009). In general, the GMPEs developed for eastern Australia appear most consistent with the western North American GMPE of Chiou and Youngs (2008) rather than those from the stable continental interior of eastern North America. This observation was also noted by Somerville *et al*. (2009). The major differences between the McPherson and Allen (2006) and Somerville *et al*. (2009) GMPEs occur in the distance range of approximately 50-150 km, where the McPherson and Allen (2006) predicts higher rates of attenuation based on the geometrical spreading coefficients of Allen *et al*. (2007). Differences between MA06 and S09 also occur at response spectral periods greater than approximately 2 seconds.

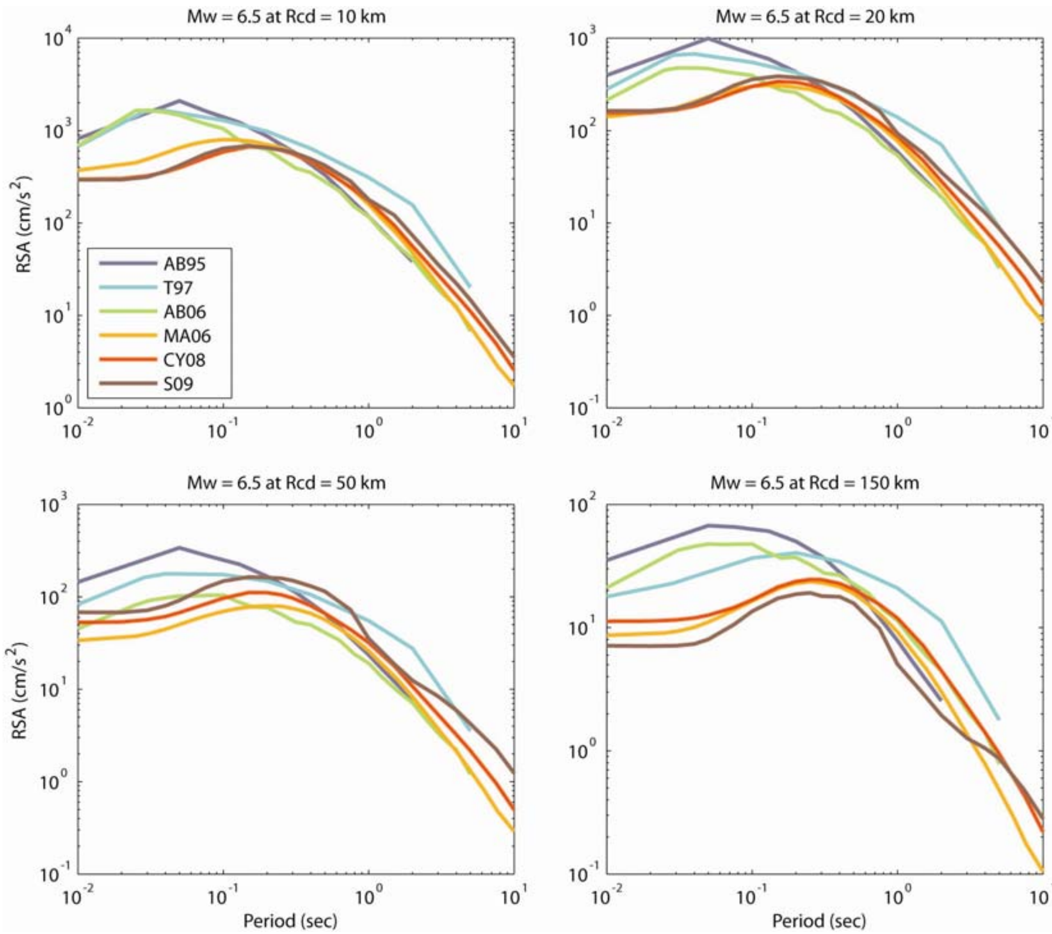
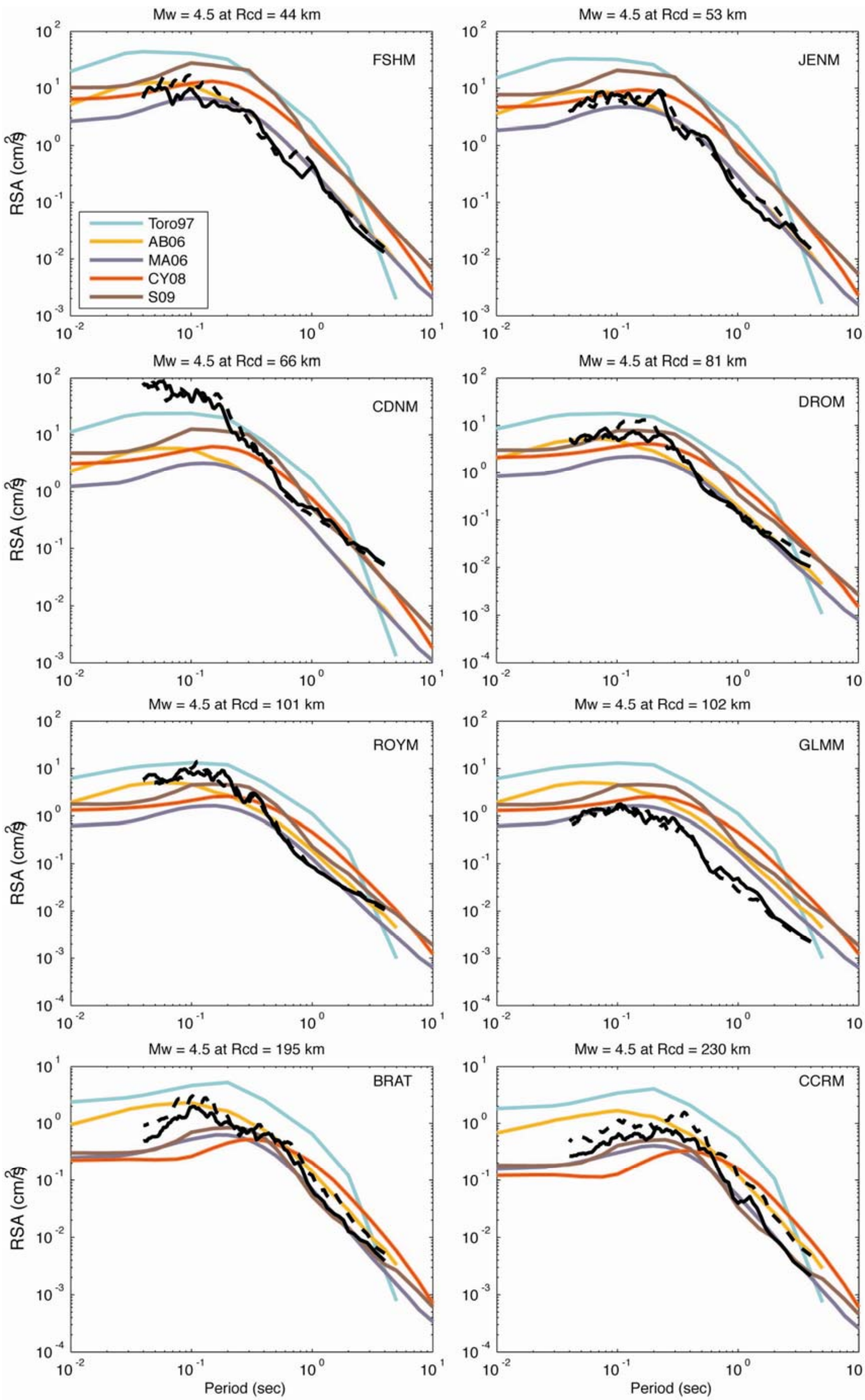



**Figure 1.** Response spectral accelerations (RSA) for several GMPEs under consideration for the revision of the National Earthquake Hazard Map: AB95 = Atkinson and Boore (1995); T97 = Toro *et al.* (1997); AB06 = Atkinson and Boore (2006); MA06 = McPherson and Allen (2006); CY08 = Chiou and Youngs, 2008; S09 = Somerville *et al*. (2009).

Next I compare a subset of those GMPEs above to recorded ground-motion data from the 6 April 2009 $M_W$ 4.5 Korumburra, Victoria earthquake, which was well recorded by permanent seismometers throughout Victoria (Fig. 2). As would be expected, the eastern Australian GMPEs model the observed ground-motion best overall, however, the faster attenuation rates approximated by McPherson and Allen (2006) at longer-periods appears more consistent with recorded small-magnitude data at shorter hypocentral distances. Neither the McPherson and Allen (2006) or Somerville *et al*. (2009) model appear to do particularly well at short-periods for some of the Korumburra records. This may either suggest limitations on the high-frequency parameter choices in the numerical models, or the inherent randomness (aleatory uncertatianty) in earthquake ground-motion. Note that some of these models – including Somerville *et al*. (2009) – are tested outside of the magnitude and distance threshold for which they were developed. Finally, we note that the Chiou and Youngs (2008) GMPE developed for western North America appears generally more similar to recorded data from the $M_W$ 4.5 Korumburra earthquake (up to $R_{hyp}$ = 150 km) than those models developed for the intraplate eastern North America.

**Figure 2 (following page).** Comparison of several GMPEs against response spectra (black lines) recorded at several stations for the 6 March 2009 $M_W$ 4.5 Korumburra, Victoria, earthquake. Solid and dashed lines indicate east-west and north-south horizontal components respectively. See Figure 1 caption for GMPE key.


Mw = 4.5 at Rcd = 44 km
FSHM
Mw = 4.5 at Rcd = 53 km
JENM
Mw = 4.5 at Rcd = 66 km
CDNM
Mw = 4.5 at Rcd = 81 km
DROM
Mw = 4.5 at Rcd = 101 km
ROYM
Mw = 4.5 at Rcd = 102 km
GLMM
Mw = 4.5 at Rcd = 195 km
BRAT
Mw = 4.5 at Rcd = 230 km
CCRM
Toro97
AB06
MA06
CY08
S09
RSA (cm/s2)
Period (sec)

# EVALUATION OF CATALOGUE MAGNITUDES

The calculation of Australian earthquake magnitudes has been the topic of several focused workshops and reports in the past (e.g., McGregor and Ripper, 1976), which have produced recommendations for the calculation of magnitude as our knowledge of the attenuation of the crust across Australia has evolved. The bulk of this work occurred in the mid 1980's through to the early 1990's where much progress was made in developing Australian-specific magnitude formulae which consider the attenuation properties of the Australian crust. However, since this period of activity, little additional work has been conducted to either validate or improve these models, despite enhancements to Australia's earthquake monitoring networks and our steadily growing database of Australian earthquake data. It is well-documented that prior to the development of Australian specific magnitude formulae, that the Richter (1935; 1958) local magnitude equation – originally developed for southern California – was almost exclusively used to calculate earthquake magnitudes throughout Australia (Leonard, 2008).

Recent practice in observational seismology has been to move away from local magnitudes towards the more physically-based moment magnitude, $M_W$. Moreover, modern GMPEs used in hazard calculations are calibrated to this measure of an earthquakes size. Consequently, earthquake catalogues that comprise magnitude estimates other than $M_W$ must first be converted to moment magnitude before hazard calculations can be undertaken. If we do not have a good understanding of our $M_L$ catalogue, then this conversion will be fraught with uncertainty.

It has been shown that Australian-specific $M_L$ equations deviate markedly from the original Richter equation at larger distances (Greenhalgh and Singh, 1986; Gaull and Gregson, 1991; Michael-Leiba and Malafant, 1992). Consequently, the introduction of these Australian-specific equations would have produced very different magnitudes to Richter from station recordings at larger distances. The discontinuities in the various magnitude scales would have manifested themselves into Australian earthquake catalogues, and to the author's knowledge, little effort was undertaken reconcile historical earthquake magnitudes based on these new equations, with the original estimates calculated using Richter remaining in the primary national earthquake catalogue. If this is the case, this presents profound implications for the recurrence of moderate-to-large magnitude earthquakes throughout Australia, and subsequently earthquake hazard in general. Herein, I document a procedure for reconciling Australian magnitudes calculated using disparate magnitude formulae across different regions of the country. Only magnitudes calculated prior to the development and implementation of Australian-specific formulae are examined. For simplicity, I assume a uniform cut-off in the use of Richter (1935; 1958) of 1990 for Western Australia and southeastern Australia.

In order to make an objective assessment of existing earthquake magnitudes, I obtained a dataset of 2,865 earthquakes with local magnitudes $M_L$ attributed to the AUST network through April 2008 from the online International Seismological Centre (ISC) catalogue (ISC, 2001) (Fig. 3).

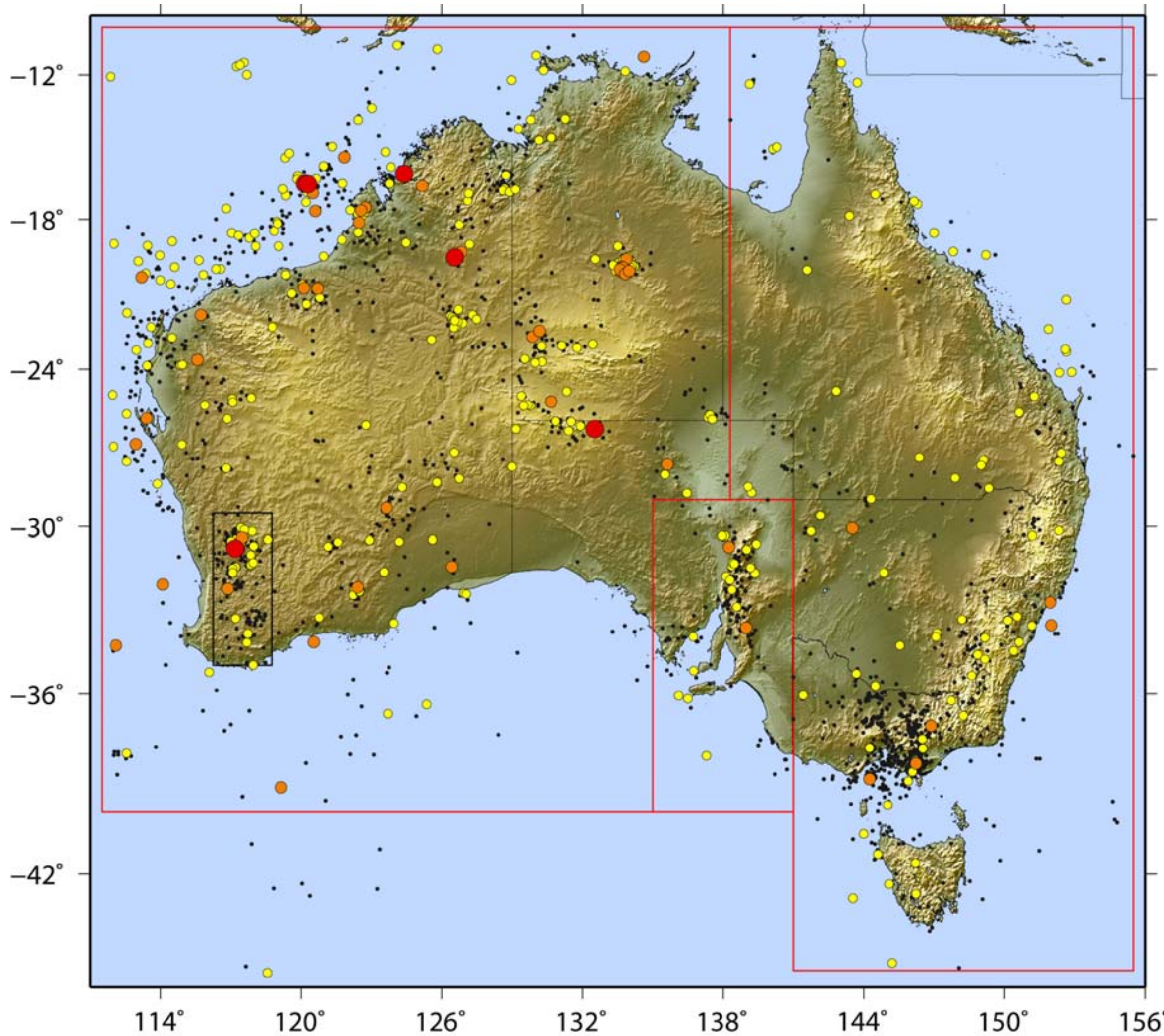



**Figure 3.** Map of earthquakes in the ISC catalogue from 1967 through 2008, which have a local magnitude $M_L$ estimates attributed to the AUST network. Red polygons indicate the zones considered to be appropriate for the regionally-specific local magnitude equations. The southwest seismic zone is also indicated (black polygon). Grey symbols, $M_L < 4.0$; yellow symbols, $4.0 \le M_L < 5.0$; orange symbols, $5.0 \le M_L < 6.0$; red symbols, $M_L \ge 6.0$.

Ideally, this analysis would require actual amplitude and period observations at each station (or at least individual station magnitudes) in order to provide a reliable recalculation of magnitude for pre-1990 earthquakes (approximately pre-1986 for South Australia). However, these data are not explicitly available from the ISC catalogue, or easily obtained from Geoscience Australia's catalogues for the time period of interest. Consequently, some basic assumptions were made in order to re-evaluate the magnitudes. In general, it is observed that Australian-specific local magnitude formulae are approximately consistent with the original Richter formula between epicentral distances of 50 and 180 km (Fig. 4). The general procedure is thus outlined as follows:

1. Earthquakes are grouped into three zones indicated in Figure 3: Central and Western Australia (CWA), the Flinders and Mt Lofty Ranges (FMLR), and Eastern Australia (EA).
2. For each earthquake $i$, calculate the epicentral $R_{epi}$ and hypocentral $R_{hyp}$ distances to each recording station $j$ indicated in the ISC for that event.
3. Identify sites used for magnitude recalculation using the preferred logic below:
   a. Select all sites between $50 \le R_{epi} \le 180$ km

  b. If condition *a* cannot be satisfied, select site with minimum $R_{epi}$

4. Given the AUST catalogue $M_L$ value, back-calculate the recorded earthquake peak displacement amplitude, log $A_{ij}$ assuming Richer (1958) –log $A_0$ corrections for the selected sites above.
5. Substitute log $A_{ij}$ values from above into existing Australian-specific formulae to obtain revised magnitude estimates: Gaull and Gregson (1991) for CWA; and Michael-Leiba and Malafant (1992) for EA.
6. If more than one station is selected for event *i* in step 3, calculate mean revised magnitude.

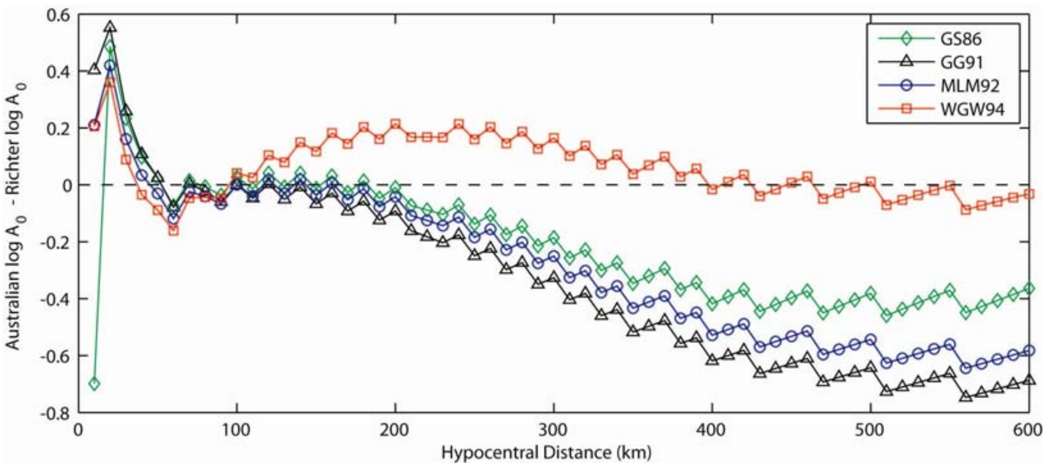



**Figure 4.** Comparison of several Australian-specific –log $A_0$ curves minus the Richter (1935; 1958) –log $A_0$ curve: GS86 = Greenhalgh and Singh (1986); GG91 = Gaull and Gregson (1991); MLM92 = Michael-Leiba and Malafant (1992); and WGW94 = Wilkie *et al.* (1994), updated using Wilkie (1996) coefficients. Most of the Australian local magnitude –log $A_0$ curves are similar to the Richter coefficients between $50 \leq R_{epi} \leq 180$ km. It is well-acknowledged that the Richter (1958) curve underestimates attenuation (and magnitude) in southern California at distances less than $R_{epi}$ 30 km (e.g., Bakun and Joyner, 1984). This finding appears consistent with the Australian –log $A_0$ curves presented above.

For brevity I will only discuss results for CWA herein. Earthquakes within the CWA polygon were extracted from the ISC catalogue and local magnitudes for these events were recalculated for pre-1990 earthquakes using the above procedure assuming the Gaull and Gregson (1991) magnitude equation. Figure 5 indicates histograms of the residuals of the catalogue (AUST) $M_L$'s minus the revised $M_L$'s from the present study. When we consider all earthquakes within the CWA polygon, we observe a clear bimodal relationship of magnitude residuals, with the largest peak at zero and a secondary peak at approximately 0.75 magnitude units (Fig.5a). The largest peak indicates that magnitudes for many earthquakes do not change significantly due to the present revisions. However, the second peak suggests that a significant number of earthquakes in the ISC catalogue may have magnitudes that are too large by about 0.75 magnitude units. The reason we do not observe larger residuals is because the attenuation curves of Richter (1958) and Gaull and Gregson (1991) generally do not deviate by more than 0.75 magnitude units for distances less than 600 km (see Fig. 4).

If we only consider epicentres located within the SWSZ polygon and plot a histogram of the magnitude residuals, then we observe one clear peak, with its centre near zero (Fig.5b). The primary reason for this is that the SWSZ had continuous monitoring for much of the period considered. Consequently, most epicentres in the SWSZ were located within about 180 km from the nearest seismic recorder. As previously mentioned the Australian-specific local magnitude equations were generally similar to the original Richter (1958) equation in the distance range between $50 \leq R_{epi} \leq 180$ km.

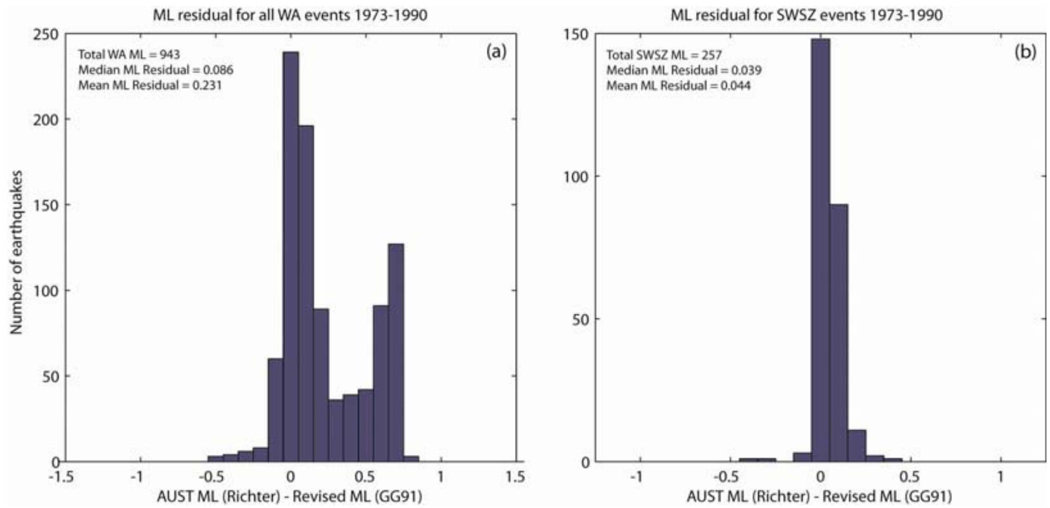



**Figure 5.** Histograms indicating residuals of AUST catalogue magnitudes minus revised magnitudes based on methodologies herein for (a) all of CWA region and (b) for the southwest seismic zone as indicated in Figure 3.

Figure 6 shows the cumulative number of earthquakes exceeding the original Richter and revised $M_L$'s for all epicentres in the CWA zone until 1990. We generally observe that 93% of earthquakes which had Richter magnitudes of $M_L \geq 2.5$, also exceed this magnitude with their revised magnitudes (Fig. 6a). The primary reason for the catalogue and revised datasets being so similar is likely due to the threshold of detection and location of small local events. Because the SWSZ was well instrumented relative to the rest of CWA pre-1990's, most earthquakes of magnitudes 2.5 and greater were captured with the networks of the day. Furthermore, owing to the relative similarity of the Richter $M_L$ equation and Gaull and Gregson (1991) at distances less than approximately 180 km, magnitudes for these earthquakes do not change significantly. Small earthquakes outside this zone are not likely to have been recorded well enough to determine a magnitude and epicentre. It is worth noting that even in some regions of northern Australia today, we do not yet have catalogue completeness for earthquakes less than $M_L$ 3.0 (Leonard, 2008).

In Figure 6b, we plot the cumulative exceedance curves for earthquakes exceeding $M_L$ 3.4 prior to 1990. Now we observe that there is approximately 32% less earthquakes with revised magnitudes exceeding $M_L$ 3.4. This trend holds as we progress towards larger magnitudes (Fig. 6c-d). Consequently, we can confidently state that the contribution of the secondary peak in Figure 5a is likely due to larger earthquakes ($M_L$ > 3.4) recorded at large distances from the epicentre to the nearest recording station.

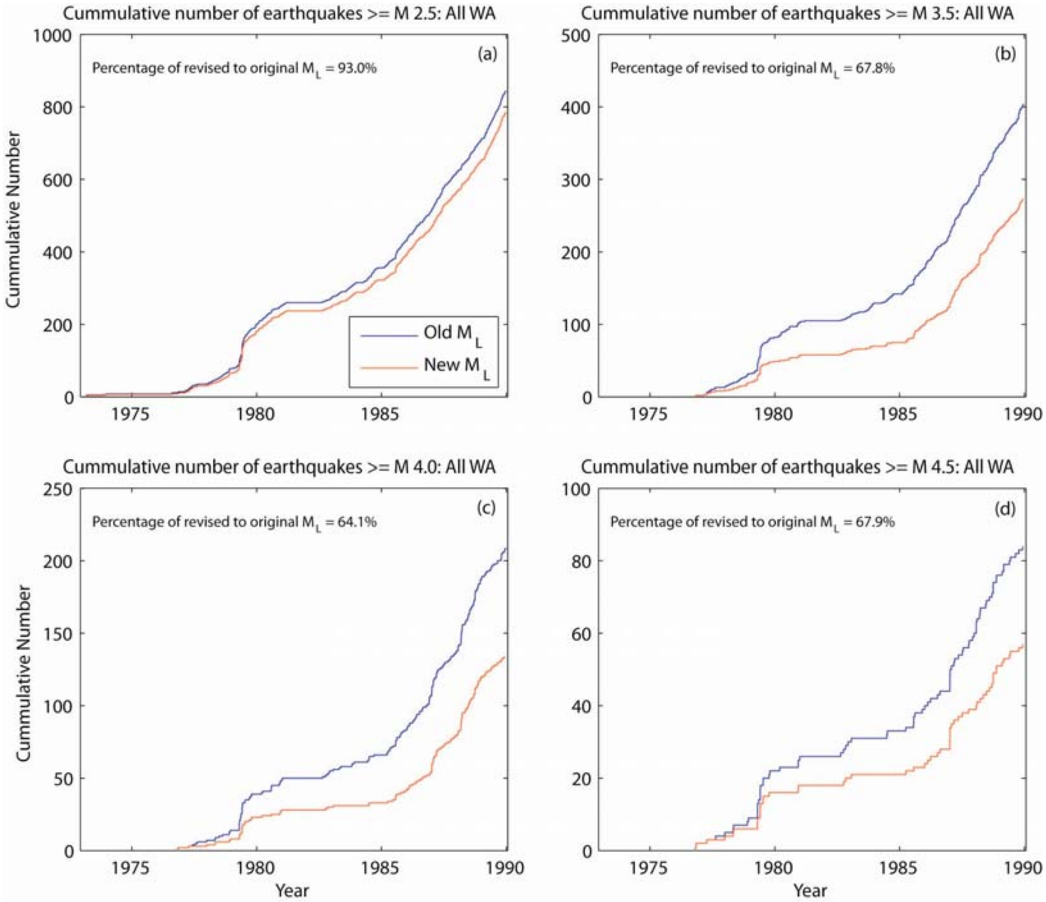



**Figure 6.** Cumulative number of earthquakes exceeding $M_L$ 2.5, 3.5, 4.0 and 4.5 for original and revised magnitudes for all epicentres in the CWA zone indicated in Figure 3 until 1990.

Next I plot the same cumulative magnitude exceedance plot for earthquakes within the SWSZ only (Fig. 7). As identified in Figure 5b, differences between original catalogue magnitudes and revised magnitude for this region are relatively minor. The major discrepancies between the catalogue and revised magnitudes appear to occur around the time period of the 1979 Cadoux earthquake. This may be because large-magnitude earthquakes from this sequence forced nearby seismometers to full scale. Consequently, magnitudes from these events may have been calculated from distant stations. Other than that time-period, the magnitude estimates for the SWSZ are remarkably consistent.

## CONCLUSIONS

In this paper I have summarised some of the progress made in attempting to better understand ground-motion attenuation in Australia over the past decade by several researchers. I have also provided an insight into Geoscience Australia's vision for dealing with attenuation-rated issues for the revision of the Australian National Earthquake Hazard Map. However, given this progress, there are still significant advances to be made in the near future. In particular, the revision of the National Earthquake Hazard Map will provide additional opportunities to enhance our understanding on ground-motion attenuation and magnitude determination for Australian earthquakes. Other research presently being undertaken at Geoscience Australia – but not explicitly discussed here – that supports further understanding of attenuation and magnitude determination within the continent includes:

- Augmentation of recently-recorded ground-motion data to existing databases

- Detailed evaluation of seismic source, path and site parameters; in particular trade-offs between the stress parameter and near-surface site parameter kappa (e.g., Boore *et al.*, 1992)
- Evaluation of commonly used local magnitude equations
- Extending magnitude corrections to those earthquakes not in the ISC catalogue
- The impact of Geoscience Australia's new routine observatory practice for estimating $M_L$ from:
    - Use of the correct Wood-Anderson (Anderson and Wood, 1925) magnification of 2,080 rather than the incorrect magnification of 2,800 which existing magnitude equations are based upon.
    - Difference in magnitudes between picking the peak-to-peak amplitude and period from the velocity time-histories, as opposed to the peak amplitude from the displacement time-histories convolved with the response of the Wood-Anderson seismometer response
- $M_L$ to $M_W$ conversions

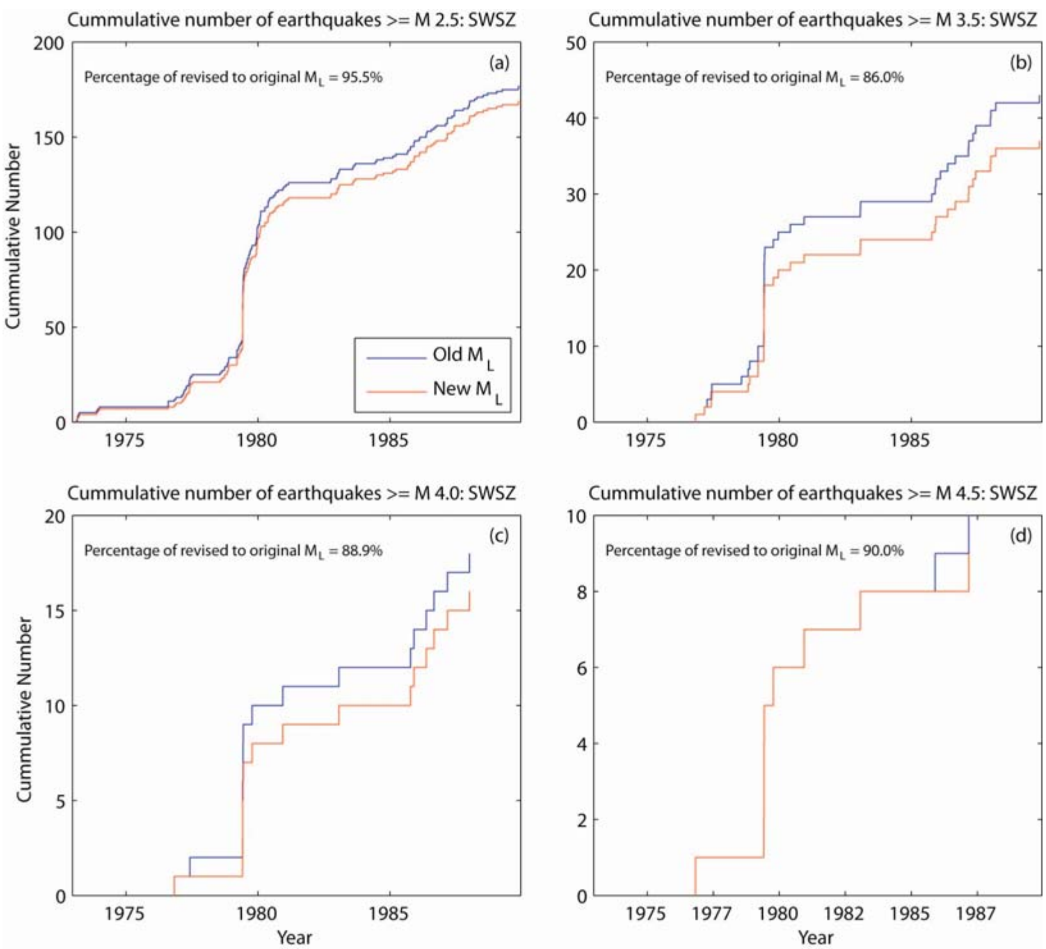



**Figure 7.** Cumulative number of earthquakes exceeding $M_L$ 2.5, 3.5, 4.0 and 4.5 for original and revised magnitudes for all epicentres in the SWSZ zone indicated in Figure 3 until 1990.

# ACKNOWLEDGEMENTS

Mark Leonard, Clive Collins, David Burbidge, and Phil Cummins are thanked for useful discussions and contributions to this work. Figure 3 was generated using Generic Mapping Tools (Wessel and Smith, 1991). Trevor publishes with the permission of the Chief Executive Officer of Geoscience Australia.

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