# The 2012 Australian Seismic Hazard Map – Catalogue and Ground Motion Prediction Equations

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## ABSTRACT

This paper discusses two of the key inputs used to produce the draft National Earthquake Hazard Map for Australia: 1) the earthquake catalogue and 2) the ground-motion prediction equations (GMPEs). The composite catalogue used draws upon information from three key catalogues for Australian and regional earthquakes; a catalogue of Australian earthquakes provided by Gary Gibson, Geoscience Australia's QUAKES, and the International Seismological Centre. A complex logic is then applied to select preferred location and magnitude of earthquakes depending on spatial and temporal criteria. Because disparate local magnitude equations were used throughout Australia, we performed first order magnitude corrections to standardise magnitude estimates to be consistent with the attenuation factors defined by contemporary local magnitude $M_L$ formulae. While most earthquake magnitudes do not change significantly, our methodology can result in reductions of up to one magnitude unit in certain cases with a median decrease in magnitude of 0.03 magnitude units. Subsequent $M_L$-$M_W$ (moment magnitude) corrections were applied. The catalogue was declustered using a magnitude dependent spatio-temporal filter. Previously identified blasts were removed and a time-of-day filter was developed to further deblast the catalogue.

Secondly, a suite of candidate GMPEs were systematically tested against 5% damped response spectra recorded from Australian earthquakes in eastern and western Australia, respectively. Since many GMPEs are developed for earthquakes larger than approximately $M_W$ 5.0, much of the data recorded in Australia is below the magnitude threshold prescribed by these equations. Nevertheless, where necessary, we extrapolate these equations to lower magnitudes to test the general applicability of the GMPEs for different source zones across Australia. The relative weights of the GMPEs for the draft national hazard model were initially determined objectively by the authors using these analyses as a basis. Final GMPE weights will be assigned through consultation with key stakeholders through the AEES.

**Keywords:** earthquake catalogues, ground-motion prediction equations, GMPEs, response spectra

## INTRODUCTION

Fundamental to any earthquake hazard model is a reliable catalogue of historical seismicity. Information from historical earthquakes provides us with an estimate of the likely recurrence period for an earthquake of a given magnitude in a particular area. Consequently, it is important to ensure that locations and magnitudes of historical earthquakes are as accurate as possible. In modern probabilistic seismic hazard analyses (PSHA), it is necessary to examine the recurrence of earthquakes using catalogues that have had all foreshocks and aftershocks removed. Algorithms to remove (or decluster) these events are common. However, they must be calibrated for each region.

Another key component of any earthquake hazard model is the estimation of the likely ground-motions that could result from future earthquakes. These ground motions are generally estimated from ground-motion prediction equations (GMPEs), which are a necessary component of any PSHA. Furthermore, the selection of appropriate GMPEs is often considered one of the largest contributors to uncertainty in PSHA. In stable continental regions, such as Australia, we have very few ground-motion recordings from moderate-to-large earthquakes with which to develop empirical GMPEs. However, a few Australian-specific GMPEs developed using numerical simulations have recently been published (e.g., Lam *et al.*, 2000; Liang *et al.*, 2008; Somerville *et al.*, 2009).

In this paper we discuss the earthquake catalogue developed for the update of the Australian National Earthquake Hazard Map. In particular, we discuss methods used to determine preferred magnitudes, in addition to catalogue declustering. Secondly, using recorded data from moderate magnitude earthquakes in both Western Australia and south-eastern Australia, we evaluate candidate GMPEs presently being considered for the national hazard model.

## CATALOGUE SOURCES

For the revision of the National Earthquake Hazard Map (NEHM) a composite earthquake catalogue was compiled. The primary data sources for this catalogue are:

1. GG-Cat: An earthquake catalogue compiled by Gary Gibson.
    - Covers the area 110°E/156°E/48°S/10°S from 1788-06-22 to 2010-05-26
2. QUAKES: Geoscience Australia's catalogue of Australian and regional events.
    - Covers the area 110°E /155°E /45°S /9°S from 2010-05-27 to 2010-08-26
    - Note that of the subset of ~2500 earthquakes used to derive the source parameters, 14 came from this catalogue

Supplementary data were obtained from:

3. ISC AUST: All earthquakes in the International Seismological Centre's catalogue attributed to the network AUST.
    - Covers the area 111.9°E /155.2°E /44.9°S /10.4°S from 1967-01-31 to 2008-04-30
    - This catalogue was included to assist with the validation of catalogue magnitudes because it provides easily accessible station information
4. ISC Regional: Additional earthquakes beyond that captured in GG-Cat.
    - Covers the area 108°E /160°E /50°S /4°S from 1906-06-14 to 2011-04-17
    - These data were added to allow the calculation of recurrence parameters for offshore seismic sources that may affect Australia
    - Note that no offshore seismic sources are included in the draft presented at this conference.

All key attributes from the aforementioned catalogues were merged into a master catalogue. Attributes carried through include hypocentre information from each data source, all magnitude types and sources, in addition to any comments for each earthquake. Future revisions of the composite catalogue are likely to include the updated Queensland earthquake catalogue compiled by Jack Rynn and Dion Weatherly (J. Rynn, pers. comm., 2011).

GG-Cat was the primary source of data within the Australian continent, which includes offshore areas of Australian continental crust. A complex logic was used to determine preferred location and magnitude for each event. This logic specifies a magnitude-dependent range for selecting the preferred magnitude type and is also based on the time period and the observatory to which the solution is attributed. For example, where moment magnitude $M_W$ has been assigned, this is taken as the preferred magnitude type across the full magnitude range, whereas, local magnitudes $M_L$ are taken below $M$ 6.0 and the larger of $M_S$ or $m_b$ above $M$ 6.0. Full details on this approach will accompany the documentation for the national hazard map.

Finally, we filter the catalogue for sources we deem to be unreliable within the Australian region, such as those that do not discriminate between natural and anthropogenic sources (e.g., the Comprehensive Nuclear-Test-Ban Treaty Organization's International Data Centre). In our analyses, we assumed that the number of real earthquakes these sources identified that were missed by the various Australian seismic agencies were negligible.

### *Declustering and Deblasting*

Two primary methods were used to decluster the catalogue. Method 1 used the expert judgement of Gary Gibson to determine whether an earthquake was a foreshock, aftershock or swarm. Method 2 used the techniques proposed by Leonard (2008), which estimates the magnitude-dependent duration and spatial area of likely aftershocks from Eqs. 1 and 2. The duration $T$ (in days) for which earthquakes can be considered aftershocks can be given by:

$$T = 10^{(M-A)*B} + c \qquad \text{Eq. 1}$$

where the coefficients $A$, $B$, $c$ are 1.85, 0.69, 0.0 (for the original Method 2) as published in Leonard (2008) and the revised coefficients are 2.7, 1.1, 4.0. The radius $R$ (in km) from the epicentre within which earthquakes that satisfy Equation 1 are considered to be aftershocks can be given by:

$$R = 10^{(M-A')*B'} + c' \qquad \text{Eq. 2}$$

where, and the coefficients $A'$, $B'$, $c'$ are 3.82, 0.6, 10.

The coefficients in Equation 1 were varied from those of Leonard (2008) to account for the proposed long aftershock periods for large continental earthquakes (Stein and Liu, 2009). For Method 2, parameters $A$ and $B$ in Equation 1 were selected such that an aftershock period for a $M$ 4.0 earthquake is ~30 days and the period for a $M$ 7.5 earthquake is 500-600 years, where $M$ is a generic magnitude metric. The algorithm treats every earthquake as a potential mainshock, so aftershocks can also have aftershocks. To remove foreshocks, Method 3 was used. Method 3 consisted of using Method 2 (using the same coefficients) in reverse, followed by Method 1. Table 1 summarises spatio-temporal declustering criteria applied for the two sets of coefficients for Method 2 for discrete magnitudes. Earthquakes with a seismic moment greater than 80% of the associated mainshock moment were not considered to be aftershocks. This preserved data such as the 2000-02 Burakin (WA) sequence, which comprised five earthquakes of $M_L \geq 4.7$. Each of these "mainshocks" had an aftershock sequence, but the five are not considered aftershocks of each other (Leonard, 2002).

***Table 1.*** *The period of time that the original and new version of Method 2, using Equation 1, will consider an earthquake to be an aftershock. The time period T, is converted to number of weeks. The third row shows similar results for distance using Equation 2.*

| Magnitude | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 7.5 |
|---|---|---|---|---|---|---|
| Method 2 (orig) (weeks) | 0.9 | 4.3 | 21 | 104 | 511 | 1130 |
| Method 2 (new) (weeks) | 0.9 | 4.4 | 49 | 610 | 7670 | 27200 |
| $R$ (km) | 10.3 | 11.3 | 15.1 | 30.3 | 91 | 171 |

Table 2 summarises the number of associated events captured using the various declustering techniques. Methods 1 and 2 remove a similar number of aftershocks but they are overlapping sets. In some cases Method 1 is superior. For example, the aftershocks of the Simpson Desert sequence in the 1970's were often >100 km from the mainshock and so were not removed by Method 2, but the expert judgement of Method 1 correctly removed them. In areas of higher seismicity (e.g. the Yilgarn Craton and Adelaide Geosyncline), Method 2 removed aftershocks not identified by Method 1. The likely explanation is that with many potential mainshocks and aftershock sequences it is very difficult to associate them manually. The final declustering methods used for the draft map were Method 2 (aftershock removal), then Method 3 (foreshock removal) and then Method 1 (aftershock & foreshock removal). GG-Cat identified two ≥ M6.3 Tennant Creek earthquakes as foreshocks; these were moved back into the mainshock catalogue to preserve the total moment release of the earthquake sequence.

***Table 2.*** *The number of associated earthquakes removed by different combinations of Methods 1 & 2 (aftershocks) and Method 3 (foreshocks). Here, Method 2 uses the revised coefficients presented herein.*

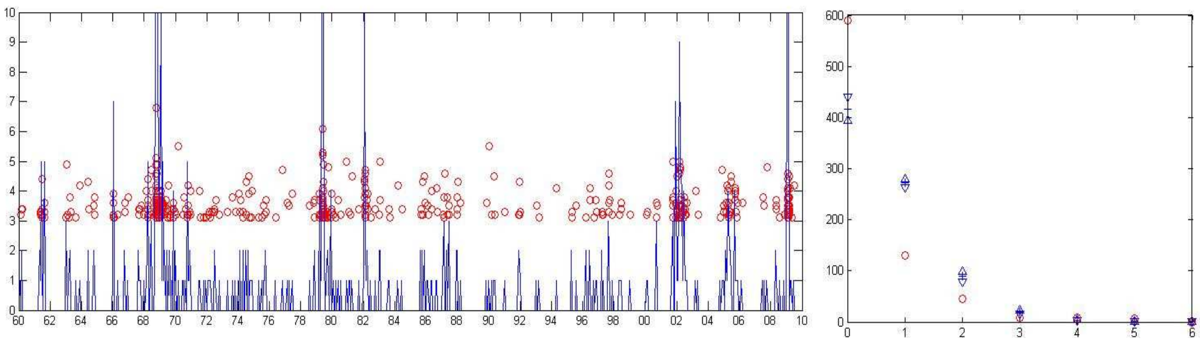
| **Method** | **Input Events** | **Independent Events** | **Associated Earthquakes** |
|---|---|---|---|
| Method 1 | 35,312 | 26,186 | 9,125 |
| Method 2 | 35,312 | 25,454 | 9,857 |
| Method 2 & 3 | 25,454 | 24,299 | 1,156 |
| Method 2, 3 & 1 | 24,299 | 22,901 | 1,398 |

## *Effectiveness of Declustering*

### Yilgarn Craton

A declustered earthquake catalogue should be approximately Poissonian in time (Gardner and Knopoff, 1974; Reasenberg, 1985). Consequently, an ideal declustering algorithm should produce a Poisson distribution. To test this hypothesis we compare the clustered and declustered catalogues for the Yilgarn region of Western Australia. This area tends to have very active aftershock sequences, earthquake swarms and clusters of related earthquakes. Due to major changes to the seismic network the catalogue also has a high degree of variability in its epicentral accuracy. These factors make declustering the catalogue from this region challenging.

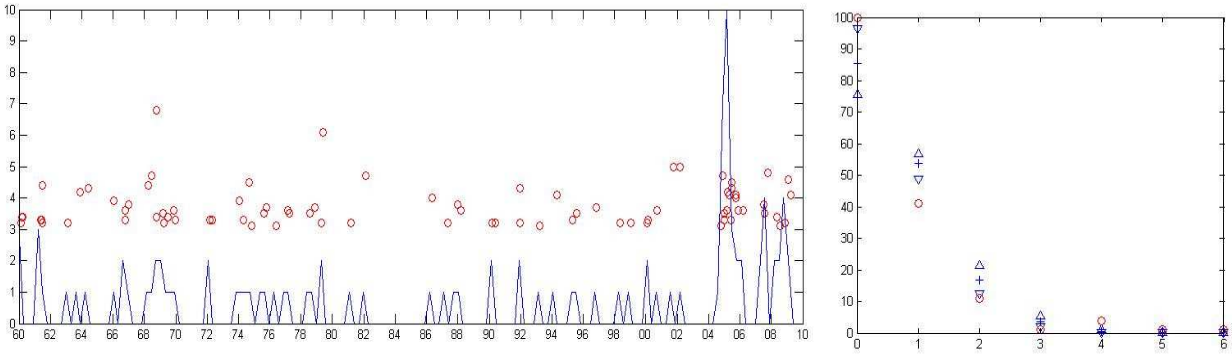
The data was tested using the Poisson analysis method discussed by (Leonard, 2010). The distribution of earthquakes in time and their Poisson statistics are shown in Figure 1. The number of time windows (bins) is ~1.6 the number of earthquakes giving a probability of 0.625 that an earthquake will occur in any particular bin. The subsequent probability of six earthquakes occurring in any single bin is $4e^{-5}$. Consequently, for a catalogue of 500 earthquakes and 800 bins, Poissonian statistics suggest that six or more earthquakes are expected to occur in only 0.04 bins. As shown in Figure 1a, there are more than seven bins with six or more earthquakes. This is reflected in the Poisson distribution (Fig. 1b) where there are more bins than expected with zero earthquakes, less bins than expected with one and two earthquakes, and more bins than expected with five or more earthquakes.



(a) (b)

***Figure 1.*** *The occurrence of all earthquakes >M 3.0 in the Yilgarn region of Western Australia between 1960 and 2010 and the Poisson statistics of the earthquake catalogue. (a) The red circles represent all earthquakes ≥ M3.0 and the blue lines are the number of earthquakes per bin for the 800 bins between 1960 and 2010. X-axis is the year and y-axis is the number of earthquakes per bin. (b) The theoretical (blue triangles) and actual (red circles) Poisson statistics for 580 earthquakes in 800 bins. The number of bins with 0 events is more than expected, while the number of bins with 1 or 2 events is less than expected. Given the small uncertainties in the theoretical distribution the actual data can unequivocally be considered non-Poissonian. X-axis is the number of earthquakes per bin and y-axis is the number of bins.*

Following application of the aforementioned combination of declustering algorithms, almost all the peaks apparent in Figure 1a have been removed (Fig. 2a). The exception to this is the spike in activity centred around 2005. This spike was the second biggest surge of activity in the Yilgarn since 1980. It consisted of eight earthquakes of *M* 4.0 or greater. Unlike the localised Burakin (2002) and Beacon (2009) sequences, this activity consisted of five clusters spread over a 50 × 80 km area. Within the clusters, events within 0.2 magnitude units occurred several months apart and accordingly were not identified as aftershocks by the algorithm. Excluding this surge of activity, the declustering algorithm has effectively declustered the catalogue. An analysis of the declustered data between 1960 and 2003 gives results which are highly consistent with a model of Poisson earthquake occurrence (Fig. 3).



(a) (b)

***Figure 2.*** *The declustered catalogue of earthquakes >M 3.0 in the Yilgarn region of Western Australia between 1960 and 2010 and the Poisson statistics of the earthquake catalogue. (a) Except for the surge of activity in 2004 and 2005 the spikes have been removed.*

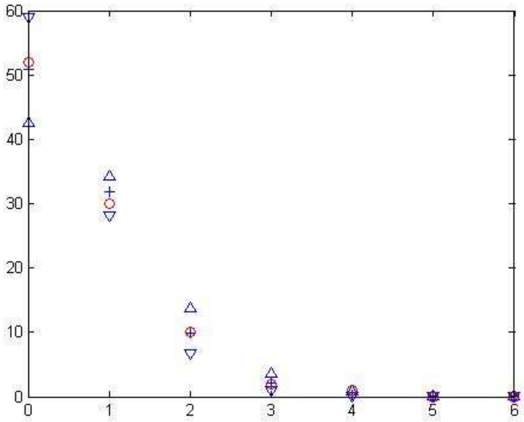
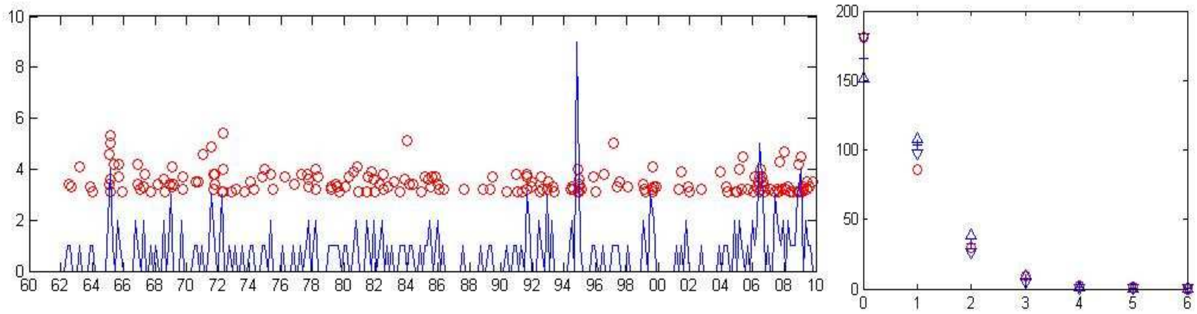


***Figure 3.*** *Actual (red circles) and theoretical (blue triangles) Poisson statistics for the declustered catalogue of earthquakes in the Yilgarn between 1960 and 2002. This data is consistent with the assumption of earthquake occurrence in time being a Poissonian process.*

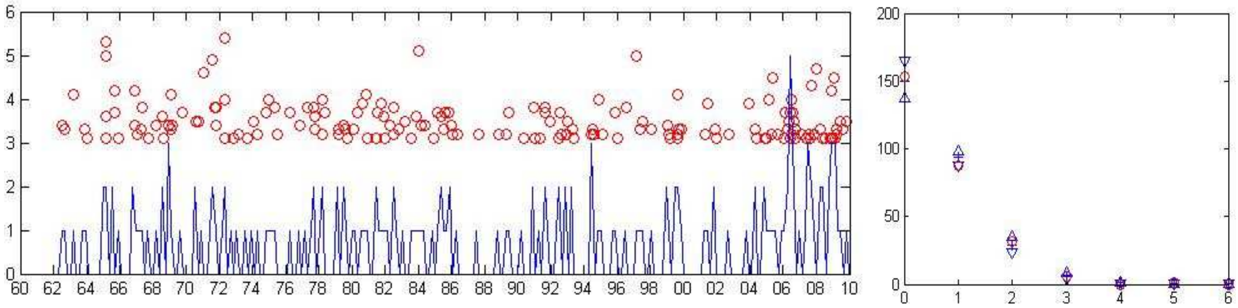
## <u>Adelaide Geosyncline (Flinders and Mt Lofty Ranges)</u>

A similar analysis was undertaken in the Flinders and Mt Lofty ranges (FLR) region. The full catalogue is close to a Poisson distribution (Fig. 4). The declustered catalogue is close to being a Poison distribution with only a few anomalous periods (e.g., 2006 - see Figure 5). Further investigation identified that these periods were caused by mining blasts that had not been captured in the aforementioned declustering process. Removing these events from the catalogue manually, the statistics of earthquake occurrence are identical to the theoretical Poisson distribution (Fig. 6). This raises the possibility that some of the other peaks in activity identified in other regions or catalogues are unidentified mine blasts.



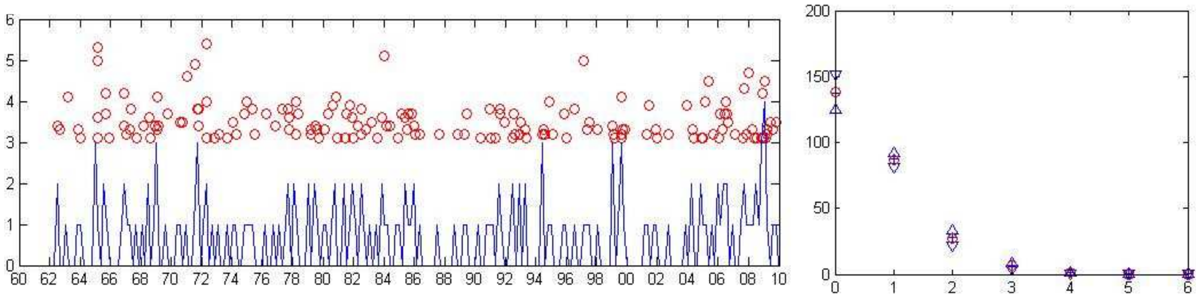

(a) (b)

***Figure 4.*** *Statistics for the full (non-declustered) catalogue from Flinders and Mt Lofty Ranges (FLR) showing that the distribution is close to Poissonian.*




(a) (b)

***Figure 5.*** *Statistics for the declustered catalogue for FLR showing that, with the exception of the peak in 2006,the distribution can be considered Poissonian.*




(a) (b)

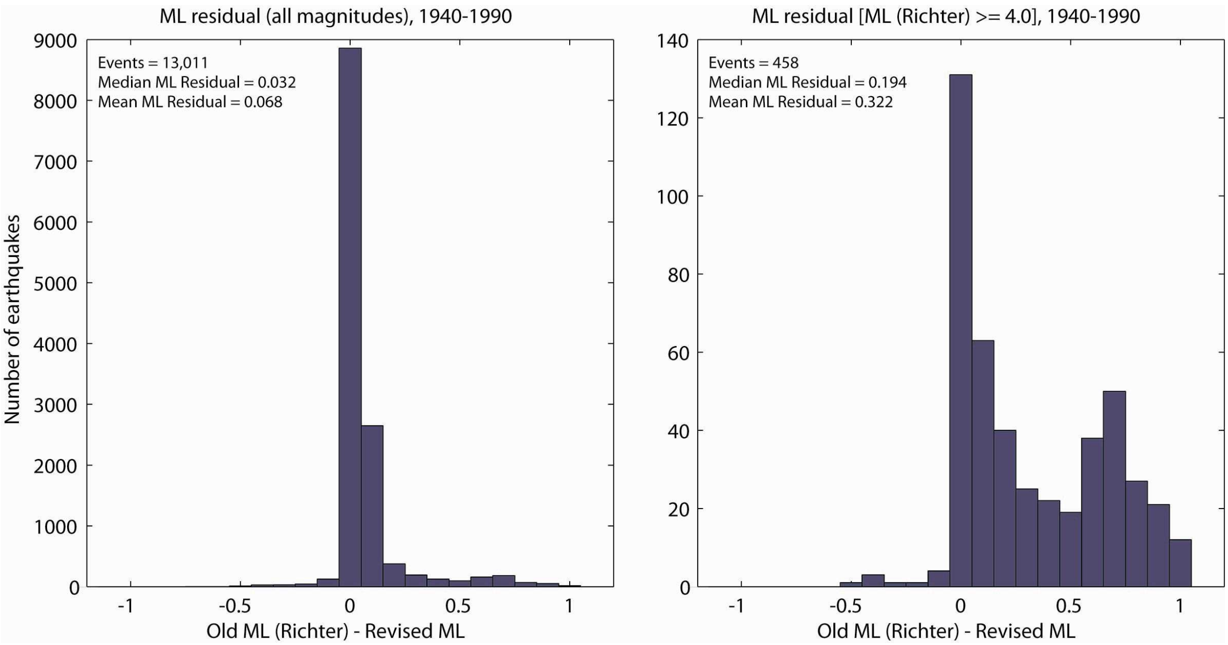
***Figure 6.*** *Statistics for the declustered catalogue for FLR with the mine blast peak in 2006 removed.*

## MAGNITUDES

### *Revision of Local 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; Denham, 1982), which have produced recommendations for the calculation of earthquake magnitudes in Australia. The primary advances in the development of Australian-specific magnitude formulae occurred in the mid 1980s through to the early 1990s, when much progress was made in developing magnitude formulae which consider the attenuation properties of the Australian crust. It is well documented that, prior to the development of Australian-specific magnitude formulae, that the Richter (1958) local magnitude equation – originally developed for southern California – was almost exclusively used to calculate earthquake magnitudes throughout Australia (e.g., Leonard, 2008).

Allen (2010) describes a method to correct catalogue local magnitudes ($M_L$'s) to be consistent with contemporary magnitude calculations for specified regions across Australia. The basic technique corrects magnitudes using the difference between the Richter and local magnitude attenuation curves at a distance determined by the nearest recording station likely to have recorded the earthquake. Results of this method of re-evaluating magnitudes for western and central Australia have previously been discussed by Allen *et al.* (2011). Herein we discuss the utility of these magnitude corrections for the full catalogue of continental Australian earthquakes (pre-1990). Magnitudes attributed to the ADE network were preserved from 1968 (e.g., White, 1968). This correction, in general, results in minimal departure from original magnitudes when we consider the full catalogue of Australian earthquakes, with the median change in magnitude for all events being 0.03 magnitude units (Fig. 7a). However, if we only consider earthquakes that have catalogue (i.e. Richter) magnitudes $M_L \geq 4.0$, we observe a significant secondary residual peak at approximately 0.7 magnitude units (Fig. 7b), with some residuals up to one magnitude unit. These data suggest that many moderate-magnitude pre-1990 earthquakes occurred in remote locations at distances far from the nearest recording instrument. Consequently, magnitudes were likely overestimated by using an inappropriate $M_L$ formula (e.g., Richter, 1958).




(a) (b)

***Figure 7.*** *Histograms indicating residuals of original (Richter) Australian catalogue (1940-1990) magnitudes minus revised magnitudes based on methodologies in Allen (2010) for (a) all magnitudes and (b) $M_L$ (Richter) $\geq 4.0$.*

Because we cannot access original amplitude and period data recorded at each seismic station to re-evaluate $M_L$ with an appropriate equation, this technique must make assumptions about the magnitude equation used and the configuration of the seismic network over time. In addition, we use only the nearest hypothetical station to determine the magnitude correction. This assumption will be at a distance where the differences between the original (Richter) and new $M_L$ attenuation corrections are smallest. Consequently, this could lead to an underestimation of the actual correction required. Figure 8 shows the change in magnitudes by spatial location. As can be observed, earthquakes of larger Richter magnitudes occurring in remote locations (relative to seismic networks) are those earthquakes that have the most significant shift in magnitude. This is because the aforementioned method assumes that magnitudes determined from inappropriate attenuation formulae (e.g., Richter, 1958) and a sparse network overestimate local magnitudes relative to magnitude formulae used by modern seismic observatories.

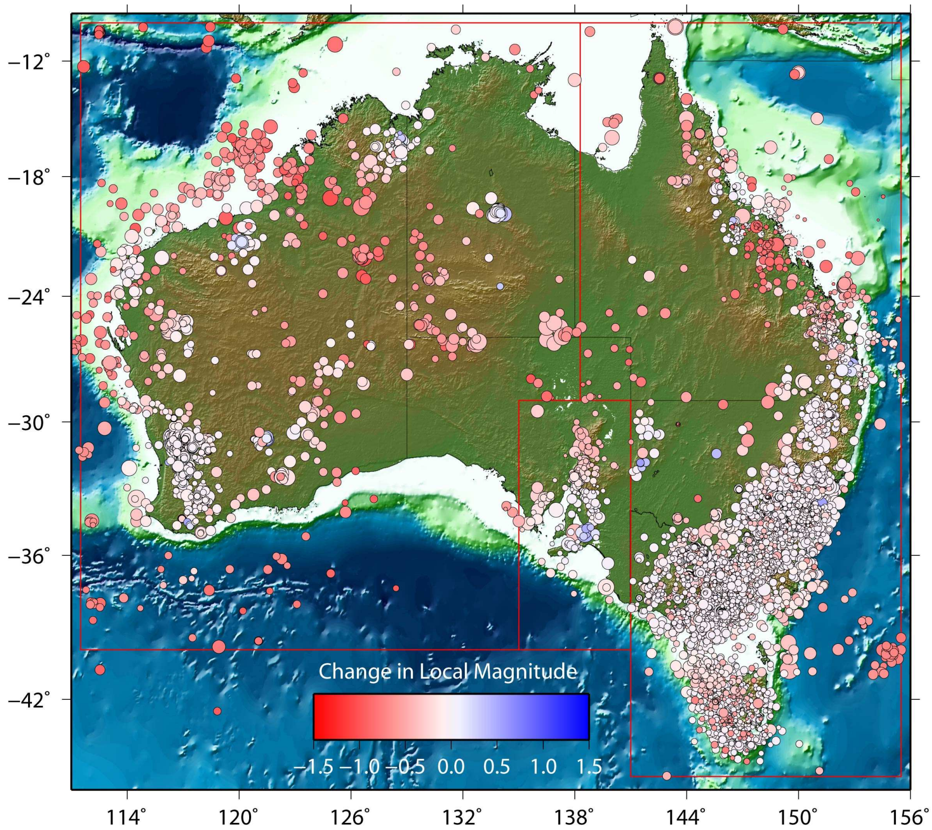



***Figure 8.*** *Map of Australian epicentres for pre-1990 earthquakes indicating the change in local magnitude $M_L$ using the conversion factors described by Allen (2010). Changes most commonly translate to a decrease in magnitude. Red lines indicate spatial bounds controlling the logic used for magnitude corrections. This technique will be fully described in the National Hazard Map documentation.*

## $M_L$ to $M_W$ conversions

Probabilistic seismic hazard assessments rely on a catalogue of earthquakes that provide an estimate of the recurrence of different magnitude earthquakes per unit area. Commonly, these catalogues are composed of disparate magnitude types calculated by different methods. These differences are seldom considered by practitioners to any level of rigor, particularly in stable continental settings. However, to obtain a more reliable estimate of earthquake recurrence, it is prudent to convert all earthquake magnitudes to a single magnitude type. Moment magnitude ($M_W$) has become the most commonly used magnitude scale in seismic hazard assessments because it provides a more physical measure for any given earthquake, and accordingly is scalable to all magnitudes. Consequently, most modern ground-motion prediction equations (GMPEs) are now calibrated to $M_W$. The methodology presented above describes the standardisation of Australian catalogue magnitudes for $M_L$ only and does not consider $M_W$. Consequently, we require additional conversion factors for all magnitude types in the Australian earthquake catalogue.

Many equations have been developed to convert other magnitude scales to $M_W$, most commonly from surface-wave magnitude, $M_S$ and body-wave magnitude, $m_b$ (e.g., Scordilis, 2006). These equations can be derived relatively easily by combining various global earthquake catalogues because the magnitude calculation technique for these magnitude types is generally consistent across global networks. However, deriving a universal conversion equation to convert from $M_L$ to $M_W$ cannot be easily achieved without consideration of the local magnitude equation itself. The divergence of –log $A_0$ correction factors between Richter and several Australian $M_L$ equations at near-source distances demonstrate the necessity for region-specific $M_L$ to $M_W$ conversions (Allen, 2010).

Allen *et al.* (2011) used a more complete dataset of $M_W$ and improved $M_L$ estimates than previous studies (e.g., Allen *et al.*, 2004; 2006) to develop more reliable equations for converting between local and moment magnitudes for Australian earthquakes. These conversions are used to develop a homogeneous

$M_W$ catalogue that can be incorporated into hazard estimates. Uncertainties associated with these conversions are yet to be quantified, but should also be considered in any PSHA.

## GROUND MOTION PREDICTION EQUATIONS

One of the key challenges in assessing earthquake hazard in Australia is in understanding the attenuation of ground-motion through the stable continental crust. There are now a handful of GMPEs that have been developed specifically to estimate ground-motions from Australian earthquakes. For the draft hazard map presented at this meeting, semi-quantitative weightings were assigned based partially on the performance of the candidate models against recorded data, as well as professional judgement. In this section we test several candidate GMPEs under consideration for use in the final NEHM against recoded ground-motion data.

***Table 3.*** *Candidate GMPEs under consideration for use in the next Australian earthquake hazard model. Note, preliminary weightings shown are for the two continental background zones. These weightings are indicative of those used for other zones.*

| Reference | Region | Magnitude Range | Distance Range (km) | Site Condition ($V_S30$ in m/s) | Back-ground West Weights | Back-ground East Weights |
|---|---|---|---|---|---|---|
| Gaull *et al.* (1990) | Southeastern Australia | $4.5 \leq M_L \leq 7.2$ | $10 \leq R_{hyp} \leq 500$ | - | | |
| Gaull *et al.* (1990) | Western Australia | $4.5 \leq M_L \leq 7.2$ | $10 \leq R_{hyp} \leq 500$ | - | | |
| Toro *et al.* (1997) | Eastern North America (Midcontinent) | $5.0 \leq M_W \leq 8.0$ | $1 \leq R_{JB} \leq 500$ | 2,800 | | |
| Campbell (2003) | Eastern North America (Hybrid) | $5.0 \leq M_W \leq 8.2$ | $1 \leq R_{JB} \leq 1000$ | 2,800 | | |
| Atkinson and Boore (1995) | Eastern North America | $4.0 \leq M_W \leq 7.25$ | $10 \leq R_{hypo} \leq 500$ | 2,800 | | |
| Atkinson and Boore (2006) | Eastern North America (Rock) | $4.0 \leq M_W \leq 8.0$ | $1 \leq R_{rup} \leq 1000$ | > 2,000 | | |
| Atkinson and Boore (2006) | Eastern North America (BC Site) | $4.0 \leq M_W \leq 8.0$ | $1 \leq R_{rup} \leq 1000$ | 760 | 0.4 | 0.4 |
| Liang *et al.* (2008) | Southwest Western Australia | $4.0 \leq M_L \leq 7.0$ | $1 \leq R_{epi} \leq 200$ | - | | |
| Somerville *et al.* (2009) | Yligarn Craton | $5.0 \leq M_W \leq 7.5$ | $1 \leq R_{JB} \leq 500$ | 865 | 0.2 | |
| Somerville *et al.* (2009) | Non-Cratonic Australia | $5.0 \leq M_W \leq 7.5$ | $1 \leq R_{JB} \leq 500$ | 865 | 0.2 | 0.2 |
| Chiou and Youngs (2008) | Western North America (California) | $4.0 \leq M_W \leq 8.5$ | $1 \leq R_{rup} \leq 200$ | 760 | 0.2 | 0.4 |
| Allen (2006, unpublished) | Southeastern Australia | $4.0 \leq M_W \leq 7.5$ | $1 \leq R_{rup} \leq 500$ | 760 | | |

The models chosen for the final hazard map will be objectively weighted based on their performance relative to these data. Table 3 shows the candidate GMPEs and their specific conditions of use. The initial assessment of candidate models presented herein only uses data for earthquakes of moment magnitude ($M_W$) 4.0 and greater. It should be noted that this magnitude range is less than that prescribed by many of the models (see Table 3). However, it can be argued that GMPEs adequately calibrated at longer periods for large-magnitude earthquakes – periods that determine earthquake magnitude – should also be well-calibrated at lower magnitudes. Consequently, if properly calibrated, any response spectral models should still result in small residuals (observed minus predicted amplitudes) at longer periods for small earthquakes. The performance of GMPEs outside their prescribed magnitude range at short periods may not be expected to be as satisfactory because of source affects that might alter the high-frequency spectrum of the earthquake (e.g., magnitude-dependent stress drop).

The models evaluated are a combination of Australian-specific models and models from other stable continental regions (e.g., eastern North America), in addition to those from active tectonic regions. In the following section we compare candidate GMPEs against recorded data from both Western Australia and eastern Australia.

### *GMPE Comparisons with Western Australian Data*

A dataset of 38 ground-motion records for earthquakes occurring in the Yilgarn Craton of Western Australia were compiled. The records, mostly recorded on strong-motion instruments, are for magnitudes $M_W$ 4.1-4.6 at distances less than 200 km from their respective earthquake sources. The primary source of the data is from the 2001-02 Burakin earthquake sequence. As discussed in Allen *et al.* (2006) it is not certain whether the Burakin earthquake sequence can be considered as typical of earthquakes in the Yilgarn Craton. The swarm-like nature of the sequence and the likelihood that many of the earthquakes would have occurred on recently-ruptured surfaces resulted in anomalously low stress drops for these events relative to published estimates from other stable continental regions. Despite these uncertainties in the Burakin dataset and in the absence of alternative data, they are still valuable for evaluating candidate GMPEs and should be expected to be characteristic of longer period ground-motions.

Figure 9 shows the median residuals ($\pm 1\sigma$) across the full range of response spectral periods for 12 candidate GMPEs evaluated in the present study. The two sets of curves in each subplot represent median residuals for data recorded at hypocentral distances $R_{hyp} \leq 80$ and $\leq 200$ km, respectively. In our semi-objective assessment of weightings for the draft hazard map, the former set of curves were considered to be the most instructive, because these distance ranges generally represent the greatest contribution to ground-shaking hazard (e.g., Jones *et al.*, 2005). The distance of 80 km was chosen because it is approximately twice the crustal thickness, and therefore the distance range in which we expect the transition of direct body wave spreading to post-critically reflected waves (e.g., Burger *et al.*, 1987).

As observed in Figure 9, many of the candidate GMPEs overestimate recorded ground-shaking across all periods of interest. The data considered herein are generally recorded at sample rates of 100 samples per second. Consequently, we can only compare response spectral periods at one-quarter the sample rate (i.e., 0.04 seconds) with any level of certainty owing to Nyquist frequency and aliasing effects.

The first Australian-specific attenuation models of Gaull *et al.* (1990), on which the present Australian hazard map is based, are compared to the data. Since Gaull *et al.* (1990) only produced models for peak ground motions (i.e., PGA and PGV), we tie spectral shape factors from those recommended in Standards Australia (2007) to Gaull *et al.* (1990) PGA estimates. Of note in the comparison of Western Australian data, the Gaull *et al.* (1990) model for Western Australia appears to work very well at short periods of ground shaking. However, at longer periods, where the model is dependent on the Standards Australia (2007) spectral shape factors, it performs poorly. The Liang *et al.* (2008) GMPE developed for Western Australia also performs quite well at short periods, but appears to overestimate ground shaking at longer periods.

While there is no model that perfectly matches the Western Australian dataset in the near-source distance range, the GMPEs that appear to perform the best across all periods are Atkinson and Boore (2006; BC crust), Allen (unpublished) and Chiou and Youngs (2008). The general overestimation of ground-motion by commonly used GMPEs (e.g., Toro *et al*., 1997) is of particular concern because previous studies have indicated that the de-aggregated hazard (and risk) is largely due to moderate-magnitude earthquakes at small distance ranges (e.g., Jones *et al.*, 2005). Since the Western Australian earthquakes we evaluate here are within the magnitude range in which the dominant hazard is expressed from previous studies, the results in Figure 9 suggests that previous studies in Western Australia which relied on these GMPEs have overestimated the hazard and risk associated with moderate-magnitude earthquakes.

The absence of ground-motion recordings from large-magnitude Australian earthquakes with which to validate GMPEs inevitably makes model selection subjective. The models currently included in the draft PGA map for cratonic Western Australia are Atkinson and Boore (2006; BC), Chiou and Youngs (2008), Liang *et al*. (2008), and Somerville *et al*. (2009; Cratonic) with weights between 0.1 and 0.5.

### *GMPE Comparisons with Eastern Australian Data*

We follow a similar analysis as above for the Eastern Australian dataset (Fig. 10). In total we aggregate 103 records across a range of $M_W$ 4.0-5.2 at distances less than 300 km. As above, we find that many of the GMPEs commonly considered for earthquake hazard analysis in stable continental regions appear to overestimate ground-motions recorded in eastern Australia for these moderate magnitude earthquakes. However, in the present analysis we note that both the hard rock and BC crustal models of Atkinson and Boore (2006) appear to have consistently low residuals across all period ranges against the eastern Australian data at distances less than 80 km. Other models that perform well are Chiou and Youngs (2008) and Allen (unpublished). While the coefficients for the Allen (unpublished) are not openly available, and will not be considered in the development of the draft hazard model (Burbidge and Leonard, 2011, present volume), the authors recognise that critical data were ignored in the development of this preliminary model, leading to an underestimation of ground-motion at short periods. This model does, however, tend to predict longer-period ground-motions most reliably across the full distance range considered. This confirms that the geometrical spreading model developed by Allen *et al.* (2007) – which controls longer period ground-motion – is generally suitable for use in eastern Australia.

In summary, GMPEs currently included in the draft map for eastern Australia are Atkinson and Boore (2006; BC), Chiou and Youngs (2008), and Somerville *et al*. (2009; Non-cratonic) with weights between 0.2 and 0.4.

## CONCLUSIONS

Herein we have described several techniques used to generate a more complete and homogenous earthquake catalogue to be used in the update of the Australian National Earthquake Hazard Map. Firstly, the catalogue takes advantage of an additional two decades of earthquake data gathered by seismic networks across the Australian continent. Relative to the previous version of the NEHM which used 9,000 earthquakes (Gaull *et al.*, 1990), the present analyses consider a base dataset of over 35,000 events to assess the average recurrence of earthquakes across continental Australia and the region. The catalogue is subsequently enhanced though the application of modern declustering and deblasting techniques. These techniques remove dependent events and anthropogenic sources from the catalogue, which would otherwise bias hazard estimates.

We have applied innovative techniques to account for use of disparate magnitude equations throughout the continent over time and standardise catalogue magnitudes. All known moment magnitudes from Australian earthquakes have been compiled to develop conversion equations between $M_L$ and $M_W$. These conversions deliver magnitudes that are consistent with the moment magnitude scale commonly used to calibrate modern GMPEs.

Ground-motion data recorded from earthquakes in Western Australia and eastern Australia have been compared to several candidate GMPEs currently being considered for use in the national hazard model update. Whilst no quantitative assessment of the candidate models has been undertaken at this time, we provide a semi-quantitative evaluation of various GMPEs based on simple residual analysis. In this analysis many of the models evaluated tend to overestimate ground motions across all periods of shaking. In particular, we find that the spectral shape factors tied to PGA, as recommended by Standards Australia (2007), overestimate ground-motions for moderate-sized earthquakes by over an order of magnitude at some periods. While the current Australian Standard specifies earthquake hazard as PGA, the spectral shape factor used to extend PGA predictions to other response spectral periods may be inappropriate relative to existing PGA hazard models and observed ground-motions.

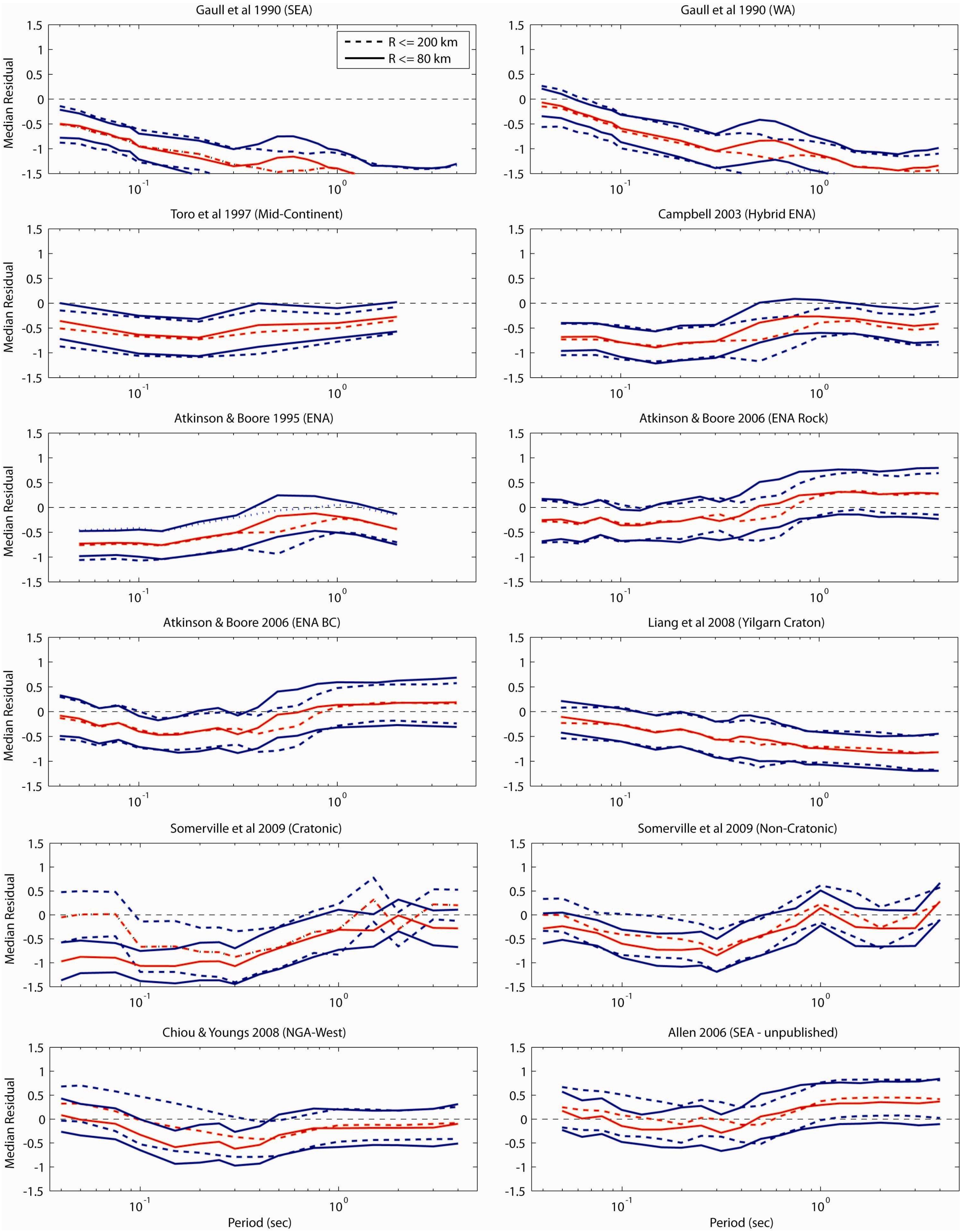



***Figure 9.*** *Residuals (log10 observed – log10 predicted) of 5% damped response spectral accelerations recorded from $M_W \geq 4.0$ earthquakes in the Yilgarn Craton, Western Australia at distances less than 80 km (solid lines) and less than 200 km (dashed lines), respectively. Median residuals (red lines) are plotted against spectral period with $\pm 1\,\sigma$ indicated (blue lines). Earthquake magnitudes are converted back to $M_L$ using the relations of Allen et al. (2011) for implementation in Gaull et al. (1990) and Liang et al. (2008). The Gaull et al. (1990) PGA models are combined with the spectral shape factors for rock sites as published in Standards Australia (2007).*

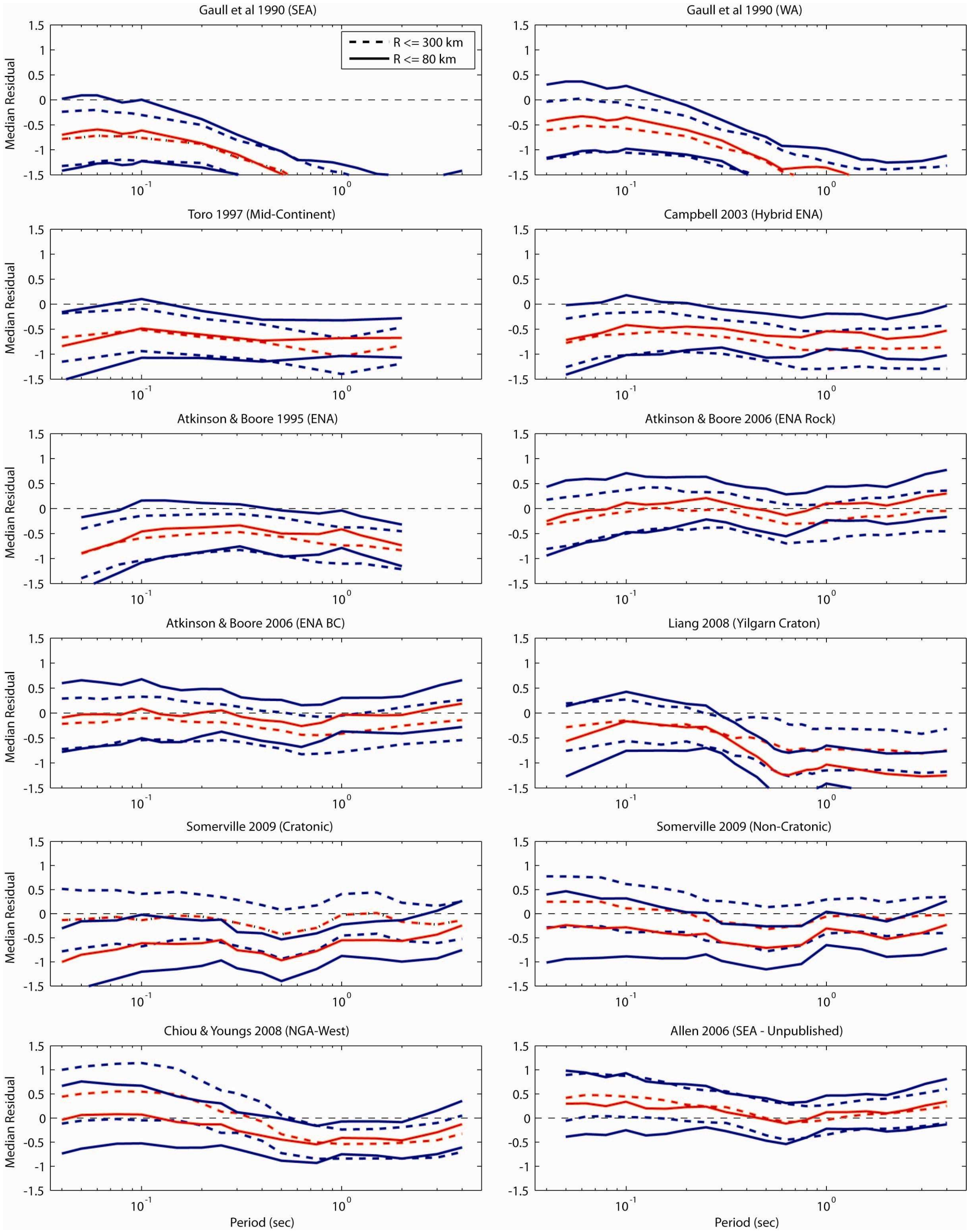



***Figure 10.*** *Residuals (log10 observed – log10 predicted) of 5% damped response spectral accelerations recorded from earthquakes in eastern Australia at distances less than 80 km (solid lines) and 300 km (dashed lines), respectively. Median residuals (red lines) are plotted against spectral period with ± 1* $\sigma$ *indicated (blue lines). Earthquake magnitudes are converted back to* $M_L$ *using the relations of Allen et al. (2011) for implementation in Gaull et al. (1990) and Liang et al. (2008). The Gaull et al. (1990) PGA models are combined with the spectral shape factors for rock sites as published in Standards Australia (2007).*

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