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Seismic hazard estimation in stable continental regions: challenges and opportunities

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ABSTRACT

Damaging earthquakes in Australia and other regions characterised by low seismicity are considered low probability but high consequence events. Uncertainties in modelling earthquake occurrence rates and ground motions for damaging earthquakes in these regions poses unique challenges on forecasting seismic hazard and the subsequent use of this information for improving seismic safety within our communities. Key challenges for these regions are explored, including: the completeness and continuity of earthquake catalogues; the identification and characterisation of neotectonic faults; the difficulties in characterising earthquake ground motions; the uncertainties in earthquake source modelling, and the use of modern earthquake hazard information to support the development of future building provisions.

1 INTRODUCTION

Forecasting seismic hazard in stable continental regions (SCRs) brings unique challenges to hazard modellers and practitioners in terms of the characterisation of seismic sources and their ground motions. By their very nature, SCRs experience significantly lower earthquake rates compared to tectonic plate margins, such as New Zealand. As a consequence, the typical observation period of historical (instrumental) seismicity is significantly shorter than the seismic cycle of rare large earthquakes that may generate extreme damaging ground motions on any given fault.

Seismic hazard assessments in SCRs are often more dependent on earthquake catalogues and the relationships between small-to-large earthquakes (e.g., Gutenberg & Richter 1944) than in seismically active regions, with a high-dependence on the rates of small-magnitude earthquakes to inform the occurrence rates for larger events. The completeness of earthquake catalogues, together with changes in observatory practice over time delivers challenges in ensuring the catalogue provides a consistent representation of an earthquake's size over time, making the estimation of earthquake occurrence parameters highly sensitive to these practices and the relative detection thresholds of the seismic networks.

The characterisation of seismic sources can be undertaken using several philosophical approaches, each of which are scientifically defendable. For the 2018 National Seismic Hazard Assessment (NSHA18) of Australia (Allen *et al.* 2018a), the epistemic uncertainty of seismic sources was incorporated through the inclusion of 19 independent models (Griffin *et al.* 2018), contributed by Geoscience Australia and third-party sources. This allowed for the exploration of source-model uncertainty, but presented further challenges in assessing the utility of different source-model types (e.g., smoothed or zoned seismicity) over different spatial scales and return periods of interest.

In Australia, the limited observation period is exacerbated by the sparse seismic recording network relative to the size of the continent. This means that even when a moderate-to-large earthquake does occur within the continental crust, it will often be poorly recorded in terms of its ground-motion accelerations. For example, the nearest seismic station to the 2016 M_W 6.1 Petermann Ranges earthquake in the Northern Territory (Hejrani & Tkalčić 2018; King *et al.* 2018) was located more than 160 km from the earthquake's coseismic rupture. Consequently, the use of rapid seismic deployment kits for these events are key, not only to understanding the mechanism of the earthquake rupture, but to also capture strong-motion data from potential large aftershocks. Nevertheless, the relative paucity in strong-ground motions recorded from Australian earthquakes presents challenges in characterising earthquake ground-motions and being able to weight appropriate ground-motion models (GMMs) for seismic hazard analysis (e.g., Ghasemi & Allen 2018). These models are commonly adopted from analogue tectonic regions. However, there are some unique characteristics for Australian earthquakes and recorded ground motions that make these decisions challenging in the absence of reliable locally-developed models.

In this contribution, some of the challenges facing seismic hazard analysis in slowly deforming continental interiors are discussed and opportunities to overcome these challenges are considered. Opportunities to advance earthquake hazard science for Australia to support improved building provisions are discussed in the context of the NSHA18 results.

2 IDENTIFICATION AND CHARACTERISATION OF ACTIVE FAULTS

Unique challenges are faced in modelling the seismic hazard from active (or neotectonic) faults in intraplate regions. Low fault slip rates relative to landscape modification rates often lead to poor discoverability of fault sources, and result in incomplete characterisation of rupture behaviour (e.g., Clark & Leonard 2014). As a case in point, none of the nine historical surface-rupturing earthquakes occurring within the Australian continent could have been identified from a topographic signature prior to their causative event (Clark & Allen 2018). However, regional and local assessments have demonstrated that fault sources assigned with activity rates consistent with paleoseismic observations have the potential to significantly impact on probabilistic seismic hazard assessments in Australia (Somerville *et al.* 2008; Clark & Leonard 2014; Griffin *et al.* 2016; Allen *et al.* 2018a).

Incompleteness of the neotectonic fault catalogue might be expected to result in an under-estimate of the hazard, especially in regions where landscape modification rates are comparable to, or exceed the rates of tectonic relief building (Clark *et al.* 2012; Clark & Leonard 2014). However, incompleteness in the fault catalogue might be offset by the knowledge that faults with lower slip rates and thus, low potential of discovery, are not expected to contribute significantly to ground-motion hazard for return periods that may affect ordinary-use structures (e.g., 475 or 2475 years). Nevertheless, the seismogenic characteristics (in terms of frequency, magnitude and temporal variability) of various combinations of geology, crustal architecture and geological history are underexplored and relatively poorly understood in terms of their seismic potential. These are significant challenges that face seismic hazard modellers in SCRs. However, new, openly-available high-resolution topographic datasets (e.g., elevation.fsdf.org.au/) are now becoming available across much of the continent. These data, combined with dedicated field investigations could enable improved discoverability and seismogenic characterisation of neotectonic faults across Australia.

3 DEVELOPING CONSISTENT CATALOGUES

Earthquake catalogues that have well-defined magnitude-completeness thresholds with magnitudes that are uniformly derived are fundamental inputs into any probabilistic seismic hazard assessment (PSHA) and are used to establish earthquake occurrence rates for a given area source zone (e.g., Leonard 2008) or spatially varying *smoothed seismicity* models (e.g., Griffin *et al.* 2017). In practice, neither the magnitude of completeness or consistent nor the magnitude consistency can be known to a high degree of certainty. Consequently, the reliance on this information to deliver occurrence forecasts for large earthquakes can contribute large uncertainties in seismic hazard.

Prior to the early 1990s, most Australian seismic observatories relied on the Richter (1935) local magnitude (M_L) formula developed for southern California (Leonard 2008). At regional distances (where many remote earthquakes are recorded), the Richter scale tends to overestimate M_L relative to modern Australian magnitude formulae (e.g., Michael-Leiba & Malafant 1992) by up to half an order of magnitude or more (Allen 2010). Consequently, historical earthquakes of the same energy release could have very different magnitudes depending on their location relative to the recording network.

Modern probabilistic seismic hazard assessments (PSHAs) rely on earthquake catalogues consistently expressed in terms of moment magnitude, M_W. However, M_W is still not commonly calculated for small local events by many national networks, including Australia. For use in earthquake recurrence calculations (i.e., Gutenberg & Richter 1944), magnitude conversion equations are often applied to convert M_L to M_W. Unless these conversions are time-dependent, they commonly assume that M_L estimation has been consistent for the observation period. Consequently, for earthquakes in Australia, there is a need to correct pre-1990 magnitude estimates to ensure continuity with current observatory magnitude estimation methods (Allen *et al.* 2018b). Ideally, this could be achieved using original amplitude and period picks. However, this presently cannot be easily achieved for pre-digital (and even some post-digital) data.

The challenge for the NSHA18 was to develop a catalogue of earthquakes with consistent local magnitudes, which could be converted to M_W. A method was developed that corrects magnitudes using the difference between the original (inappropriate) magnitude formula and the Australian-specific corrections at a distance determined by the nearest recording station likely to have recorded the earthquake. These corrections have decreased the rates of M_L 4.5+ earthquakes in the Australian catalogue by 50% or more (Figure 1). Secondly, the use of *ML-MW* conversion equations further decreases the magnitudes of moderate-sized earthquakes by approximately 0.2-0.3 magnitude units (Ghasemi & Allen 2017; Allen *et al.* 2018b).

To address ongoing challenges for catalogue improvement, Geoscience Australia is digitising printed and hand-written observations preserved on earthquake data sheets. Once complete, this information will provide a valuable resource that will allow for further interrogation of pre- and early-digital data and enable refinement of historical catalogues to improve future seismic hazard estimation.

4 GROUND-MOTION CHARACTERISATION

The aleatory variability within, and epistemic uncertainty between ground-motion attenuation models is often considered to contribute some of the largest uncertainties in PSHAs (Bommer & Abrahamson 2006; Al Atik *et al.* 2010). This is particularly true of SCRs such as Australia with few data recorded from moderate-to-large earthquakes. Nevertheless, ground-motion models (GMMs) that predict the intensity of ground shaking for a given magnitude and distance (on a given site class) form an essential component to modern

PSHAs. Whilst there is a paucity of data from which to develop empirical GMMs, simulation-based approaches (e.g., Liang *et al.* 2008; Somerville *et al.* 2009; Allen 2012) can be applied through the use of local earthquake source and propagation path characteristics (e.g., Allen *et al.* 2007).

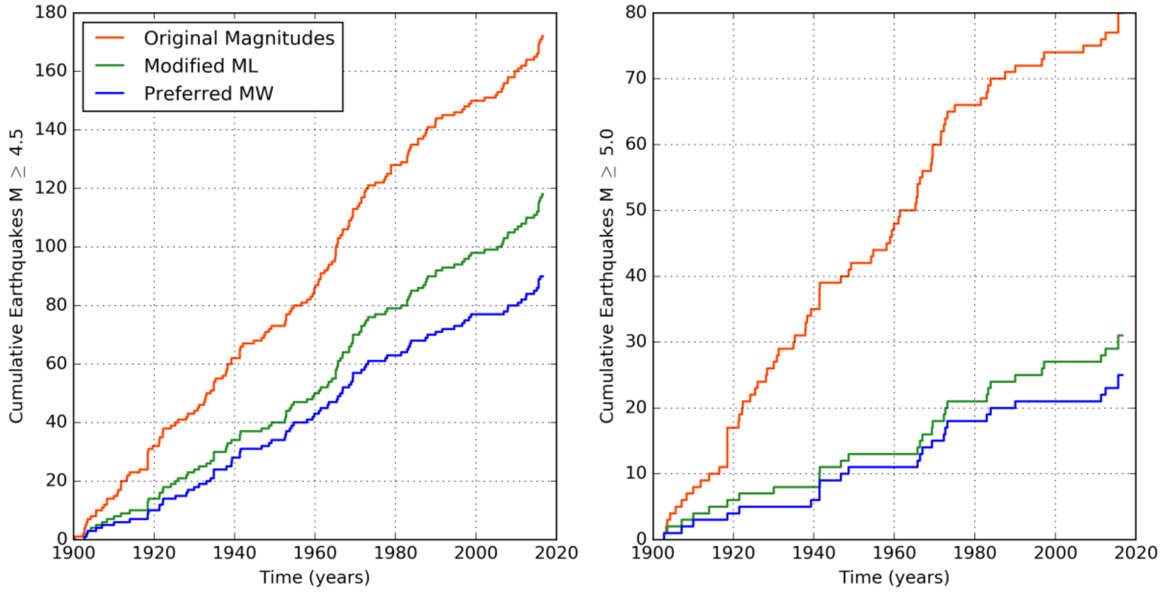

Figure 1: Cumulative number of earthquakes exceeding magnitude (left) 4.5 and (right) 5.0 for earthquakes in eastern Australia (east of 135°E longitude) since 1900. The different curves show different stages of the NSHA18 catalogue preparation: original preferred magnitudes (red curve), modified magnitudes (green curve; only local magnitude modified), and preferred M_W (blue curve; for all earthquakes).

The number of GMMs available for use in PSHAs continues to grow rapidly (e.g., Douglas 2018; Goulet *et al.* 2018) and choosing appropriate models for any given tectonic region type is a challenging task. Various measures can be applied to provide quantitative rankings of GMMs from local and analogue tectonic regimes (e.g., Scherbaum *et al.* 2009). Whilst these quantitative analyses can be informative, care should be taken not to over-interpret the results, particularly given the sparsity of ground-motion datasets available in Australia (Ghasemi & Allen 2018). For example, the use of quantitative ranking measures often reflect the overall performance of a model against the entire ground-motion dataset. However, this may undermine some desirable features of a GMM, such as model performance against near-field or long period data (e.g., Somerville & Ni 2010). Consequently, there is an ongoing need for professional judgement in this aspect of PSHAs for Australia.

Additionally, Australia possesses some ground-motion characteristics that are largely unique to the continent, which mean that it is difficult to simply use “off-the-shelf” GMMs from tectonically analogous regions. For example, many of the earthquakes occurring in Western Australia occur in the upper few kilometres where low-angle crustal detachments (e.g., Drummond *et al.* 2000) combined with high near-surface crustal stresses (e.g., Denham *et al.* 1980) appear to favour the occurrence of earthquakes at shallow depths. The very shallow hypocentres combined with a shallow lower-velocity crustal layer allow for the excitement of large *Rg* phases (Somerville *et al.* 2009) that dominate acceleration spectra at periods near 1 second (e.g., Somerville & Ni 2010) (Figure 2).

Other unique ground-motion characteristics are observed in northern Australia. At its nearest, Australia is just over 400 km from an active convergent plate margin. This complex tectonic region combines active plate subduction and the collision of the Sunda-Banda Arc with the Precambrian North Australian Craton (NAC) at the Timor Trough. This convergence is thought to be largely accommodated through the Flores and

Wetar backarc thrust zones (McCaffrey 1996), with recent studies suggesting the Timor Trough continues to accommodate some of this convergence (Saqab *et al.* 2017).

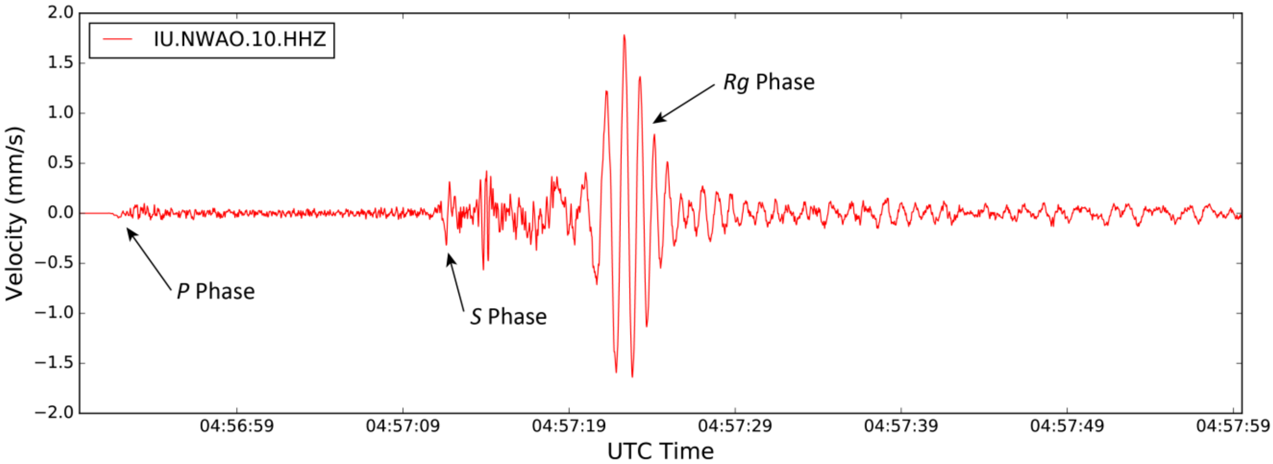

Figure 2: An example of a velocity seismogram, recorded at Narrogin (NWAO) during the 16 September 2018 M_W 5.3 Lake Muir, southwestern Western Australia earthquake. The station was approximately 170 km from the earthquake's epicentre. The record shows a strong Rg phase arrivals at longer periods (indicating a shallow rupture depth), which is characteristic of seismic recordings from this region.

Ground-motions generated from earthquakes on these sources have particular significance for northern Australian communities and infrastructure projects, with several large earthquakes in the Banda Arc region having caused ground shaking-related damage in Darwin over the historical period (Hearn & Webb 1984; McCue 2013). There are very few regions of the world where cold cratonic crust abuts a convergent tectonic margin with subduction earthquakes. Most ground-motions recorded from earthquakes in typical subduction environments are highly attenuated as they travel through volcanic back-arc regions (e.g., Ghofrani & Atkinson 2011). However, seismic energy from earthquakes in the northern Australian plate margin region are efficiently channelled through the low-attenuation NAC (Fishwick *et al.* 2005; Wei *et al.* 2017), which acts as a waveguide for high-frequency earthquake shaking (Kennett & Furumura 2008). The low rate of attenuation means that choosing ground-motion models for these subduction earthquakes that reflect both the earthquake source and attenuation characteristics of the region is a major challenge in PSHAs. For the NSHA18, a mélange of GMMs from different tectonic environments were applied to model ground motions from earthquakes in this environment. Subsequent analysis of recorded data from earthquakes in the region suggests that several of the selected GMMs tend to underestimate recorded ground motions from large ($M_W \geq$ 6.0) offshore plate boundary earthquakes (Figure 3). No one model performs well across all spectral periods. This demonstrates the need to develop new GMMs that are appropriate for the unique tectonic environment in northern Australia for application in future national-scale and site-specific seismic hazard assessments.

There is still much to do in terms of characterising ground-motions from Australian earthquakes for use in seismic hazard assessments, particularly due to the sparse recording networks and low rates of seismicity. However, knowledge in the character of ground-motion attenuation throughout the country is gradually evolving and recent successes, such as the rapid deployment of aftershock equipment following the 16 September 2018 M_W 5.3 Lake Muir, Western Australia earthquake, have yielded quality near-source data for other moderate-magnitude earthquakes (up to M_W 5.2) from the sequence. These data will have significant utility to enable more informed choices for GMMs for future hazard assessments and will underpin future empirical and simulated ground-motion studies for the nation. Ongoing enhancements to seismic monitoring networks also provide opportunities to augment existing ground-motion datasets.

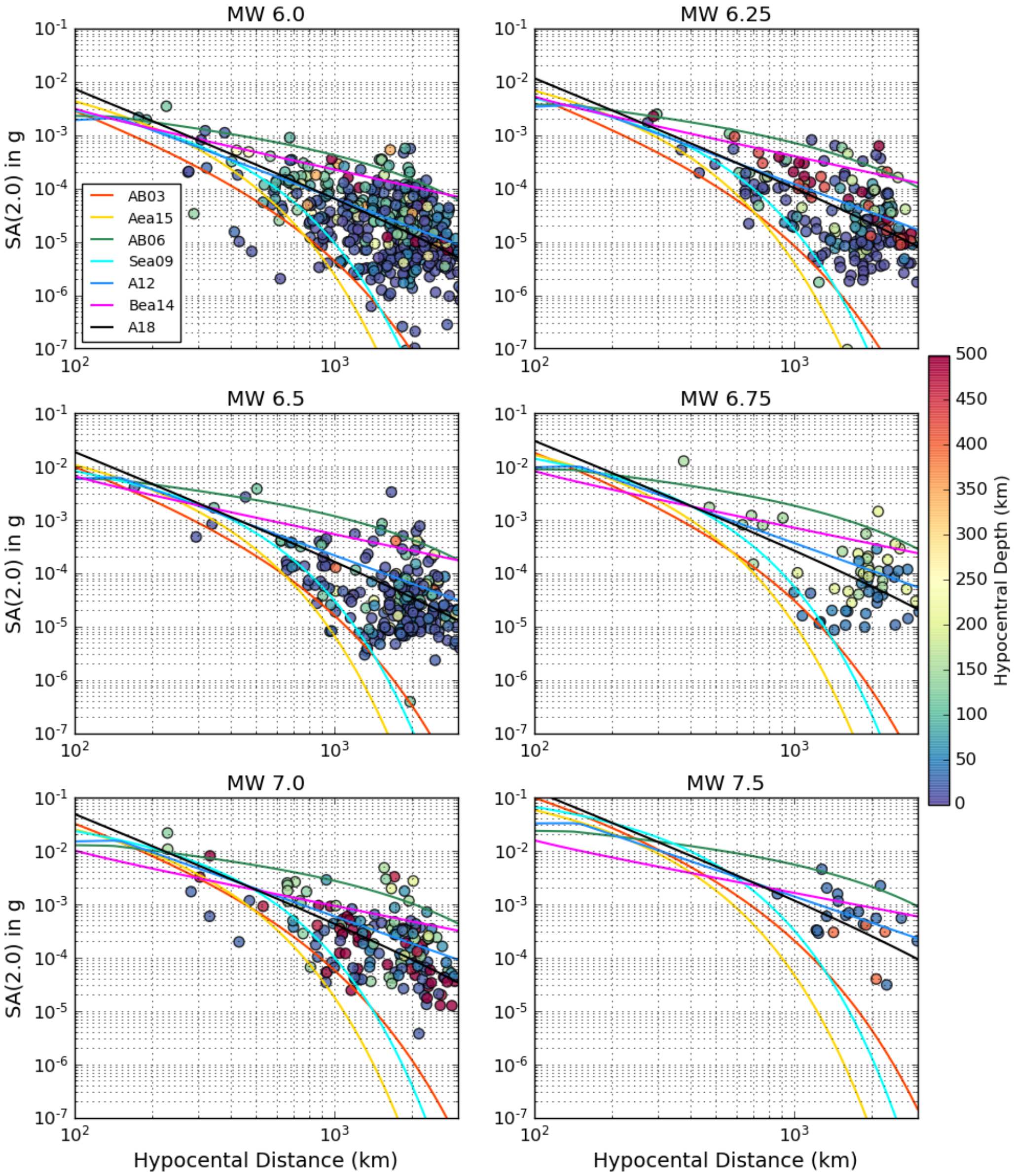

Figure 3: Recorded spectral accelerations (Sa) at 2.0 seconds at Australian sites from earthquakes occurring in the Sunda-Banda Arc region. Data are binned in 0.25-magnitude unit bins and are compared to GMMs nominated for use in the NSHA18 for the plate margin region for a rock site class: i.e., Atkinson & Boore (2003; AB03; intraslab);Abrahamson et al. (2016; Aea16; intraslab); Atkinson & Boore (2006; AB06; eastern US); Somerville et al. (2009; Sea09; Australia non-cratonic); Allen (2012; A12; southeastern Australia), and; Boore et al. (2014; Bea14; active crust). The A18 model refers to a "far-field" GMM in development at Geoscience Australia. Observations are colour-coded by the earthquake's hypocentral depth.

5 SEISMIC SOURCE CHARACTERISATION

Alternative seismic source models combined through a logic-tree approach are often used in PSHA to capture the epistemic uncertainty of multiple scientifically defensible alternatives (e.g., Bommer 2012). The calculated ground-motion hazard can be very sensitive to the location of classical area-source-model boundaries (Leonard *et al.* 2014). The placement of these boundaries is often subjective and can be dependent on the modeller's professional judgment and experience. Furthermore, if the modeller only considers one zone-based seismic-source model, the strongest hazard gradients will often tend to occur in the vicinity of the area source boundaries. Because the area-source boundaries developed by two (or more) independent modellers are unlikely to be duplicated exactly, the use of multiple seismic source models will introduce "fuzzy" source-zone boundaries and will act to damp these strong spatial hazard gradients. In the NSHA18, five different seismic source-model classes were used (Allen *et al.* 2018a). These include:

- *Background* area source zones that use broad geographic zones within which large earthquakes can occur anywhere with equal probability. These are typically models with 20 or fewer area-source zones on a national scale;
- *Regional* area source zones that assume the spatial distribution of seismicity is non-uniform at the scale of *background* source zones and that the distribution of historical seismicity is useful to forecast future earthquake occurrence. These are typically models with 30 or more area sources;
- *Seismotectonic* models (e.g., *regional* zones combined with a *fault-source* model; Clark *et al.* 2016);
- *Smoothed seismicity* data-driven models that yield spatially-varying earthquake occurrence rates by smoothing the observed rates of earthquake occurrence with a given smoothing kernel (e.g., Frankel 1995). These models assume that historical seismicity is a good predictor of future seismic hazard;
- *Smoothed seismicity* combined with a *fault-source* model.

The latter two source-model types represent minor variations on the *regional* and *smoothed seismicity* models. In total, the NSHA18 used 19 independent seismic source models for estimating the rates of earthquake occurrence at any given location in continental Australia (Allen *et al.* 2018a). These source models were weighted through a logic-tree framework (Griffin *et al.* 2018) and each provide a unique spatial representation of hazard (Figure 4). As demonstrated in Figure 4, the consequence of using *background* source models (Figure 4a) may lead to lower seismic hazard values where seismicity has been relatively stationary in the instrumental era (Leonard 2008) (Figure 4b-c). This raises questions over the appropriateness of including *background* zones for some areas such as the Flinders Ranges, the Latrobe Valley and the eastern highlands regions, where a century of historical data suggests seismicity in these regions is relatively stationary in space and time (Leonard 2008).

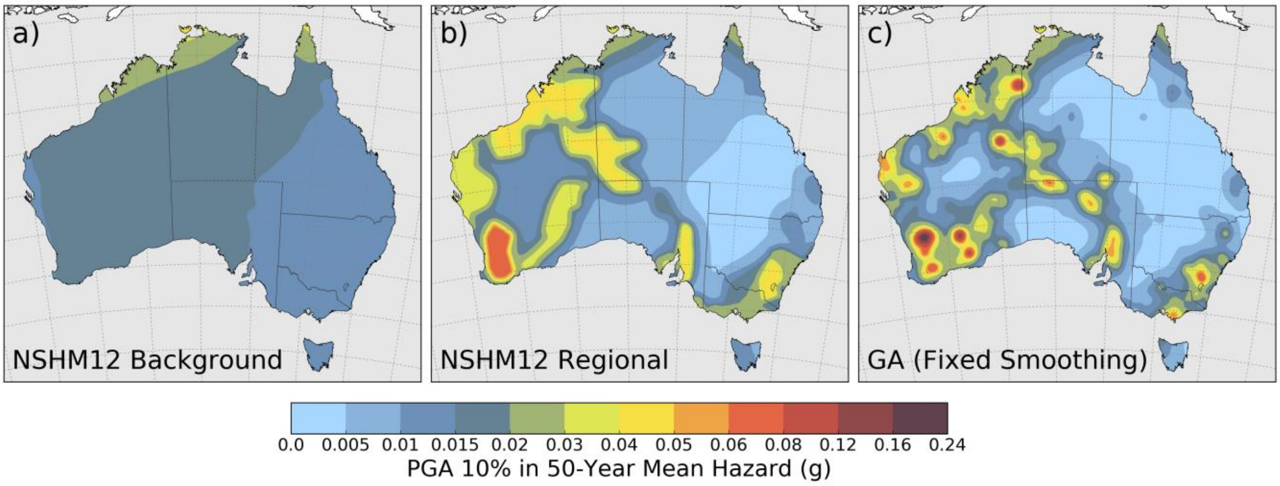

Figure 4: The mean 10% in 50-year PGA hazard expressed by three end-member source model types as used in the NSHA18: a) broad background zones (NSHM12; Leonard et al. 2012); b) regional area sources (NSHM12; Leonard et al. 2012), and; c) smoothed seismicity (GA Fixed Kernel; Griffin et al. 2017).

One challenge for forecasting seismic hazard for SCRs is the long recurrence times for large earthquakes. While the use of *background* source models may need to be reconsidered for eastern Australia, there is mounting evidence in central and western Australia to suggest that seismicity is non-stationary over time and could vary over decade-long timescales (Leonard 2008; Clark *et al.* 2012; Clark & Allen 2018). Therefore, the use of *background* source models that allow for large earthquakes to migrate spatially over longer timescales may become more important. Hazard modellers must therefore strike a balance between these end-member models when calculating seismic hazard at national scales. Furthermore, the relative weight placed on a specific model type (e.g., *smoothed seismicity*, *regional* or *background*) might vary spatially, and also on the target return period of interest (e.g., Woessner *et al.* 2015).

6 QUANTIFYING MODELLING UNCERTAINTY

In developing national-scale PSHAs, the mean hazard is commonly presented with little attention given to the range of potential end-member solutions. This ensemble of solutions arises through the use of weighted logic-tree distributions based on the decisions of seismic-hazard modellers to consider alternative source and ground-motion models. End users often perceive the mean results from PSHAs to be an accurate representation of reality (Lee *et al.* 2018). However, it is becoming increasingly important to communicate the mean hazard results from PSHAs in the context of their uncertainties. This ensures that hazard assessments are both transparent and defensible to end users and the wider seismological community (Stein *et al.* 2012; Douglas *et al.* 2014). Exploring these modelling uncertainties can improve our understanding of the sensitivities of seismic hazard to specific choices made though the modelling process.

To provide a sense of the relative contribution of each source-model type to a national-scale PSHA, the 0^{th} to 100^{th} hazard fractiles for eight representative NSHA18 seismic-source models are calculated and plotted as cumulative density functions (CDFs). Figure 5 shows the spread of uncertainty in seismic hazard both within and between the candidate seismic-source models for the Australian capital cities. There is comparatively little epistemic uncertainty between the source models for Darwin (Figure 5b) because the hazard is driven by the plate margin seismic source model (Griffin & Davies 2018), which is common between all source models.

For the eastern capital cities (e.g., Canberra, Melbourne and Sydney), the *background* and *regional* source model CDFs tend to cluster in their respective model classes, with the *regional* models typically forecasting larger ground motions than the *background* models at the 10% probability of exceedance in 50-year level. The between-model variability for Canberra (Figure 5f), in particular, shows significant disparities between the *background* and *regional* source models. Given the relatively high and steady rate of seismicity in the Canberra region, the use of *background* seismic source models that envelope Canberra and characterize the chance of random earthquakes occurring anywhere within a broad tectonically analogous region, may have limited applicability. Consequently, it is recommended that for future national-scale hazard assessments for Australia, that the consequences of choices made during the expert elicitation process (Griffin *et al.* 2018) be reviewed prior to finalising the hazard model. The primary limitation to this approach, however, is that the experts may prejudice their responses to achieve specific outcomes. The benefits of this approach therefore need to be balanced against the potential for undermining the original intent for the expert elicitation.

7 SHAPE OF HAZARD CURVES

One of the major differences in seismic hazard between active tectonic regions (ATRs) and SCRs is how the shape of the hazard curve changes with decreasing probabilities of exceedance. Figure 6 shows a comparison of seismic hazard curves for selected Australian sites as calculated in the NSHA18 relative to hazard curves from a recent assessment of seismic hazard for sites in New Zealand (Abbott *et al.* 2019, in prep.). By normalising the curves to an arbitrary exceedance probability (Figure 6b), the difference in the rate of change of the hazard curves between the SCR and the New Zealand ATR sites is more clearly expressed, with the hazard for a typical Australian site increasing at a much faster rate at low probabilities (or longer return periods) than typical sites in New Zealand. This is a common feature found in other hazard assessments that consider both SCRs and ATRs (e.g., Leyendecker *et al.* 2000).

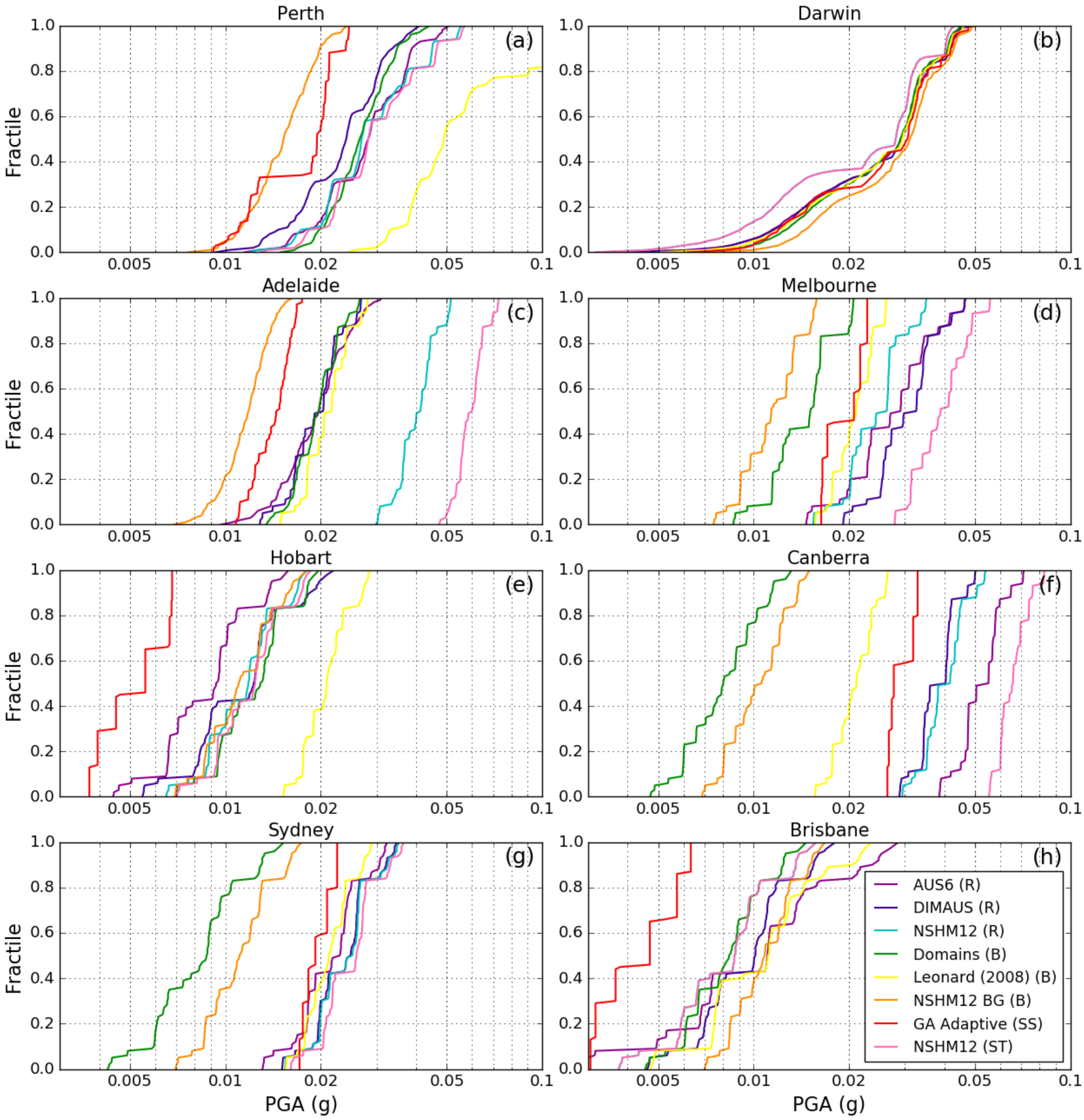

Figure 5: Cumulative density functions between representative regional (R), background (B), smoothed seismicity (SS) and seismotectonic (ST) seismic source models used in the NSHA18. The CDFs indicate the PGA ground-motion for a 10% exceedance probability in 50 years for Australian capital cities and show the variation in uncertainties both within and between the candidate seismic source models. Note that not all of the models represented above receive equal weighing in the final source model logic tree (Allen et al. 2018a; Griffin et al. 2018).

While the current design probability in Australia for ordinary-use structures is 1/500 annual exceedance probability (AEP), it is necessary to scale seismic hazard to different ground-motion return periods for the design of high-importance structures, in particular. In the *AS1170.4–2007*, this is achieved using the probability factor (k_p), which is equivalent to the return period factor R_S or R_U in the *NZS 1170.5–2004* (Standards New Zealand 2004). The *AS1170.4–2007* uses the same factors as defined in the *NZS 1170.5–2004*. The k_p factor is calculated by normalising the hazard curve by its value at a recurrence interval of 500 years. As with the 2012 National Seismic Hazard Maps (NSHM12; Burbidge 2012; Leonard *et al.* 2013), the k_p factors derived from the NSHA18 differ markedly from those factors given in the current Standard, with a national average of k_p = 3.15 at the 1/2500 AEP, compared to k_p = 1.8 in the *AS1170.4–2007*.

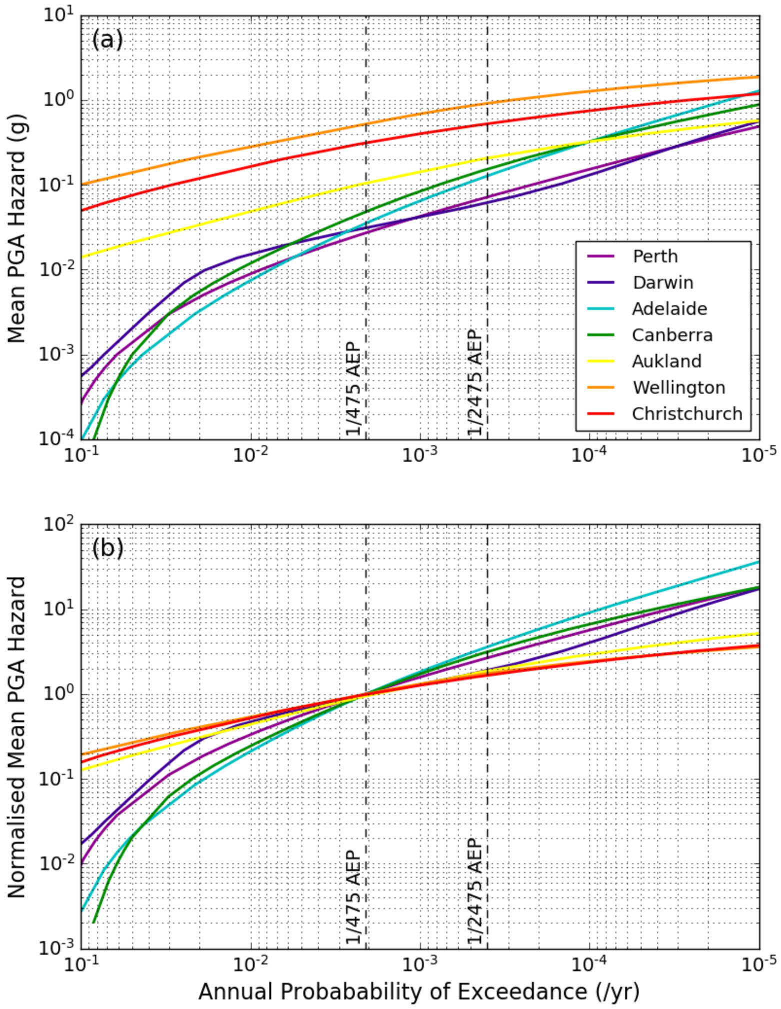

Figure 6: Top panel (a) show NSHA18 PGA hazard curves for representative Australian (Perth, Darwin, Adelaide and Canberra) and New Zealand (Auckland, Wellington and Christchurch) cities. Bottom panel (b) shows the same hazard curves normalised at the 1/475 AEP to emphasise rate of change of hazard curves between Australian (SRC) and New Zealand (ATR) localities.

Figure 7 shows the comparison of k_p factors for the eight capital cities across Australia. It is clear that there is a large variation in the k_p factors among these localities. Differences in k_p factors between localities expresses the difference in the shape of the seismic hazard curve (e.g., Figure 6). In seismically active regions, moderate-level ground shaking has a higher chance of being exceeded than in SCRs. Sites in SCRs with low 1/500 AEP hazard will start from a lower base level (e.g., Brisbane). Consequently, k_p factors will rise more rapidly when rare events occur because the 1/500 hazard levels will be more easily exceeded over longer return periods. However, this explanation does not hold true for sites affected by seismogenic faults, such as Adelaide. The k_p factors for Adelaide are among the highest because of the nearby fault sources, which do not contribute significantly to the hazard at the 1/500 AEP due to their long recurrence intervals (Clark *et al.* 2016). However, these fault sources will tend to contribute proportionately more to seismic hazard at higher return periods, as is demonstrated for the k_p curve for Adelaide.

The k_p curve for Darwin appears to mimic the factors in the *AS1170.4–2007*, which were derived from the factors determined for tectonically active New Zealand (Standards New Zealand 2004). The dominant sources of hazard to Darwin are the plate margin earthquakes off northern Australia (i.e., Griffin & Davies 2018). Because these sources occur in ATRs, northern Australian sites are likely to exceeded moderate levels of ground shaking with shorter return intervals. Consequently, the hazard increase at lower probabilities of exceedance for Darwin occurs at a slower rate relative to typical SCR sites, where the hazard contribution of large rare earthquakes leads to faster increases in seismic hazard for decreasing probabilities of occurrence (e.g., Leyendecker *et al.* 2000; Nordenson & Bell 2000). This suggests the need for site-specific hazard scaling for different return periods for future seismic design provisions.

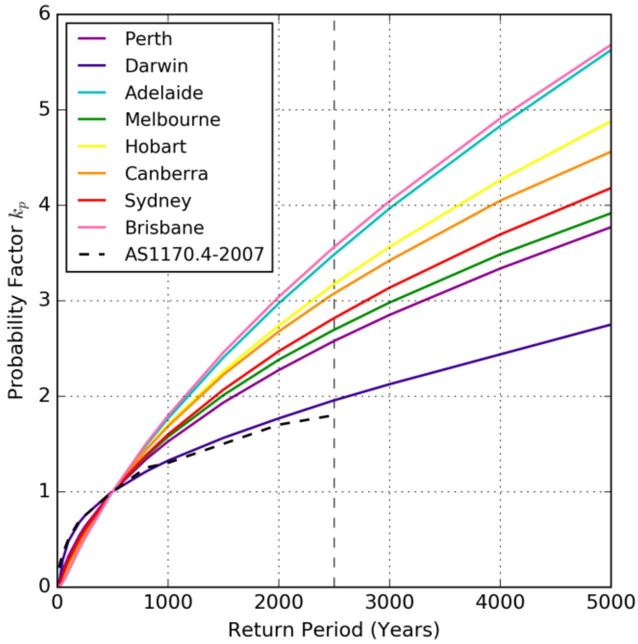

Figure 7: The PGA probability factor (k_p) for the eight capital cities compared to the k_p values in AS1170.4–2007. The factors are calibrated such that k_p = 1.0 for a 1/500 AEP. The thin vertical dashed line indicates a ground-motion return period with an annual exceedance probability of 1/2500.

The commentary above focusses on hazard expressed in terms of PGA. A recent paper by Allen & Luco (2018) discusses further opportunities to update building provisions for Australia by considering the adoption of uniform hazard spectra, which unlike the fixed spectral shape in the *AS1170.4–2007*, offers uniform hazard estimates across all oscillation periods at all localities (e.g., McGuire 1977).

8 CONSIDERATIONS FOR FUTURE BUILDING PROVISIONS

The selection of the 10% exceedance probability in 50 years for the first United States (US) National Seismic Hazard Maps was originally a rather arbitrary decision and appeared to be a “reasonable” choice to ensure structures “remain operable” following large earthquakes (Algermissen & Perkins 1976). This probability level was generally viewed to be appropriate for the average recurrence of large damaging earthquakes in well-studied ATRs such as California, and was also considered suitable for collapse prevention. Given that this was best practice for the time, this exceedance probability was also adopted by the *National Construction Code of Australia* (e.g., Australian Building Codes Board 2016) for use in the first edition of the *AS1170.4–1993* (Standards Australia 1993).

However, in the late 1990s, concerns were raised by engineers and seismologists in the US that anchoring design hazard values to 1/475 AEP would result in significant disparities in the seismic performance of ordinary-use structures across the country, with regions of low-to-moderate levels of seismicity being considerably more at risk to extreme ground-motion events (e.g., Nordenson & Bell 2000; Federal Emergency Management Agency 2004; Wilson *et al.* 2008). These concerns led to the adoption of seismic design ground-motion demands for a 2% probability of exceedance in 50 years (1/2475 AEP) for the *International Building Code* developed in the US. This change in the exceedance probability level was adopted in the *National Building Code of Canada (NBCC)* shortly thereafter (Heidebrecht 2003). The 1/2475 AEP level is thought to more closely relate to the probability of structural collapse for regular structures (Bommer & Pinho 2006). The adoption of this ground-motion exceedance probability leads to several advantages:

- In low-to-moderate seismicity regions, there is a larger difference between 1/475 and 1/2475 AEP ground-motions than in more tectonically active regions (e.g., Allen & Luco 2018). Transitioning to lower exceedance probabilities in the national design provisions reduces the risk in low-to-moderate seismicity regions due to rare extreme ground motions (Leyendecker *et al.* 2000);
- The rate of attenuation of earthquake ground-shaking is generally lower in stable continental regions (SCRs) like Australia (e.g., Frankel *et al.* 1990; Bakun & McGarr 2002). Thus, these provisions protect against rare events that have the potential to affect larger areas than in tectonically active regions;
- Structures in low-to-moderate seismicity regions would be designed with more comparable seismic resistance (combined strength and ductility) to structures in high seismicity regions;
- In many cases, effective seismic resistance for new construction can be achieved at minimal incremental cost (Nordenson & Bell 2000).

Australia has much in common in terms of the vintage of urban development and tectonic setting with eastern North America (e.g., Bairoch & Goertz 1986). Given that both Canada and the United States have recognised that 10% probability of exceedance in 50 years does not provide seismic protection to extreme ground motions from rare events in their low-seismicity settings, it would seem sensible that Australia too, should review appropriateness of the probability levels currently required for ordinary-use structures by the *National Construction Code*. This is underscored by the significant reductions in its seismic hazard forecasts at the 1/500 AEP through the NSHA18 (Allen *et al.* 2018a).

In general terms, a 1/500 AEP means that in any 50-year period, we should expect approximately 10% of the Australian continental landmass to experience shaking exceeding mapped values (e.g., Ward 1995; Allen *et al.* 2009; Vanneste *et al.* 2018). This exceedance level is approximately equivalent to a fractional area equivalent to the state of New South Wales. As earthquake scientists and engineers, it is reasonable to ask whether this exceedance probability level is acceptable. The *AS1170.4–2007 (R2018)* (Standards Australia 2018) uses the original *AS1170.4–1993* seismic hazard factors, but now requires a minimum design PGA level of 0.08 g. Figure 8 maps the ratio of the NSHA18 1/500 and 1/2475 AEP PGA values relative to the *AS1170.4–2007 (R2018)* values. If we assume a 1/500 AEP is appropriate for design and construction in Australia, a pragmatist might argue that if the current provisions are adequate for all localities (Figure 8a). Therefore, there would be little-to-no risk in *not* updating the underlying hazard maps with the modern hazard estimates. However, this all depends on whether we, as a community, are comfortable with the 10% in 50-year exceedance level. If the response is "no", and we now compare the existing provisions required for ordinary-use structures with the NSHA18 1/2475 AEP PGA values, we see that there are now several localities where the lower-probability seismic hazard exceeds that of the current design provisions (Figure 8b). Critically, some of these localities include major urban centres of Canberra, Melbourne and Adelaide, as well as strategically important localities such as Morwell in the Latrobe Valley (Victoria) and Port Hedland off the northwest shelf (Western Australia). Therefore, these localities could be vulnerable to ground-motions from extreme events. In line with the *AS1170.4–2007* amendment adopted in 2018, minimum base shear design values could apply for the remaining low-hazard jurisdictions (e.g., Humar 2015). Consequently, any considerations for updating future design provisions in Australia should carefully consider the seismic design probability required for ordinary-use structures and whether these design levels meet community expectations for seismic safety.

9 CONCLUSIONS

This contribution discusses some of the challenges facing seismic hazard analysis in SCRs, with emphasis on Australia. In particular, challenges relating to completeness and quality earthquake catalogues, ground-motion and seismic source model characterisation and their influence on seismic hazard estimates are discussed. While many of these challenges will require ongoing monitoring and research, there are several opportunities to improve seismic hazard estimation by utilising existing datasets and methods. However, philosophical challenges will remain in terms of how to best model seismic hazard at different spatial scales for varying return periods of interest. In the face of these uncertainties, there are still opportunities to advance earthquake hazard science for SCRs to improve building provisions and these should be prioritised to improve seismic safety within our communities and to secure major infrastructure assets.

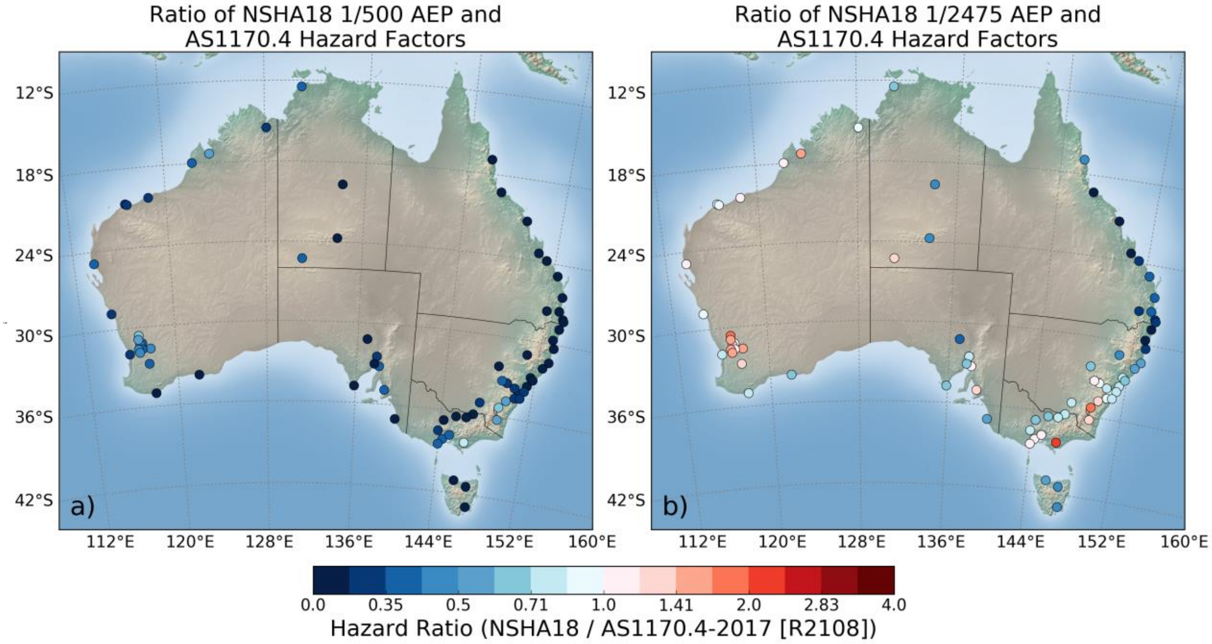

Figure 8: Comparison of seismic hazard design factors at AS1170.4 localities illustrating a) the ratio of NSHA18 1/500 AEP PGA relative to the AS1170.4-2007 [R2018] and b) the ratio of NSHA18 1/2475 AEP PGA relative to the AS1170.4-2007 [R2018] hazard design factors.

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