

Development of the 2018 Australian National Seismic Hazard Assessment (NSHA)

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Abstract

The 2018 revision of Australia's National Seismic Hazard Assessment (NSHA18) represents a substantial improvement from the 2013 NSHA. In particular, this revision will include a fault source model, an improved and more homogeneous earthquake catalogue, and greater epistemic uncertainty through a call for third party source models. This paper presents updated models of seismicity and ground motion that are currently being developed at Geoscience Australia for the NSHA. We use the OpenQuake software to calculate seismic hazard for Australia and compare with OpenQuake implementations of third-party models and the 2013 NSHA. Weighting of logic tree branches for alternative models are discussed, and how these relate to the fundamental datasets on which they are based. A smoothed seismicity source model is developed based on recent seismicity while fault source models derived from neotectonic fault data consider a much longer time history. Final weightings, including for third party models, will be determined in consultation with members of the Australian seismological community.

Keywords: national seismic hazard assessment, fault source model, area source model, smoothed seismicity



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1. INTRODUCTION

Geoscience Australia (GA), as the custodian of the Australian National Seismic Hazard Assessment (NSHA), is leading an update of the 2013 NSHA to inform the 2018 revision of earthquake loading standards under AS1170.4. The NSHA is being developed collaboratively by the Australian seismological community, who are invited to contribute national scale earthquake source models. This paper firstly outlines the fundamental improvements compared with the 2013 NSHA (Burbidge 2012; Leonard *et al.* 2013, 2014). Secondly, the source models that are being developed by GA (seismotectonic, background and smoothed seismicity models) are presented. This is followed by outlining the process by which all source models (i.e. GA's and third party contributions) will be implemented into the OpenQuake probabilistic seismic hazard assessment (PSHA) software (Pagani *et al.* 2014), and the expert elicitation methodology that will be used to assign weights to the different models and sub-components.

2. ADVANCES SINCE THE 2013 NSHA

There are three fundamental advances that are expected to improve the robustness of the 2018 NSHA compared with the 2013 NSHA: inclusion of a fault source model into a seismotectonic source model; a homogenised earthquake catalogue; and inclusion of epistemic uncertainty around source models through a logic tree approach.

2.1 Inclusion of a fault source model

Geoscience Australia's neotectonic features database (ANFD, <http://www.ga.gov.au/earthquakes/staticPageController.do?page=neotectonics>) captures faults that have surface expressions in the Australian landscape. Palaeoseismological studies of a limited number of neotectonic faults indicates variation in fault behaviour across different geological provinces of the Australian continent, and this has been captured in the neotectonics domain model (Clark *et al.* 2012). This model allows us to characterise the seismicity of individual fault features within a domain based on those features where earthquake histories have been recovered through palaeoseismological studies. The 2013 NSHA used the neotectonic domains model to characterise spatial variation in maximum magnitudes, but individual fault features were not modelled. For the 2018 revision, a fault source model will be combined with area source zones to create a seismotectonic source model (see Clark *et al.* 2016).

A key challenge in including fault source models is accounting for the episodic fault behaviour that is seen in the palaeoseismological record (Clark 2012; Clark *et al.* 2014b, 2015b), where several large earthquakes may occur on a fault over several thousand to a few tens of thousands of years followed by tens to hundreds of thousands of years with no apparent activity. Inclusion of epistemic uncertainty around whether the episodic model is correct (compared with a periodic model), and if it is, whether we are currently in an active or quiescent period, can be included through a logic tree approach following Stirling *et al.* (2011) and Petersen *et al.* (2015). This is discussed further in Clark *et al.* (2016).

2.2 Towards a homogeneous earthquake catalogue

This component involves development of a consistent earthquake catalogue based on moment magnitudes (M_w) that will primarily be derived from the mixed magnitude type (primarily M_L) GGCat earthquake catalogue (Gary Gibson, *pers. comm.*). A first

step is the calculation of moment magnitudes using recent instrumental data (at present M_w has been calculated for ~100 earthquakes between 2005-2015, see Ghasemi *et al.* (2016). This database of earthquakes with M_w will then be used to revise local magnitude (M_L) scales resulting in development of a new scale that is pinned to the moment magnitude scale using a methodology similar to that used to revised New Zealand's M_L scale (Ristau *et al.* 2016). This will allow recalculation of events with digital waveform data to a consistent M_L that can directly be converted to M_w . The final step is then developing regressions to convert older M_L values, for which digital or digitised waveforms are not available, to the consistent magnitude scale.

As this work is still in progress, the results presented in this paper use the same declustered catalogue and magnitude-completeness ranges used for the 2013 NSHA. This catalogue contains earthquakes until 2010 and is shown in Figure 1. For further details on the catalogue, declustering and completeness see Burbidge (2012).

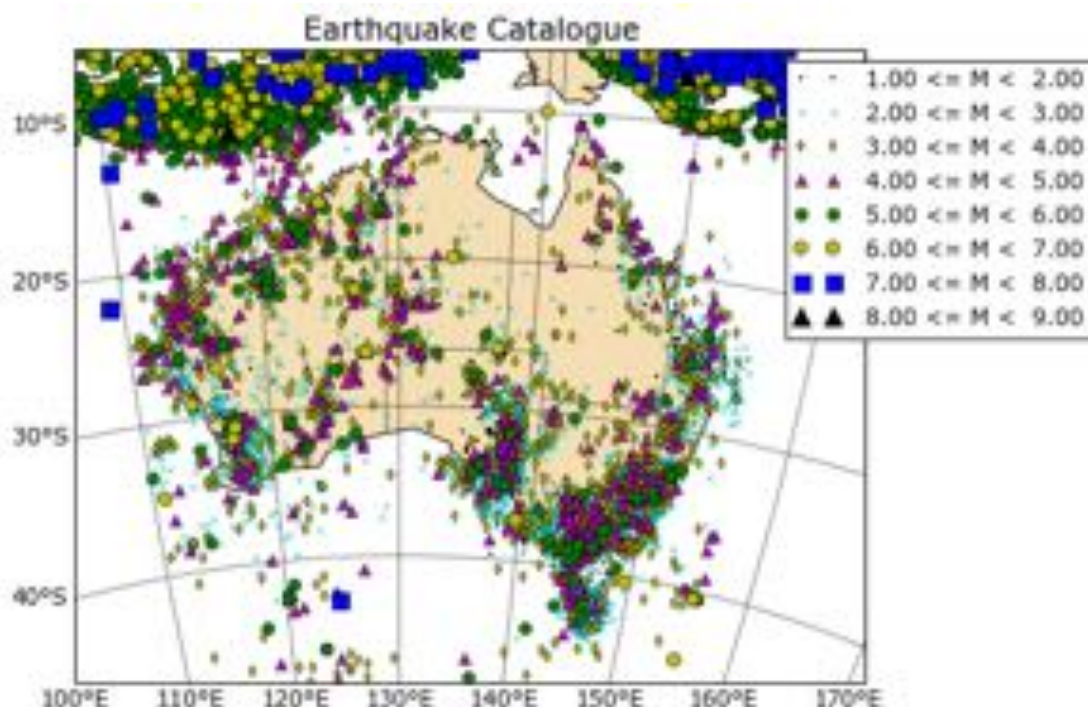


Figure 1: Declustered earthquake catalogue from 2010 used for the analysis presented in this paper

2.3 Inclusion of epistemic uncertainty through a logic tree approach

Epistemic uncertainty in hazard models can manifest through alternative models that explain the seismicity and ground motion characteristics of Australia. The 2013 NSHA included epistemic uncertainty in ground motion models (GMMs) formally through the use of logic trees. Alternative seismicity models (background, regional and hotspot) were not included using a logic tree approach, instead the results of each model were combined using various post-processing averaging of the results. For the 2018 revision, a call for third party source models has been made by GA to the Australian seismological community, through the Australian Earthquake Engineering Society, resulting in an additional five source models being contributed beyond the three developed at GA.

Alternative source models that meet the criteria outlined in the call for third party models will be included through the use of different logic tree branches. These branches will be assigned different weights using an expert elicitation methodology (Cooke 1991; Cooke & Gossens 1999; Gerstenberger *et al.* 2016). The expert

elicitation methodology asks a group of experts a series of calibration questions to assess both their understanding of the science and their capability to estimate uncertainty bounds around their own knowledge. Based on this assessment each expert is assigned a weight, which is applied to their assessment of what the weight of the different logic tree branches should be.

3. GEOSCIENCE AUSTRALIA'S EARTHQUAKE SOURCE MODELS

3.1 Seismotectonic model

GA's seismotectonic model is an update of the 2013 NSHA source model (area source zones model) with the addition of neotectonic faults from the Australian Neotectonic Features Database. New seismicity parameters (i.e. Gutenberg-Richter a and b values) for the 2013 NSHA source zones will be calculated once the final homogenised catalogue is produced (Ghasemi 2016). The geometries of faults from the ANFD have been simplified (see Clark *et al.* 2016) and modelled with constant dip (i.e. OpenQuake simple fault geometry). Although some faults are known to have depth-varying dips from seismic reflection profiles, for many there is no information concerning the characteristics and depth and dip must be inferred from the surface expression and stress regime (i.e. whether thrust, normal or strike-slip fault). Sensitivity testing presented below demonstrates that hazard results are not strongly sensitive to uncertainty in fault dip. Therefore for a first inclusion of faults into the hazard map it is reasonable to apply simple fault models that do not account for depth-varying dip.

Inclusion of fault models requires the total seismic moment in the model to be balanced between area and fault sources. Four methods can be proposed for doing this:

1. Adding the fault source model to the area source model without any moment balancing. This may lead to double counting of the seismic moment rate in areas where a significant portion of observed seismicity (used to parameterise the area source model) occurs on faults included in the fault source model.
2. Using the instrumentally observed catalogue to define the magnitude-frequency distribution for small magnitude events (e.g. $M_w < 6.0$) only for area source models, and modelling all larger events as occurring on faults (e.g. Stirling *et al.* 2012). This method has the advantage of being relatively simple to implement, however has the disadvantage that it does not account for the possibility of a large magnitude earthquake occurring on an unknown fault (e.g. the 21 May 2016 M_w 6.1 Petermann Ranges earthquake). Given the incompleteness of the fault database, particularly for northern Australia, and the long periods of time for which faults can be quiescent allowing surface expressions to be eroded, it is important to allow for maximum magnitude earthquakes to occur in regions where active faults haven't been mapped.
3. Reducing the maximum magnitude locally for those regions within an area source model that are within a defined distance (e.g. 10 km) of a fault. This is similar in approach to 2, but has the advantage of allowing larger earthquakes to occur within the area source zone away from the known faults within the fault source model.
4. Assuming that a portion of the area zone seismicity occurs on the faults within the zone, and reducing the activity rate of the fault model by the portion of background seismicity to avoid double counting seismicity (e.g. Cipta *et al.* 2016). This method is sensitive to assumptions about what volume of the area source zone should be considered to capture the seismicity on the fault, with

Cipta *et al.* (2016) defining a 10 km buffer based on formal earthquake location uncertainties in their catalogue.

Geoscience Australia is currently undertaking sensitivity analysis to test the different methods to determine which is most appropriate for the 2018 NSHA. A related challenge is that we do not have an independent constraint on the total seismic budget. Geodetic measurements undertaken by Geoscience Australia indicate a continent-wide strain rate of 0.1 +/- 0.2 mm/yr, indistinguishable from noise, although these measurements do provide an upper bound.

3.2 Background area zones (Leonard 2008) model

This background model is based on the broad zonation of Australian seismicity described in Leonard (2008) with slight modification (Figure 2). Leonard (2008) defined four areas of high seismicity: North West Australia, South West Australia, South Australia and South East Australia. The remainder of Australia is divided into zones of extended margin (North West Margin and South East Margin), cratonic (remainder of central and western Australia) and non-cratonic (remainder of eastern Australia). Gutenberg-Richter *a* and *b* values are calculated for each of the zones using a maximum likelihood method (Aki 1965) and are presented in Table 1. The *a* value is defined as the base 10 logarithm of the annual rate of earthquakes with $M_w \geq 0$. The present recurrence information is calculated from the 2013 NSHA catalogue, to be revised once the final catalogue is completed.

Table 1: Source zone parameters for the Leonard 2008 model. Note that these parameters will be revised once the homogenised catalogue is finalised.

Name	Abbreviation	Area (10000 km ²)	b	a
<i>High seismicity zones</i>				
South West Australia	SW	17.5	0.905	3.190
North West Australia	NW	119.9	0.819	3.347
South Australia	SA	40.4	1.020	3.870
South East Australia	SEA	86.3	0.841	3.536
<i>Background zones</i>				
North West Margin	NW Margin	36.9	0.940	2.276
West Central	West Central	618.3	0.840	3.595
East	East	268.5	0.810	3.238
South East Margin	East Margin	17.6	1.000	1.454

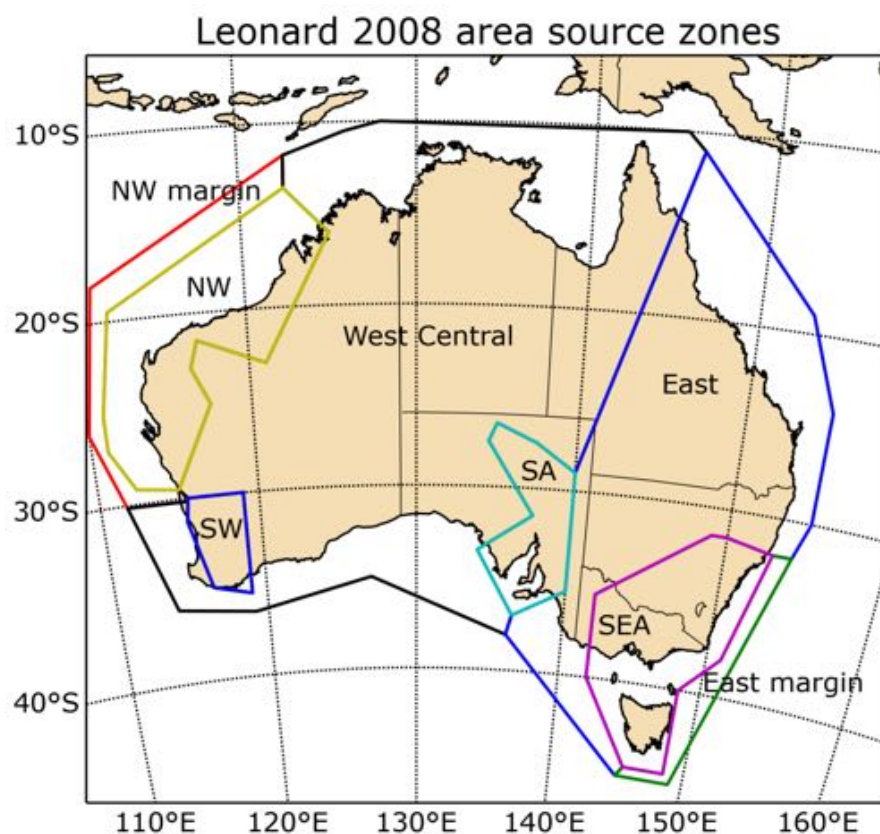


Figure 2: Source zonation for the Leonard 2008 model. See Table 1 for definition of zone name abbreviations.

3.3 Smoothed seismicity model

Smoothed seismicity models are derived purely from the earthquake catalogue and as such are less dependent on the interpretation of the model developer. This gives these models the advantage of being data-driven. However, their use is predicated on an assumption that the recently observed earthquake catalogue is representative of future seismicity. With palaeoseismological evidence showing that faults can be quiescent for tens or even hundreds of thousands of years (Clark 2012, 2014b, 2015b), this assumption clearly doesn't hold and a smoothed seismicity model does not account for future activation of a presently quiescent fault. However, an episodic model of seismicity in Australia does imply that regions that are currently seismically active may continue to be active at the geologically short timescales (e.g. 50 years) considered for seismic hazard assessments. Therefore, inclusion of a smoothed seismicity source model provides a model where the future short term seismicity rate is largely controlled by recent activity.

In developing our smoothed seismicity model we test the use of constant (Frankel 1995) and adaptive (Helmstetter *et al.* 2007) kernel methods. The Frankel (1995) model uses a fixed 50 km kernel bandwidth and smooths over 3 neighbouring cells. Large variations in the density of seismicity (e.g. high density in the Flinders ranges, low density in central Queensland) point to an advantage in using an adaptive kernel approach, where the size of the smoothing kernel is dependent on the distance to the k th nearest earthquake (Helmstetter 2007). For the Helmstetter *et al.* (2007) method the parameters are chosen by through a maximum likelihood optimisation method. For this a training catalogue (1964 – 2003) is used to generate models using a range of smoothing parameters and compared with a target catalogue (2004-2010) to find the optimal smoothing parameters that maximises the likelihood of the target catalogue.

Following (Helmstetter 2007) we test values of k from 3-50 and find $k=4$ to provide the optimal parameterisation.

3.4 Ground motion models (GMM)

The PSHA model implementations presented below use the same GMMs and relative weights as the 2013 NSHA (Burbidge 2012), as outlined in Table 2. A future component of the 2018 NSHA involves the development of a database of Australian strong motion data that will be used to rank available GMMs, including more recent GMMs not included in the 2013 NSHA, to inform assignment of logic tree weights.

Table 2: Ground Motion Models and their relative weights for cratonic and non-cratonic regions.

Region	GMM	Weight
Non-Cratonic	Allen (2012)	0.25
	Atkinson & Boore (2006)	0.25
	Chiou & Youngs (2008)	0.25
	Somerville <i>et al.</i> (2009) Non-cratonic	0.25
Cratonic	Allen (2012)	0.3
	Atkinson & Boore (2006)	0.3
	Chiou & Youngs (2008)	0.1
	Somerville <i>et al.</i> (2009) Yilgarn	0.3

4. PRELIMINARY HAZARD MODEL RESULTS

4.1 Seismotectonic model: Adelaide region case study

The open source software OpenQuake (Pagani *et al.* 2014) will be used for the 2018 NSHA. The results presented here use version 2.0 of OpenQuake. Figure 3 shows the results of the 2013 national seismic hazard model implemented using OpenQuake.

In the following we present results of sensitivity analysis for a case study of the Adelaide region where a fault source model is integrated with an area source model. The region around Adelaide is well documented with several earthquakes $M>4$ during the last 100 years. A number of faults are mapped in the surrounding area (Clark & McPherson 2011; Clark & Leonard 2014a, 2015a) and their local parameters (length, slip rate, dip etc.) estimated (Clark 2016). Sensitivity analysis to the parameters is undertaken to identify which parameter uncertainties will have the greatest influence on hazard estimates. This complements work undertaken by Clark *et al.* (2016) who have developed a comprehensive logic tree for inclusion of fault uncertainty in the hazard assessment. If parameters can be determined to have only minor influence on final hazard results, then the logic tree can be simplified, reducing unnecessary model complexity and computation time.

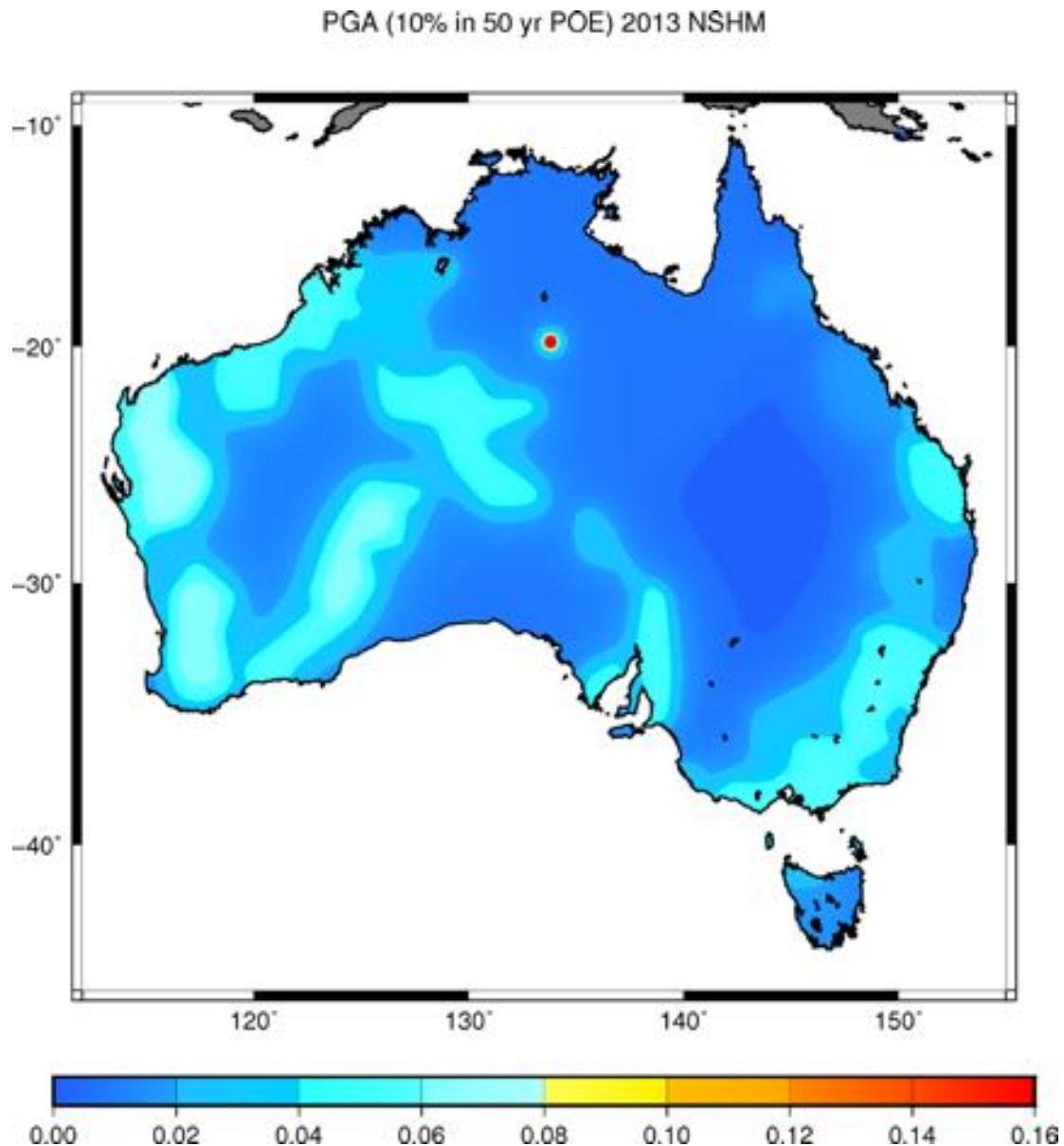


Figure 3: OpenQuake implementation of the 2013 NSHA for Peak Ground Acceleration with 10% in 50 years probability of exceedance. Ground motions are calculated for rock sites ($V_{s30} = 760$ m/s).

The choice of fault magnitude-frequency distribution is very important for the calculated seismic hazard. OpenQuake supports three types of magnitude-frequency distributions (MFD): incremental (i.e. user defined rates for each magnitude bin); Gutenberg-Richter (G-R); and characteristic earthquake model (CE) following the Youngs & Coppersmith (1985) sense. In this work we used the G-R and CE distributions to calculate hazard around faults. To understand the sensitivity to these choices we run a number of different hazard models varying one parameter choice at a time. We use the estimated fault slip rate (Table 3), fault dimensions and an average crustal shear modulus of 30 GPa to calculate the moment rate (M_T). From M_T the Gutenberg-Richter a -value can be calculated following equation 11 of Youngs & Coppersmith (1985) and assuming a b -value of 1.0. For the characteristic earthquake distribution, the moment rate (M_T) was used to derive occurrence rates assuming a characteristic MFD as defined by equation 16 of Youngs & Coppersmith (1985). The parameters tested in the sensitivity analysis are shown in Table 4.

Table 3: Parameters used for the Adelaide faults. Length and depth are in km, and slip rate in mm/Ma (from Clark *et al.* 2016).

Fault name	Length	Depth	Dip	Slip Rate	M_{max}
Androssan	111	20	50	3	7.26
Redbanks	47	20	60	37	6.9
Bremer	46	20	50	16	6.9
Sandergrove	43	20	60	17	6.71
Encounter Bay	79	20	60	74	7.17
Willunga	55	20	60	92	7.08
Ochre Cove-Clarendon	33	20	60	42	6.84
Eden-Burnside	53	20	60	18	7.1
Concordia	14	20	46	4	6.38
Hope Valley	15	20	50	7	6.52
Meadows-Williamstown	38	20	60	17	6.84
Alma	93	20	50	33	7.27
Owen	24	20	60	74	6.64
Palmer	42	20	50	39	6.85
Mirandella	55	20	50	39	6.96
Para	43	20	60	61	6.91
Burra	57	20	36	17	7
World's End	30	20	48	20	6.75
Coobowie Scarp	13	20	50	4	6.41
Yorkentown	23	20	60	9	6.66
Crystal Brook	64	20	60	58	7.01
Morgan Scarp	172	20	50	7	7.39

Figure 4 shows peak ground acceleration (PGA) at 10% in 50 years probability of exceedance for the two distributions, without (Figure 5a, c) and with (Figure 4b, d) the 2013 NSHM regional zones model. Unsurprisingly, the areas of maximum hazard are located around faults with the highest slip rate for both G-R and CE MFDs. G-R faults result in significantly higher hazard compared with the CE at this return period. The CE distribution gives fewer but larger earthquakes for the same moment release rate, therefore reducing the contribution at return periods that are short relative to the recurrence rate of the characteristic earthquake (Youngs & Coppersmith 1985). When both the background model and faults are included, the maximum hazard level is significantly higher overall (>0.1 g) than when only faults are used (Figure 4b, d). However it must be noted that in these results the moment budget has not been balanced between fault and area sources, so we expect we are over-estimating the total moment rate in these models.

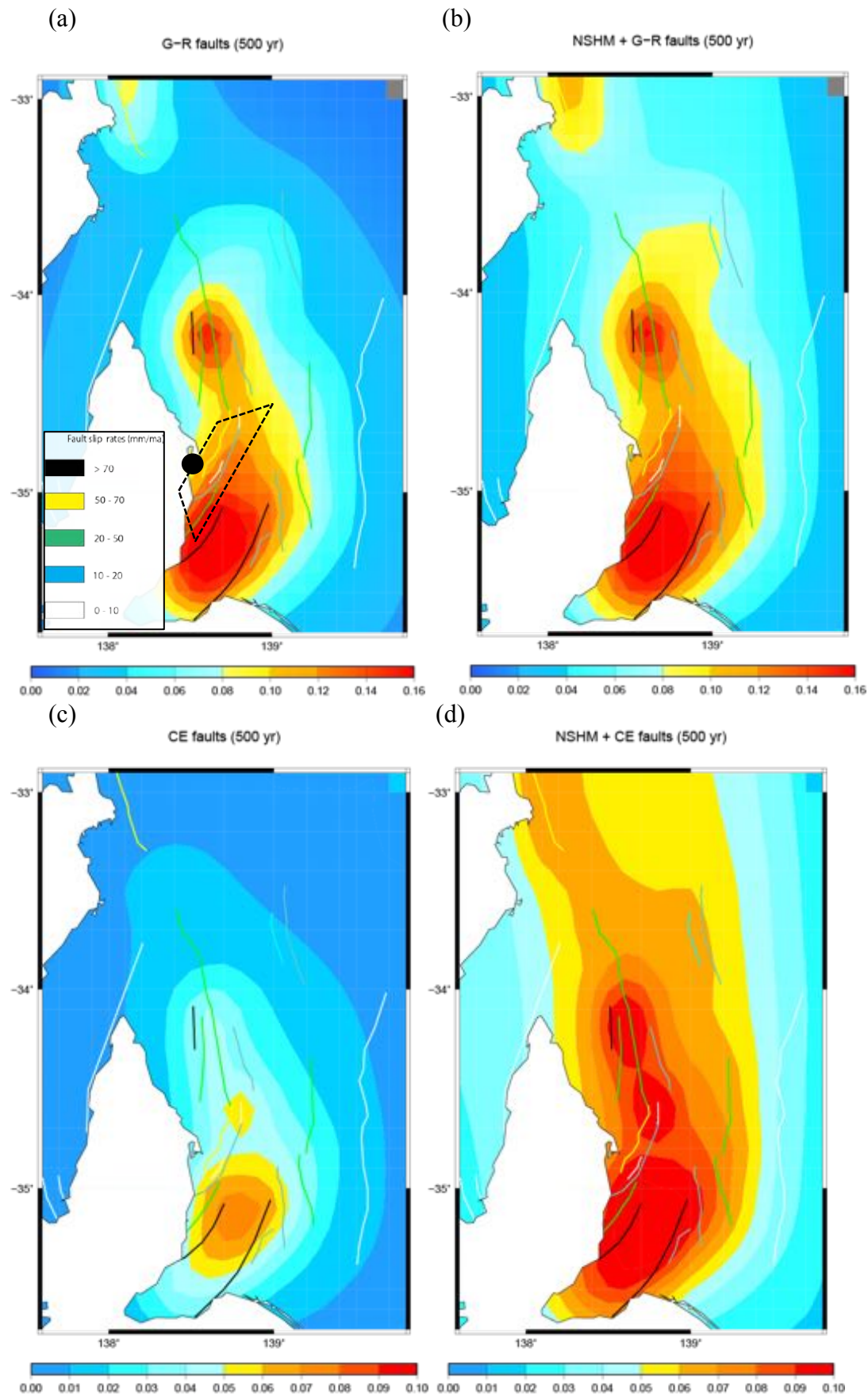
Table 4: Parameters tested in the sensitivity analysis for fault model implementation

Model	b-value	a-value	Dip	Depth	M_{\min}	M_{\max}	M_{Binwidth}
NSHM	0.7-1.1	0.2-3.7	90	20	4.5	7.5	-
G-R faults	1	0.7-3.6	36-60	20	4.5	6.3-7.4	-
CE faults	1	0.7-3.6	36-60	20	4.5	6.3-7.4	0.1

The Adelaide G-R faults were further analysed for uncertainties in maximum magnitude (M_{\max}), which can be related to the locking width of the fault, fault dip and b-value. Figure 5 shows the results. A maximum magnitude increase of +0.2 (Figure 5a), results in slightly smaller hazard at 10% in 50 years probability of exceedance. Though this seems counterintuitive, lowering the M_{\max} while preserving a constant slip (i.e. moment) rate, forces the activity rates of smaller earthquakes to increase (Omang *et al.* 2016). We observed that for longer return periods (2500 years) the difference in the hazard level without and with the M_{\max} uncertainty becomes much less (Figure 5f, g), and continues to converge at longer return periods.

Including uncertainty in fault dip angle does not have a significant effect on the hazard (Figure 4a & Figure 5b) and the same is true for the b-value uncertainty of ± 0.2 . Only the northern part of the region appears to be mildly affected (compare Figure 4a & Figure 5a).

Depth to the base of the fault is an important parameter for the hazard through its control on the maximum magnitude that the fault is capable of. For G-R faults the hazard level is higher for deeper faults (Figure 5a, b). For CE faults, the hazard level is much higher for faults that extend deeper into the crust (Figure 5c, d). Allowing faults to extend deeper into the crust increases the seismic moment rate on the fault source model, increasing the importance of considering how the total seismic moment rate is balanced between fault and area source models. Seismic reflection profiles and historical large earthquakes show that much of the faulting occurs at shallow depths, < 10 km in cratonic areas and extended to ~ 20 km in non-cratonic and extended crust regions. Furthermore, Balfour *et al.* (2015) showed that small earthquakes in the Flinders Ranges region occurred at depths greater than the location of faults mapped from seismic reflection profiles.



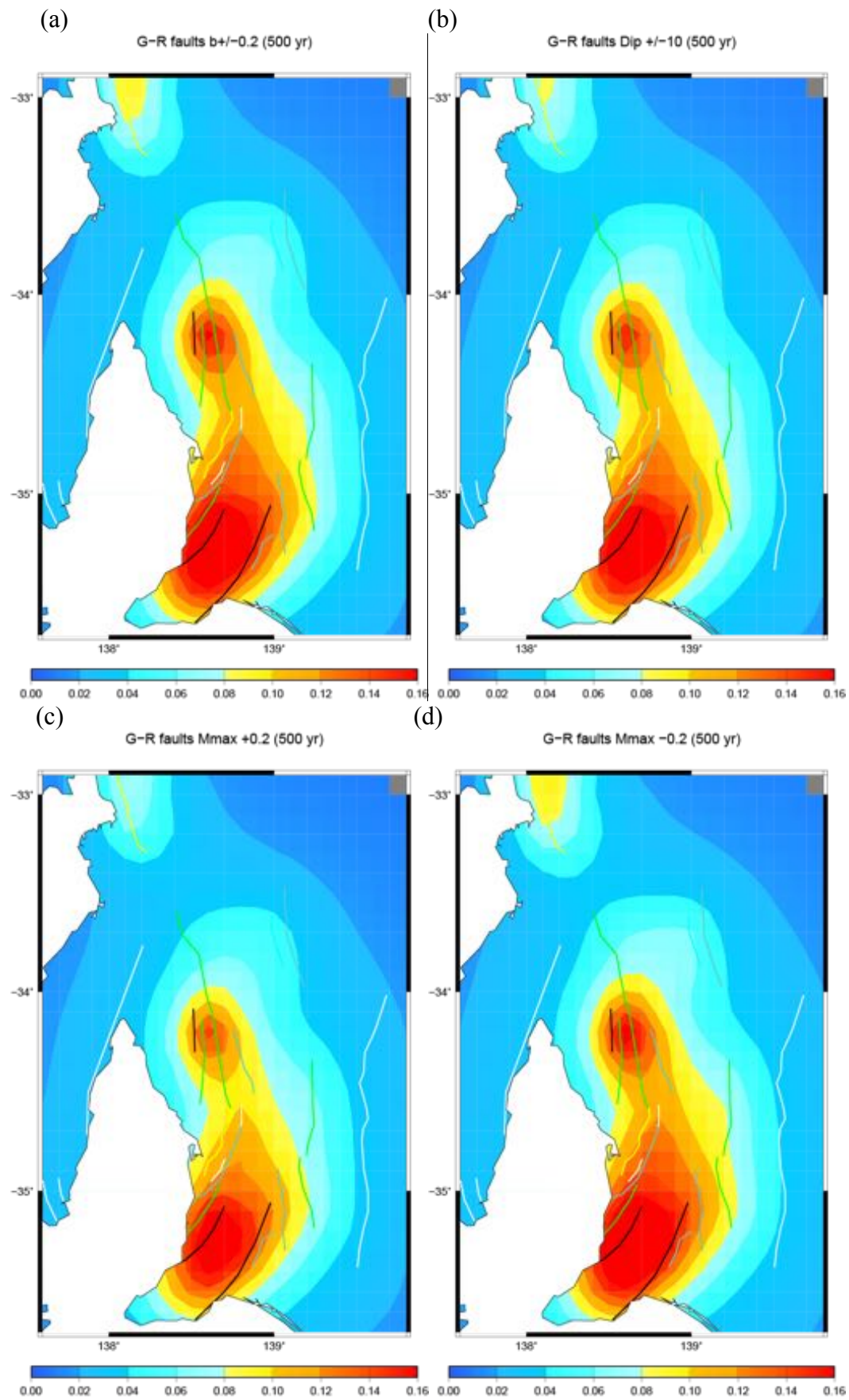


Figure 5: PGA (g) for 10% in 50 years probability of exceedance calculated using the Adelaide fault source model for (a) b -value ± 0.2 (b) dip angle $\pm 10^\circ$ (c) and (d) M_{max} uncertainty of ± 0.2 . Ground motions are calculated for rock sites ($V_{s30} = 760$ m/s).

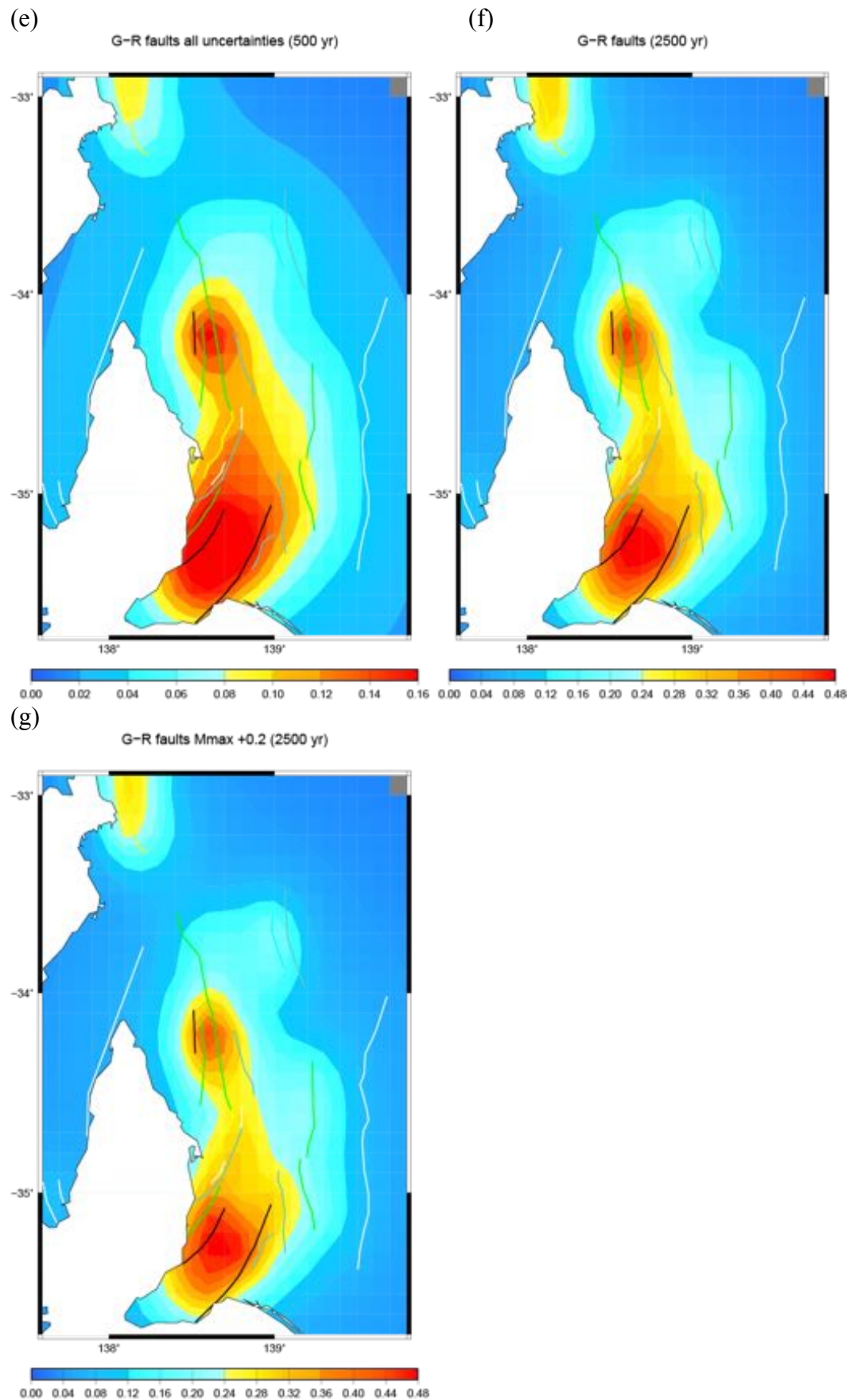


Figure 4 (continued): (e) Combination of all previous uncertainties together for a return period of 500 years (f) and (g) For a 2500 years return period (compared with 500 years), the difference in M_{\max} uncertainty of +0.2 is negligible. Note the change of scale for part (f) and (g).

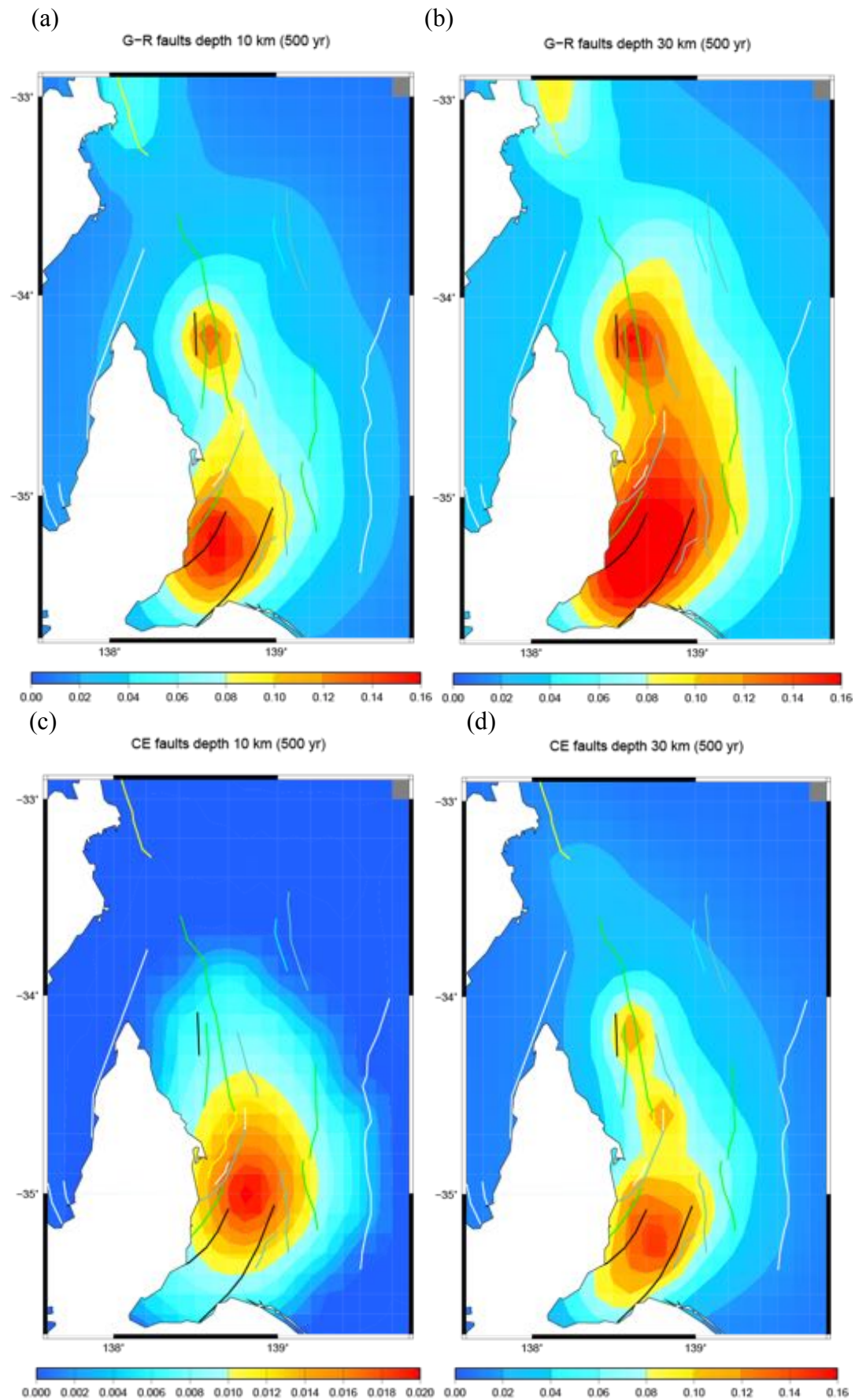


Figure 6: Earthquake hazard for the 500 year return period at a response spectral period of 0.0 s (PGA). Uncertainty in depth for the two types of faults G-R and CE. For a fault average of 20 km, +/- 10 km is considered (a) and (c) 10 km (b) and (d) 30 km.

4.2 Hazard Curves

The hazard curves calculated for the city of Adelaide are shown in Figure 7. When the slip-rate varies from the long-term (mean) slip rate by a certain value (Clark *et al.* 2016) faults can be classified as active (higher slip rate) or quiescent (lower slip rate). The weighted faults are created by assigning weights of 0.06, 0.34 and 0.6 for active, mean slip and quiescent faults, respectively. These weights favour an episodic recurrence model and are designed to conserve the long-term slip rate, but could be altered if there is evidence that a fault is currently in an active or quiescent phase. Mean slip (periodic) and the weighted faults curves differ only at probability of exceedance > 0.03 in 50 years (Figure 7a).

Figure 7b shows hazard curves for G-R and CE fault sources. At approximately 0.05 probability of exceedance in 50 years (PGA of 0.22 g) the hazard curves for G-R and CE faults cross. For $\text{PGA} < 0.22$ g the G-R curve has higher probability of exceedance than the CE (Figure 7b). This is expected as the G-R distribution has more frequent, smaller earthquakes compared with a CE distribution that has only larger earthquakes, which must be less frequent if the same total moment rate is applied.

Figure 7c shows hazard curves for the individual CE faults. The highest curve occurs for the Para Fault, which has a relatively high slip rate of 61 mm/Ma (Table 4). However, a more careful analysis shows that distance and directivity of the fault from the city of concern is more important than slip rate. Para and Hope Valley are the faults that show slow-decreasing hazard values for $\text{PGA} < 0.3$ g, and these faults are the closest to the city of Adelaide (Figure 4a, yellow and white faults inside trapeze). Another two faults, Ochre and Eden, also show less of an increase in hazard with return period compared with the rest. Those two are the next closest to Adelaide (Figure 4a, blue and green faults inside trapeze). The Willunga and Encounter Bay Faults (black faults at the south, Figure 4a), which are long and have the fastest slip rates (> 70 mm/Ma), also contribute to the hazard. In Figure 7d, the Para fault (with the highest hazard) is compared with the total hazard for CE faults. A slip rate addition of 5 and 15 mm/Ma for all faults increases the probability of exceedance without otherwise changing the shape of the hazard curve (Figure 7d). The G-R faults curve intersects all the CE curves, with the point of intersection to higher probability of exceedance and lower PGA as the slip rate for the CE model increase.

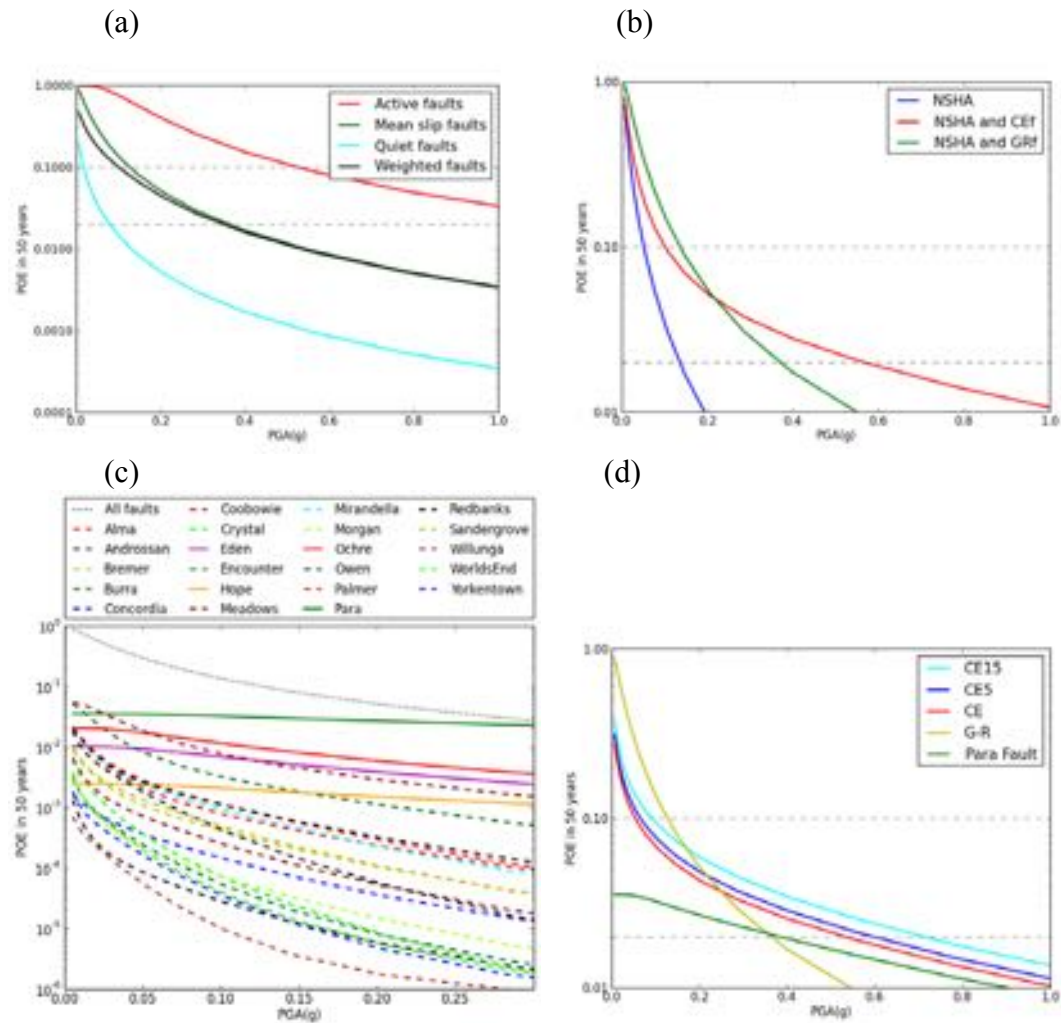


Figure 7: Earthquake hazard curves (peak ground acceleration) for the capital city of Adelaide. (a) Comparison between hazard from the mean slip rate with faults assumed to be active, quiescent or a weighted combination that preserves the mean slip rate. (b) NSHM without and with G-R and CE faults. (c) Individual faults and their hazard curves. Para, Eden, Hope Valley and Ochre Faults show almost invariable hazard values for $PGA < 0.3$ g. These faults are the closest to the city of Adelaide (Figure 4a) (d) Para fault (with the highest hazard) compared with total hazard for all CE faults. A +5 and +15 mm/yr slip rate uncertainty (for all faults) is also shown. Grey dashed horizontal lines in a), b) and d) indicate 10% and 2% probability of exceedance (POE) in 50 years.

4.3 Background area zones (Leonard 2008) model

Results for PGA at 10% in 50 year probability of exceedance are shown Figure 8. The highest hazard areas are concentrated in the SW (~0.14 g), NW (~0.09 g) and SE (~0.05 g) seismic areas. Background areas in the central and eastern parts of Australia have PGA values of 0.016-0.018 g.

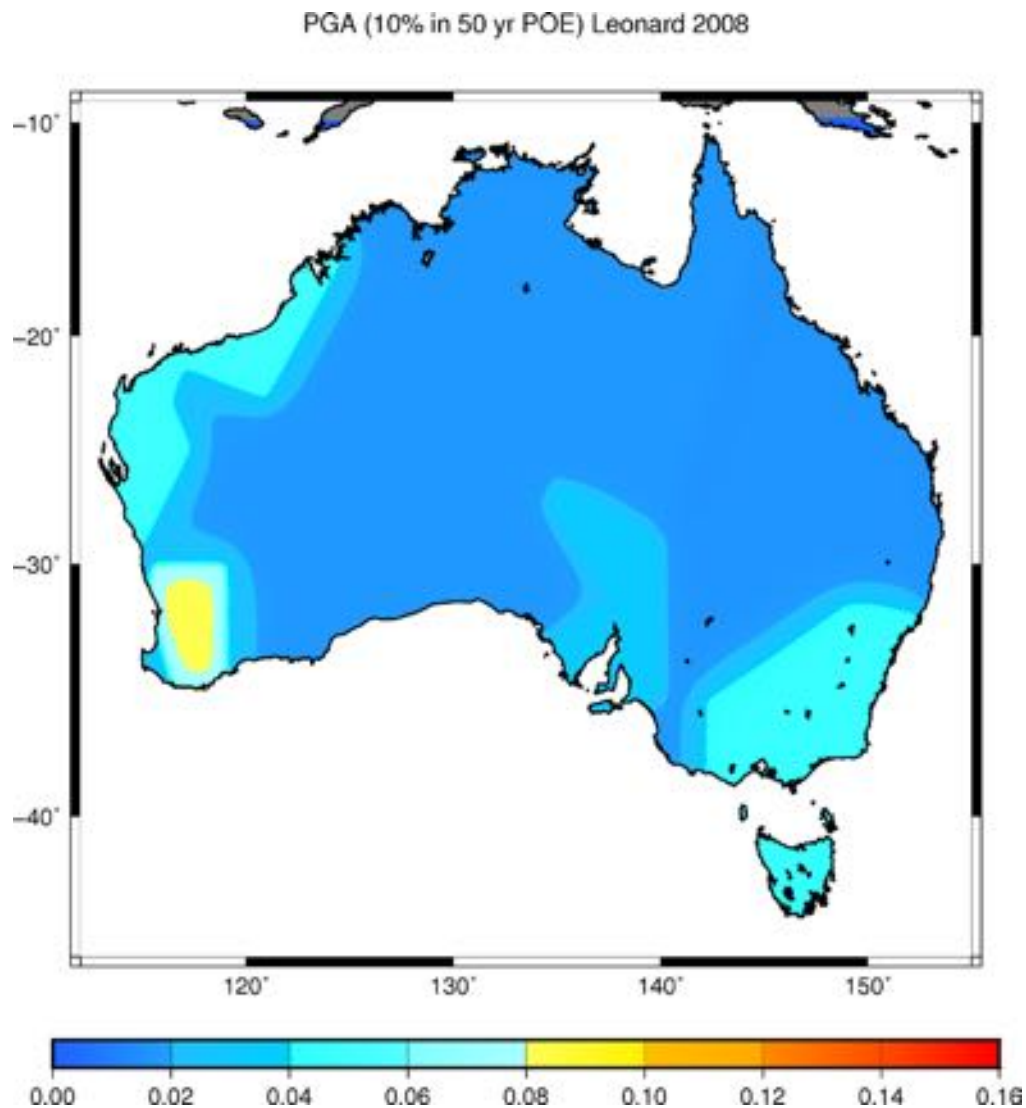


Figure 8: PGA (g) for 10% in 50 years probability of exceedance from OpenQuake implementation of the updated Leonard 2008 model. Ground motions are calculated for rock sites ($V_{s30} = 760$ m/s).

4.4 Smoothed seismicity models

The smoothed seismicity rate for the Frankel (1995) method on a 0.5 degree grid is shown in Figure 9. Note that in areas without instrumentally recorded earthquakes with magnitude > 3.0 the seismicity rate is 0.

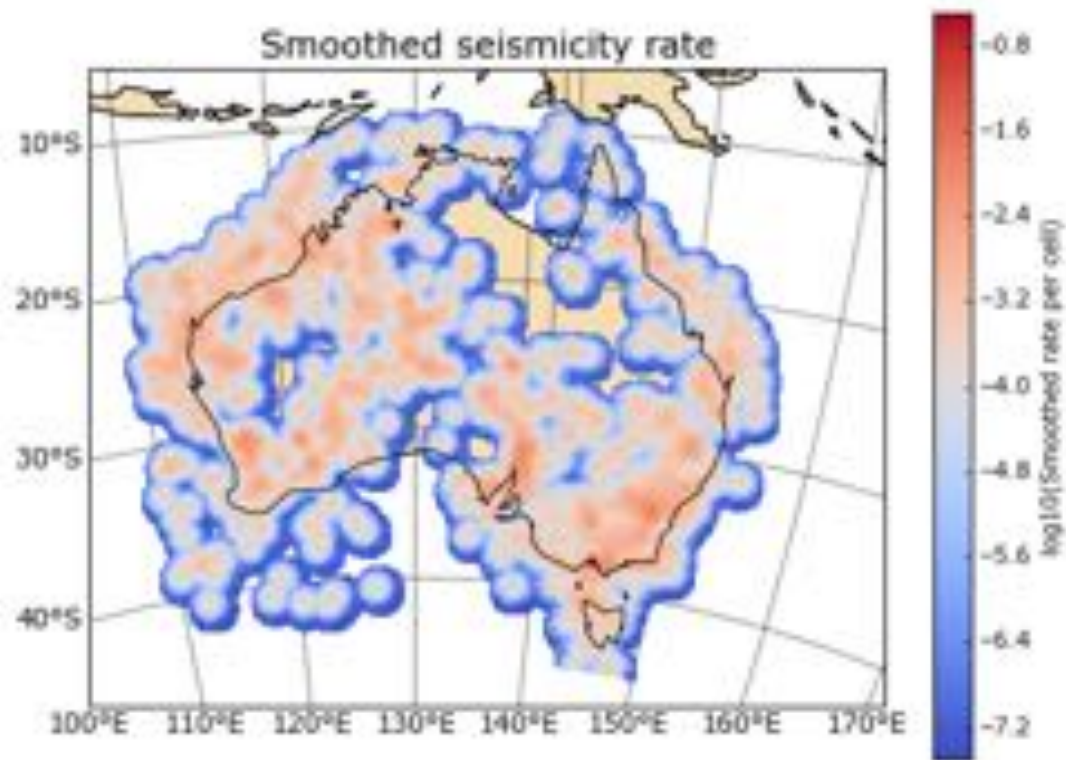


Figure 9 Smoothed seismicity annual rate of earthquakes with magnitude ≥ 3.0 using the Frankel 1995 method and the declustered earthquake catalogue. Rates are calculated on a 0.5×0.5 degree cell.

For the Helmstetter *et al.* (2007) methodology, the model is optimised using an adaptive smoothing kernel bandwidth based on the 4th nearest earthquake. The smoothed annual rate of earthquakes with magnitude greater than 3.0 on a 0.5 degree grid is shown in Figure 10. This shows greater model resolution in high seismicity areas including SE Australia, the Flinders Ranges and SW Australia, while low seismicity rates are smoothed over central northern Australia.

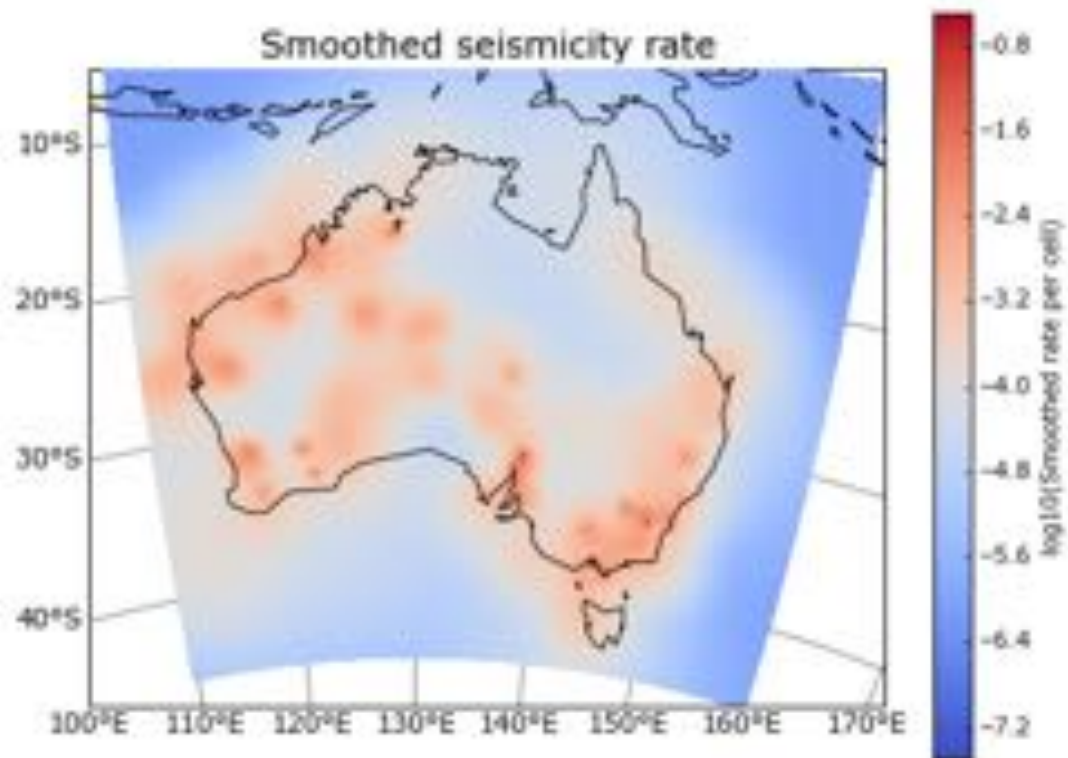


Figure 10: Smoothed seismicity annual rate of earthquakes with magnitude ≥ 3.0 for the Helmstetter *et al.* (2007) methodology, with bandwidth defined by the distance to the 4th nearest earthquake, using the declustered earthquake catalogue. Rates are calculated on a 0.5×0.5 degree cell.

The preliminary hazard for the smoothed seismicity models (Figure 11) show that both methods tend to highlight hotspots of seismic activity such as eastern Australia, the Flinders Ranges and SW Australia. The adaptive kernel Helmstetter *et al.* (2007) model also has additional high hazard hotspots in parts of NW Australia that are more strongly smoothed in the fixed bandwidth Frankel (1995) model. Both implementations are based on the rate of earthquakes with $M > 3.0$. Note that an alternative implementations of the Frankel (1995) method calculate rates for earthquakes $M > 3.5$, $M > 4$ and $M > 5$ and average the resulting rates layers (Hall *et al.* 2007). This adds more weight to the larger events creating hotspots around large, isolated events such as the three $M \sim 6.5$ 1988 Tennant Creek earthquakes that are not present in our models due to the low total number of earthquakes in this region.

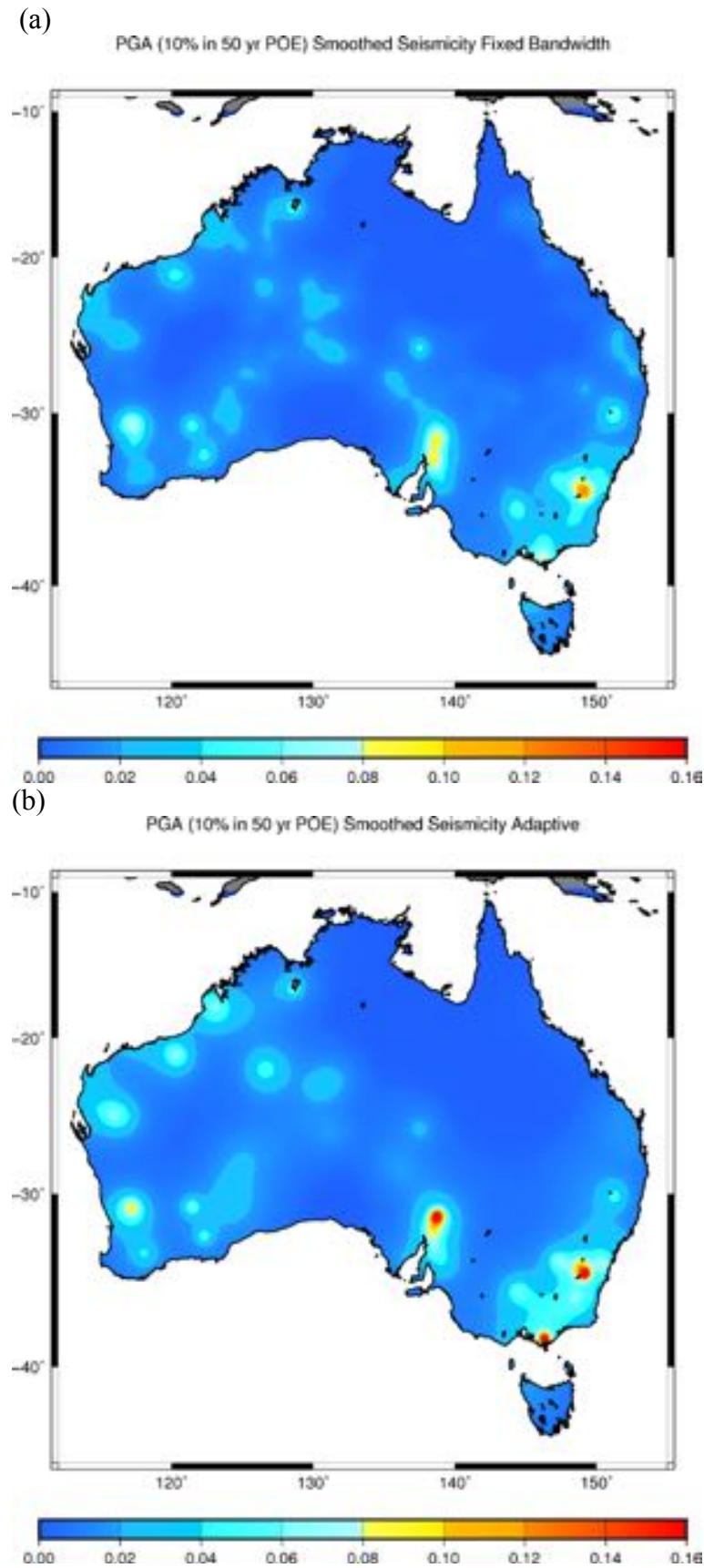


Figure 11: PGA at 10% in 50 years probability of exceedance calculated using smoothed seismicity methods: a) fixed bandwidth (Frankel 1995) and b) adaptive kernel (Helmstetter *et al.* 2007). Ground motions are calculated for rock sites ($V_{s30} = 760$ m/s).

4.5 Inclusion of epistemic uncertainty using logic trees

Epistemic uncertainty around earthquake source models and ground motion models will be included in the 2018 NSHA through the use of logic trees to capture alternative models. These alternative models should be mutually exclusive and collectively exhaustive (Bommer *et al.* 2005; Bommer & Scherbaum 2008). It is intended that different branches of the logic tree will be weighted through an expert elicitation process facilitated by an expert independent to the NSHA process, similar to that conducted for hazard assessments for Christchurch following the Canterbury earthquake sequence (Gerstenberger 2016). This process weights the relative contribution of experts to the logic tree weighting process based on an assessment of their level of expertise and capability to estimate uncertainties. This assessment is undertaken through a series of calibration questions. Based on Cooke's classical method (Cooke 1991, 1999), these are questions that the experts are not expected to know the exact answer to, but should be able to quantify their best estimate and confidence intervals to that estimate.

As a demonstration of how source model uncertainty can be included, Figure 12a shows OpenQuake implementation of a preliminary revision of the AUS6 model (Seismology Research Centre, pers. Comm. 2016) and Figure 12b shows earthquake hazard from a weighted combination of NSHA13 (Figure 2), Leonard 2008 (Figure 7) and the AUS6 model. These source models have weights of 0.4, 0.2 and 0.4 respectively. A lower weighting for the Leonard 2008 model is given due to the simplicity of the source zonation compared with the observed distribution of seismicity. Ground motion models are the same as those used for NSHA13 (Burbidge 2012; Leonard 2013). As noted previously, these will be revised for the final hazard assessment.

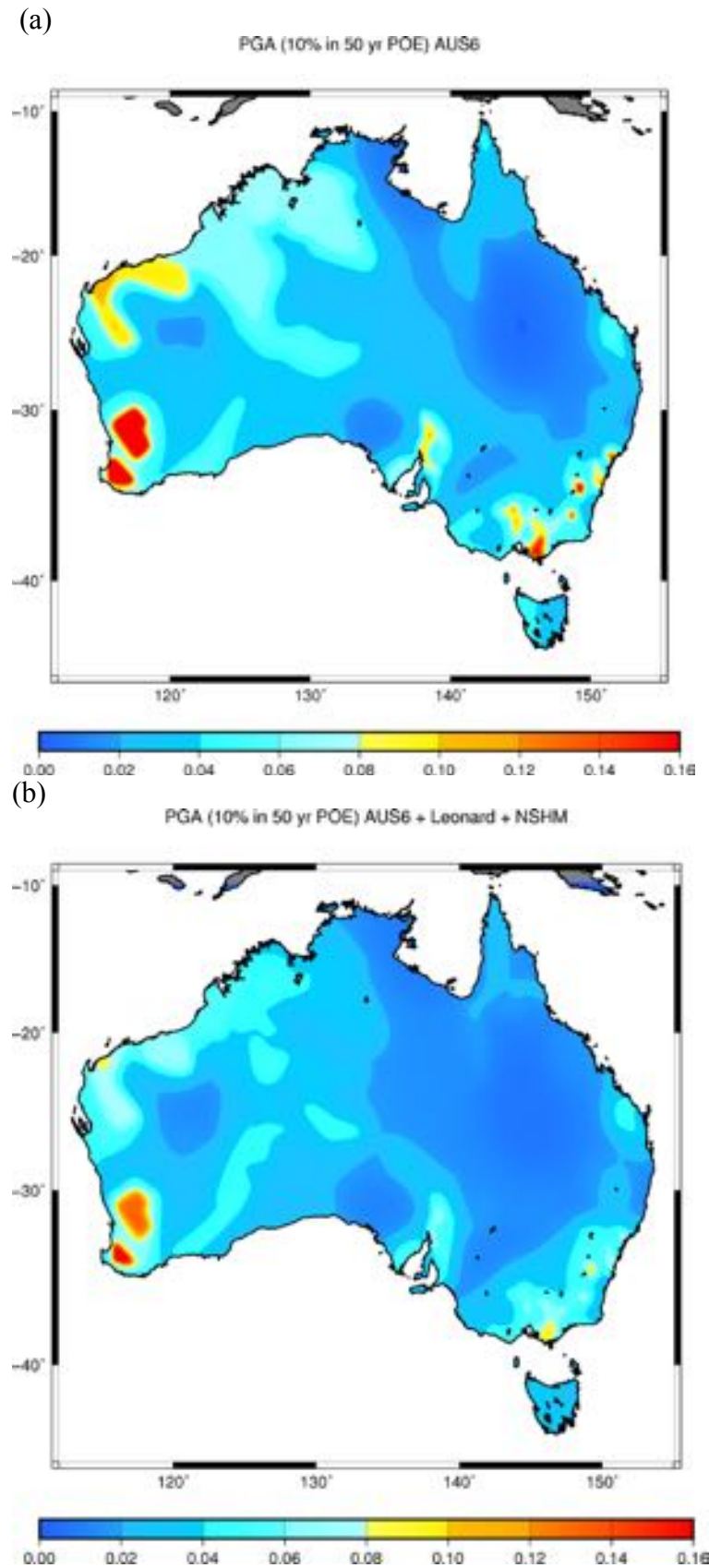


Figure 12: Peak ground acceleration earthquake hazard for 500 year return period based on (a) AUS6; and (b) a weighted combination of the NSHA13, Leonard and AUS6 models. The weights used are 0.4, 0.2 and 0.4, respectively. Ground motions were calculated out to 500 km.

5. DISCUSSION AND FUTURE WORK

The preliminary hazard results presented above demonstrate that although there are diverse ways in which seismicity can be characterised in Australia, there is also stability in overall patterns of seismic hazard across the continent: high hazard areas are concentrated in SE Australia, the Flinders Ranges and SW and NW Australia, consistent with results of the 2013 NSHA. The different methods for characterising seismicity (large source zones, small source zones and smoothed seismicity) control the spatial scale over which the hazard varies and the degree to which areas of recent high seismic activity appear as ‘hotspots’. This relates to fundamental questions about the seismicity of Australia and the degree to which the recent instrumental and historical catalogues are predictors of future seismic activity. Expert opinions on such matters will impact the relative weights of the smoothed seismicity models compared with seismotectonic models that consider more than just the catalogue.

Inclusion of faults sources characterised by palaeoseismology data provides a longer time perspective. The Adelaide case study demonstrates that hazard levels > 0.1 g for PGA at 10% in 50 years probability of exceedance can be locally achieved based purely on the fault source model, exceeding the hazard levels from the 2013 NSHA. The impact of including faults into the model is expected to be less significant in areas with lower slip rates, such as SW Australia, where the current rate of seismicity exceeds the long-term rate indicated by geomorphology (Leonard & Clark 2011). The sensitivity of the hazard assessment to uncertainty in different input fault parameters presented in this paper is used by Clark *et al.* (2016) to simplify the logic tree for the fault source model to only include the most important logic tree branches, reducing the computational demands of the final model.

The source models presented above are currently being improved by Geoscience Australia. Key improvements being undertaken are:

1. National inclusion of fault source models into the seismotectonic model.
2. Testing methods to balance the seismic moment budget between fault sources and area sources that contain the faults to avoid double counting seismicity.
3. Further sensitivity of fault sources to parameter uncertainty to implement the logic tree presented in Clark *et al.* (2016).
4. Extending the catalogue used for the smoothed seismicity models through use of spatio-temporal completeness rather than just temporal completeness models.
5. Testing sensitivity of smoothed seismicity models to declustered vs non-declustered earthquake catalogues.
6. Updating all recurrence relations once the final homogenised catalogue is completed.

6. CONCLUSIONS

Geoscience Australia is leading a process to revise the National Seismic Hazard Assessment for the 2018 revision of the earthquake loading standards contained in AS1170.4. Key advances on the 2013 NSHA are inclusion of a fault source model, development of a more homogenised earthquake catalogue, and inclusion of epistemic uncertainty in earthquake source models. Geoscience Australia will implement the final model in the OpenQuake software, including seismic source models developed at GA and third party models provide by the Australia seismological community.

Source models will be implemented with relative weightings determined through an expert elicitation process involving the Australian seismological community.

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