The 2012 Australian Seismic Hazard Map – Source Zones and Parameterisation

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Abstract

This paper describes the methods used to define earthquake source zones and calculate their recurrence parameters (*a, b, Mmax*). These values, along with the ground motion relations, effectively define the final hazard map. The selection of source zones is a highly subjective process, relying on seismology and geology to provide some quantitative guidance. Similarly the determination of *Mmax* is often subjective. Whilst the calculation of *a* and *b* is quantitative, the assumptions inherent in the available methods need to be considered when choosing the most appropriate method

For the new map we have maximised quantitative input into the definition of source zones and their parameters. The temporal and spatial Poisson statistical properties of Australia's seismicity, along with models of intra-plate seismicity based on results from neotectonic, geodetic and computer modelling studies of stable continental crust, suggest a multi-layer source zonation model is required to account for the seismicity. Accordingly we propose a three layer model consisting of three large background seismicity zones covering 100% of the continent, 25 regional scale source zones covering ~50% of the continent, and 44 hotspot zones covering 2% of the continent.

A new algorithm was developed to calculate *a* and *b*. This algorithm was designed to minimise the problems with both the maximum likelihood method (which is sensitive to the effects of varying magnitude completeness at small magnitudes) and the least squares regression method (which is sensitive to the presence of outlier large magnitude earthquakes). This enabled fully automated calculation of *a* and *b* parameters for all sources zones. The assignment of *Mmax* for the zones was based on the results of a statistical analysis of neotectonic fault scarps.

Introduction

Fundamental to any earthquake hazard assessment is the choice of the source zones and their seismicity model and their parameters *(a, b, Mmax*). The choice of source zones, either implicitly or explicitly, imply a seismicity model. For example a smoothed seismicity approach implies that seismicity is stationary and so the catalogue (typically 30-50 years if instrumental data) predicts future seismicty, independent of return period. Typical zonation models define regions which are assumed to have uniform earthquake recurrence and for which the catalogue will predict the future seismicity. Their selected are typically based on a combination of the seismicity and the geology. In this paper we briefly describe the basis for the seismicity model we have chosen and the resulting source zones.

The parameters requires for estimating the seismic recurrence within a source zone are the parameters *a* and *b* (Gutenburg and Richter 1944) and the Maximum magnitude (*Mmax*) within the source zone. To estimate *a* and *b* the magnitude of completeness (*Mc*), preferably at multiple dates is also required. There are various methods for estimating all these parameters. In this paper we give a brief overview of these various methods, their application to Australian seismicity, and which methods we chose. The results of applying the chosen methods and models are described.

Source Zones

Spatial Statistical Analysis

Method

Using the spatial analysis method described by Leonard (2010) the Australian continent was divided into 4000, 55x55 km cells and the number of earthquakes in each cell counted. The process was repeated four times with the grid displaced 27.5 km to the N, E and N&E, giving a final grid with 27.5 km cell spacing. The earthquakes used are the approximately 2400 earthquakes in the declustered catalogue since the 1st of January 1965 with a magnitude greater or equal to M3.0. These criteria were chosen to maximise the number of earthquakes under the assumption of an approximately uniform magnitude of completeness (M_C).

Figure 1 shows the spatial distribution of earthquake density, as the number of earthquakes per 55 x 55 km cell. The contour line represents a minimum value of 0.5 earthquakes per cell and the colour scale is in number of earthquakes per cell. If the earthquakes were distributed randomly 28% of the area would be expected to fall within the 0.5 contour, whereas the observed value is 18%. Similarly the area with four or more earthquakes per cell should be 13 of the 4000 cells (0.3%), whereas the actual value is 151 (3.8%), with the theoretical and actual values for five or more earthquakes are 1.6 and 91 per cell. We consider all areas with four or more earthquakes per cell to be anomalous. These areas are subsequently treated as hotspots.

Results

1. No area of Australia has been found that can be approximated by a single spatial Poisson model. All are clustered and are not randomly distributed. Almost all regions require at least 3 Poisson models, with some requiring 4, to model the spatial statistics.
2. Using the full (not declustered catalogue) 4 Poisson models are required for most regions.
3. In all cases there are more cells than expected with <1 and ≥ 4 earthquakes and a deficit of cells with 1 or 2 earthquakes.
4. The larger active areas (e.g. SW WA, ACT region, Flinders Ranges) tend to contain multiple hotspots. In addition to the very large sequences associated with the Meckering and Cadoux earthquakes in SW WA, there are several other hotspots of ongoing activity outside their source regions, and many other hotspots of either transient (eg. Burakin and Kattaning) or lower level activity. Similar behaviour is seen in Eyre Peninsular and SE Australia. In the Adelaide Geosyncline aftershocks are rarer, but a similar pattern of clustering exists.
5. Almost all hotspots are ongoing. Only a few appear to have switched on during the last 50 years.
6. Large dams can induce significant seismic activity, but this normally dies out in less than a decade (e.g. Thomson Dam, Tumut 3). This is not common and appears to apply more to deeper dams.
7. The presence of hotspots around several mining areas suggests that there are many blasts (or rock bursts) that have been misinterpreted as earthquakes, that mining-induced seismicity is relatively common, or both.

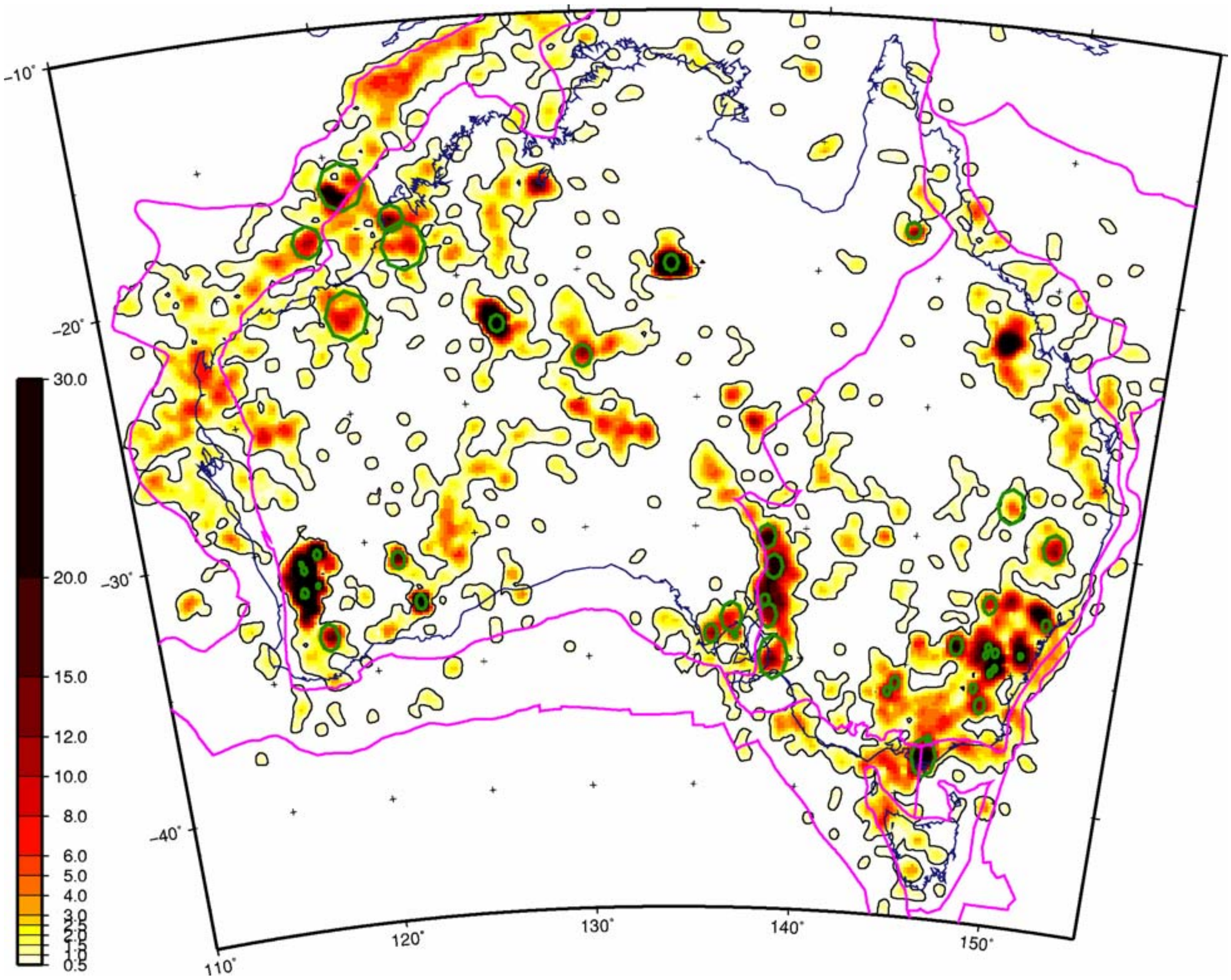

Figure 1 the earthquake spatial density of Australia, based on the full catalogue with the hotspots in green and background zones in magenta.

Implications for seismic hazard assessment

As the fundamental assumption of random (or even) distribution of earthquakes within the source zones does not hold, a single set of source zones will not correctly reflect the seismic hazard of Australia. Using a single source zone in an area may underestimate the hazard within any hotspot and overestimate it elsewhere. Most 'active' areas can be better described as a regional zone with a number of embedded hotspots.

There is strong evidence of large (≥M6.0) earthquakes exhibiting episodic behaviour. Examples include Collier Bay, Tennant Creek, Meckering, Meeberrie, Lake Tobin and Beachport. An episodic model of earthquake occurrence implies that a much larger area is involved than is observed from a short-term observation of the seismicity. Recurrence rates, based on the last 50 years of data, suggest that the area which might be considered active for these large earthquakes is approximately 20% of the continent. However, an episodic model suggests that the "inactive" 80% can best be described by large background source zones which encompass both the active and non-active areas. Such a model is consistent with emerging models of episodic fault behaviour, with the area surrounding each fault undergoing its own active/quiescent cycles, possibly with subtle stress interactions between neighbouring faults (Toda et al. 1998, Parsons 2002, Stein and Liu 2009, Li et al. 2009, Leonard and Clark 2011).

Combining the models from the spatial statistical analysis with models of episodic behaviour of large earthquakes suggests that at least three layers of zonation are required to model the observed seismicity. The first is needed to account for the small areas of very high seismic activity (i.e. hotspots). The second represents the regional scale zones of moderate seismic activity. The third accounts for the large areas encompassing areas of moderate, low and very low (background) seismic activity.

Background Zones

The background zones were defined primarily from the properties of palaeoearthquakes (Clark *et al.* 2011) with the boundaries refined using geologically and geophysically defined crustal elements. These Clark *et al*. neotectonic 'domains' were merged into three zones: the Cratonic, Non-Cratonic and Extended zones. These are approximated by the Western Precambrian area of non-extended stable continent, the eastern Phanerozoic area of non-extended stable continent and the area of extended continental crust.

Regional Source Zones

In defining the regional source zones the two primary criteria were: (i) zones should include at least 60 earthquakes since 1 January 1965 with a magnitude ≥M3.0, and (ii) the zones should encompass contiguous areas of approximately uniform earthquake density. Secondary criteria included the need for a small enough area to provide meaningful differentiation between regions, simple rather than complicated polygon shapes, and avoiding encompassing multiple major tectonic units. Figure 2 shows a plot of earthquake density overlain by the regional source zones defined here.

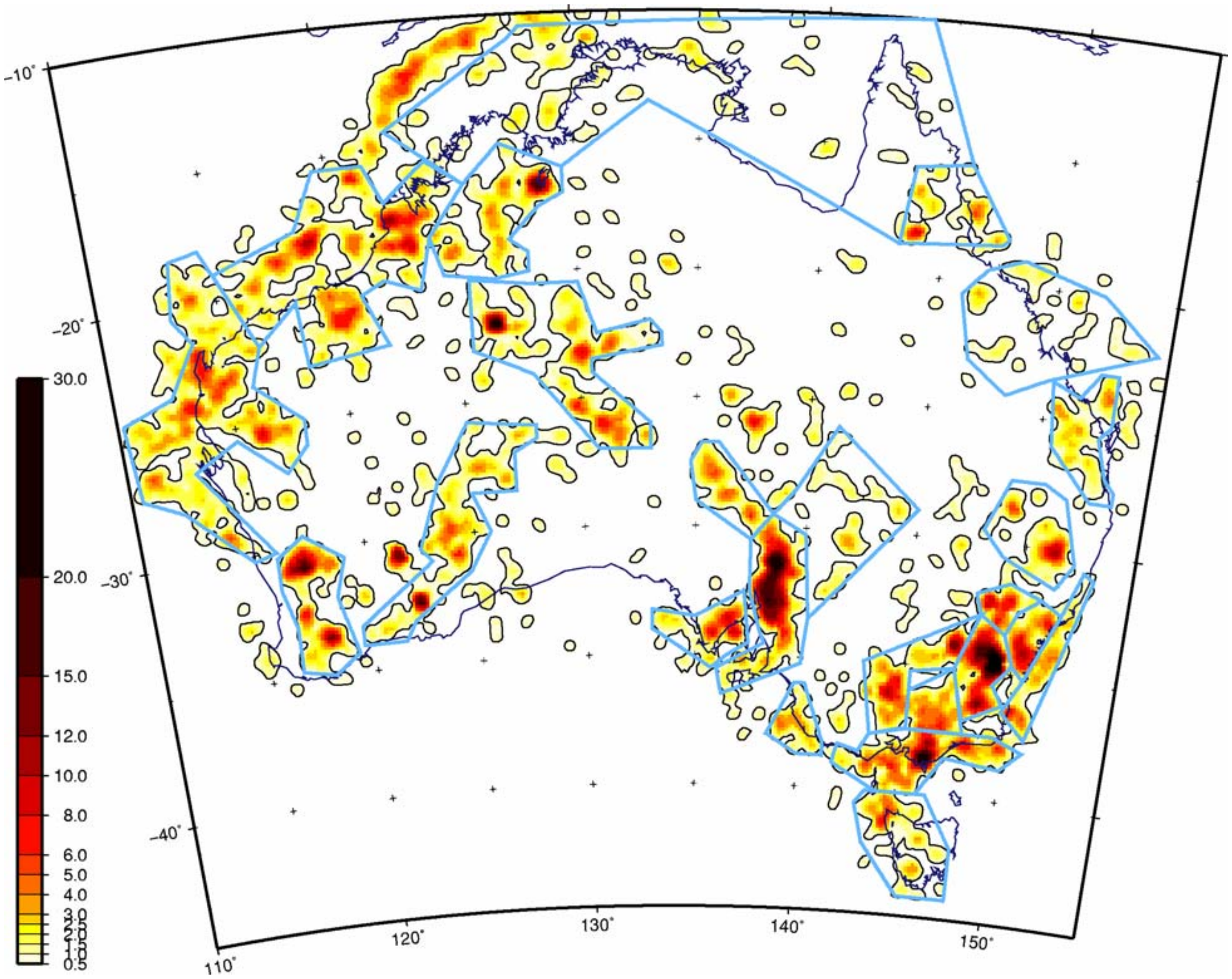

Figure 2 the earthquake spatial density of Australia, based on the declustered catalogue with the interpreted Regional zones superimposed.

Hotspots

As discussed above, if the spatial distribution of earthquakes followed Poisson Statistics, using the method and catalogue discussed above, there would be only 1.6 cells, of the 4000, with 5 or more earthquakes and none with more than 5, whereas the actual numbers are 91 and 56 respectively. This highly significant deviation from the expected Poisson distribution suggests that these areas of anomalously high activity should be treated separately. Consequently, the hotspots are defined as the areas where the spatial density is greater or equal to 5 earthquakes per cell. Based on this definition, 58 hotspots were identified.

Figures 3 – 7 show the temporal occurrence of earthquakes for 5 hotspots. The hotspot south of Cowra (Figure 3) appears to be ongoing and has no obvious correlation to the construction or filling of Wyangla Dam. Similar circumstances relate to the hotspot NE of Jindabyne (Figure 4). The apparent decrease in activity around 1990 is likely due to the closure of the Snowy Mountains network and to a lesser extent the change in magnitude formula used. The hotspot associated with the filling of Talbingo dam (Figure 5) has died out and this hotspot was not included in the hazard map. The hotspot on the southern Eyre Peninsular (Figure 6) has been ongoing at least since detection of small events became possible in the mid 1960's. The ongoing activity, which is a complicated combination of aftershocks and induced seismicity associated with the 1970 M6.0 Cadoux earthquake (Figure 7) is ongoing. This type of analysis was applied to the 58 hotspots, and14 were rejected on the basis that they were not ongoing. This left 44 hotspots in the hotspot source zone layer.

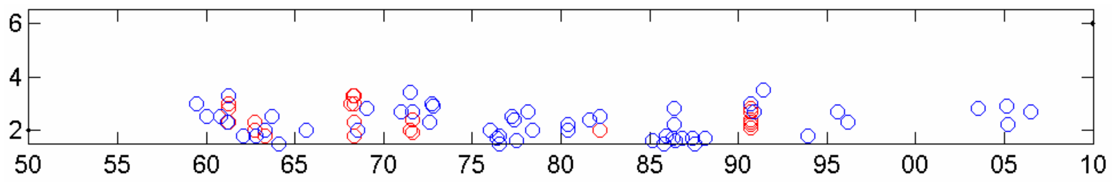

Figure 3 Mt Collins, 23km S of Cowra and 14km W of Wyangala Dam, radius 14km. The blue are mainshocks and the red circles aftershocks. This region is considered as an ongoing hotspot.

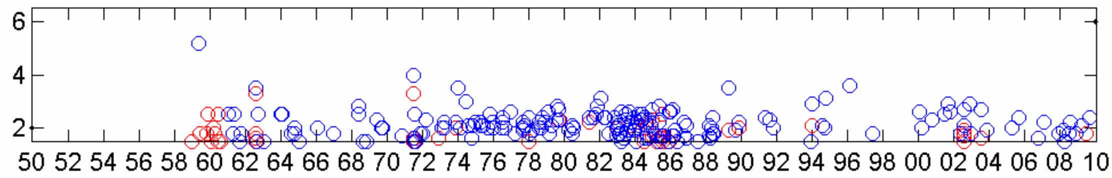

Figure 4 15km NE of Jindabyne, including lakes Jindabyne and Eucumbene. This region is considered as an ongoing seismicity.

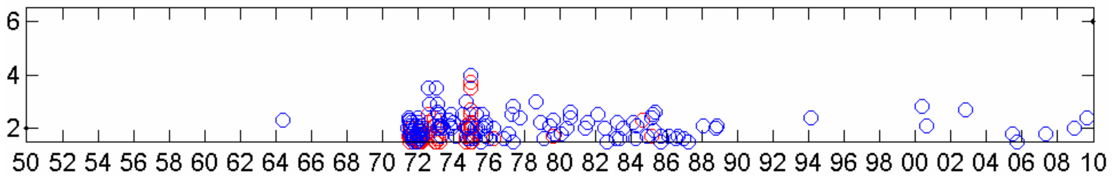

Figure 5 Talbingo Lake. Appears to be a 17 year long sequence associated with the filling of the dam. The dam was completed in 1970 and at the time was the highest in Australia at 161m. The sequence is now dying out.

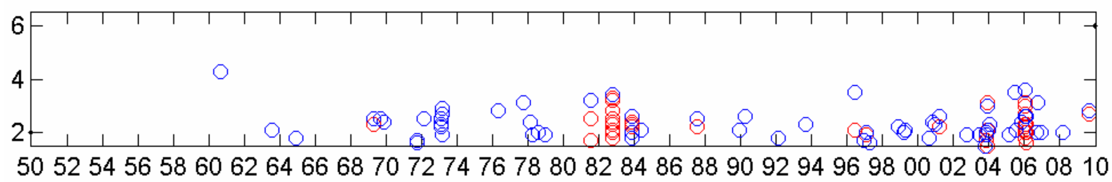

Figure 6 Southern Eyre Peninsular, radius 33km. This is an ongoing hotspot, where modest M2.5-3.0 earthquakes appear to trigger short but intense aftershock sequences.

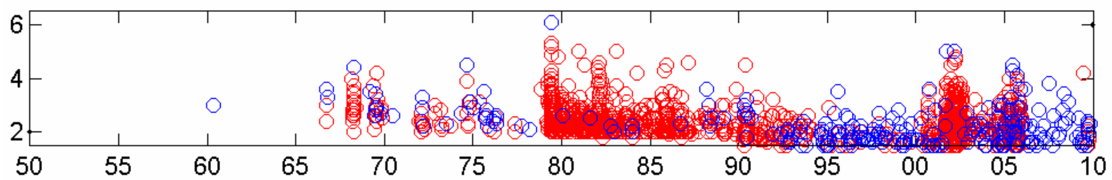

Figure 7 This hotspot is centred on the 1979 Cadoux earthquake, radius 40km. Most of the non Cadoux seismicity is spatially spread over several small clusters. This includes the ten mainshocks M > 4.0 since 2002 where each of the mainshocks is spatially distinct. The many small mainshocks between 1995 and 2002 are due to the declustering algorithm no longer considering the Cadoux earthquake capable of producing aftershocks.

Parameterisation

Estimation of 'a' and 'b'

The two primary methods for estimating the Gutenburg-Richter (G-R; Gutenburg and Richter 1944) recurrence parameters *a* and *b*, are standard least squares (hereafter referred to as ls0) and Maximum Likelihood (Aki 1965). As the Maximum Likelihood (ml0) method weights more heavily the more numerous smaller earthquakes, it is generally considered the preferred method to determine earthquake recurrence. However, the method is sensitive to the assumption that the magnitude of completeness (M_C) is known and is constant during the period of the catalogue being analysed. In the well instrumented and higher activity areas of Australia (e.g. Yilgarn Craton, Flinders Ranges and SE highlands) this assumption holds. However, across much of Australia the assumption fails. The least squares method can be sensitive to the distribution of the extreme events. Particularly when there is a gap of ≥0.3 magnitude units between the largest magnitude in the continuous recurrence data and the extreme event(s). Where the distribution of the recurrence data has a clear M_C and no off-trend extreme events, the two methods produce effectively identical results.

Many of the 25 regional zones had one or both of these two problems. To overcome the need to use "expert" judgement to determine a preferred *a* and *b*, a new algorithm was developed to minimise the problems with both the maximum likelihood and least squares regression methods. It applies the least squares method to a subset of the data which excludes the extreme events. The subset is from M_C (e.g. M3.5) until the second empty magnitude bin. Two rather than one empty bin, allows one bin to be empty and the data at higher magnitudes to be used, whilst still removing the larger "extreme" events. Hereafter, this method is referred to as ls2. We use the three aforementioned methods to calculate *a* and *b*, in addition to a method which assumes a *b*-value of one (referred to as a_1).

Schorlemmer et al. (2005) demonstrated that the *b* for thrust events is 0.93, with a range of 0.78 to 1.0 depending on rake angle. For strike-slip earthquakes the average *b* is 0.98 with a range of 0.95 to 1.1 depending on rake angle. Given that Australian earthquakes are almost exclusively thrust and that declustering a catalogue reduces the b value we consider an acceptable range of b values for the declustered Australian catalogue is 0.6 to 1.05. So the preferred values of *a* and *b* were selected according to the logical sequence:

- if b_ls2 >0.6 and <1.05, use ls2
- elseif b_ml >0.6 and <1.0, use ml0
- elseif b_ls >0.6 and <1.05, use ls0
- else use a_1 and b=1.

Of the 25 zones the ls2 method was used for 19, ml for 1, ls0 for 1 and b-1 for 4 zones.

Figures 8 – 10 show a series of examples where the ls0 (black line) and/or ml (red line) methods fail to give reliable estimates of *b*. In contrast, the ls2 (green) method does provide robust estimates of G-R recurrence parameters. In Figure 11, none of the three methods (ml, ls2 and ls0) give a reliable result so the default value of b=1 is assumed.

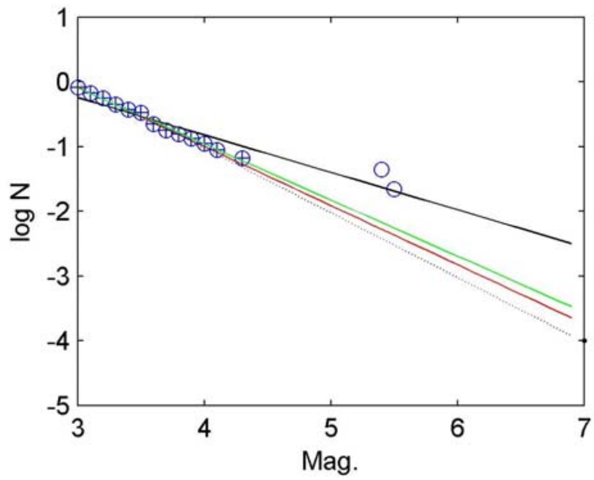

Figure 8 magnitude-frequency statistics of Zone 10 (Victorian North East). The ls0 (black) is biased low by the M5.4 and 5.5 earthquakes. The ml (red), ls2 (green) and b=1 (dashed) methods give consistent results.

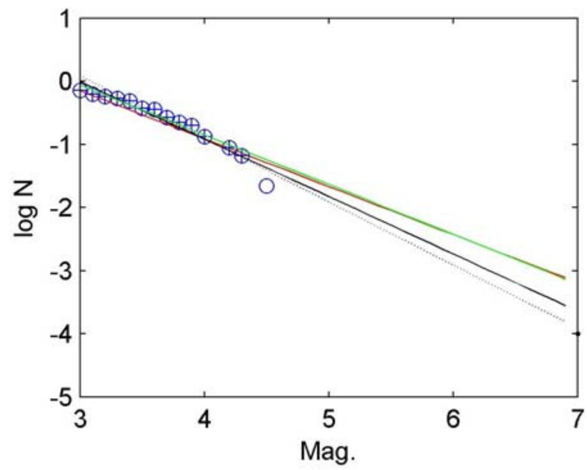

Figure 9 statistics for Zone 1 (Chillagoe-Cairns) , where ls0 is biased high but both ml and ls2 methods give consistent results

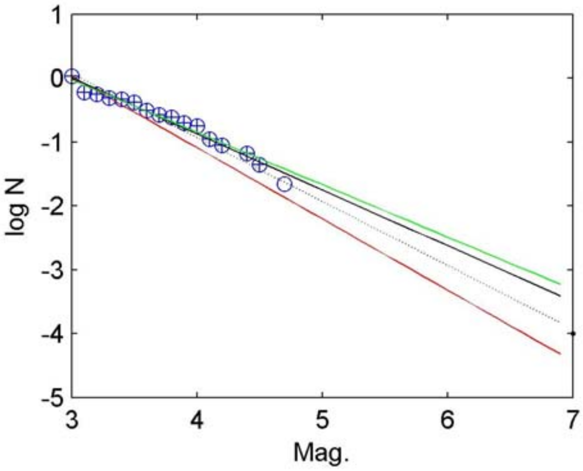

Figure 10 statistics for Zone 13 (Western Tasmania and Bass Straight), where ml is biased high but ls0 and ls2 both give consistent results.

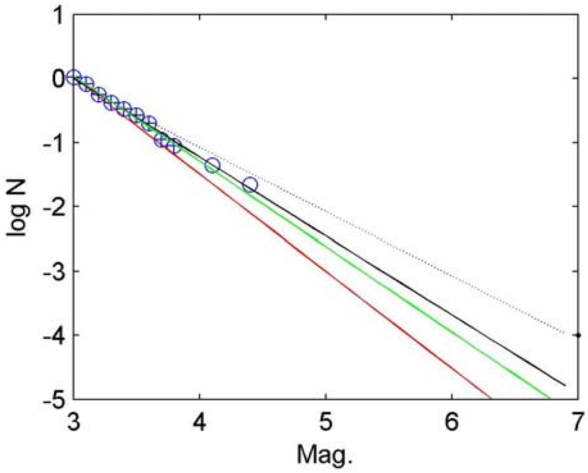

Figure 11 statistics for Zone 16 (Eyre Peninsular), where all, particularly ml, are biased high and a value of b=1 (the dashed line) has been assumed.

Mmax

Two values for maximum magnitude earthquake (*Mmax*) were used for continental Australia. The choice of *Mmax* in each region was primarily based on the results discussed in Leonard and Clark (2011), Wheeler (2009) and Clark *et al*. (2011). Leonard and Clark (2006, 2011) analysed a database of palaeoearthquake (fault) scarps to build a neotectonic earthquake catalogue. By fitting truncated Gutenburg-Richter magnitude frequency curves they estimated well constrained *Mmax* values of M7.25±0.1 in the Yilgarn Craton and M7.65±0.1 in the extended continental crust east of the Darling Fault. These values are consistent with the various estimates discussed by Wheeler (2009).

In the non-extended, non-cratonic area of stable continental crust, called Eastern Australian Phanerozoic, by Clark *et al*. (2011), we have no direct *Mmax* estimates from the work of Leonard and Clark (2011). Wheeler (2009) focused exclusively on North America east of the

Rocky Mountains (CEUSAC) and this provided little guidance for non-cratonic Australia. In the absence of any other information an intermediate value of 7.45 was initially chosen. However, Clark *et al*. (2011) suggest that the *Mmax* in Eastern Australian Phanerozoic is likely in the range 7.4 to 7.9. This is closer to that for extended continental crust (7.65) than for cratonic non-extended continental crust (7.25). In lieu of a more definitive value we have chosen the value of M7.65 for the non-extended, non-cratonic background zone. We note that changing from a *Mmax* of 7.45 to 7.65 makes a negligible difference to the seismic hazard, with the 500 year PGA increasing by 1.5% and the 10,000 year PGA by 4.5%. A change of *Mmax* from 7.25 to 7.85 increases the 500 and 10,000 year PGA hazard by 5.5% and 12% respectively. Given the other uncertainties in estimating PGA (zonation, parameterisation, attenuation, etc) these variations are minor.

Each regional zone was allocated the *Mmax* of the background zone in which it was located. Where regional zones overlapped two types of continental crust, the *Mmax* of the type it was primarily located was assigned for the whole source zone. All the hotspots were allocated an *Mmax* of M6.25.

Completeness Period

The magnitude of completeness (M_C) is defined as the lowest magnitude above which all earthquakes in a space-time volume are detected (Weimer and Wyss 2000). In recent years there have been numerous attempts at quantifying M_C across Australia (Cuthbertson 2006, 2007; Sagar and Leonard 2007, 2008; and Dent 2009). All have encountered difficulties due to the combination of Australia's low level of seismicity, distribution and history of seismic stations, and heterogeneous properties of the Australian crust. The most commonly utilised methods were developed in areas of both high seismicity and high network density and their application to Australia has proved problematic.

Sagar and Leonard (2007) applied the ZMAP software (Wiemer and Wyss 2000) to the Australian catalogue but the results were overly complicated. As Dent (2009) states "In a low seismicity region like Australia, a seismograph may run for a long time and unequivocally indicate that no earthquake occurred in the region of the seismograph over a relatively long period. However, the ZMAP program would interpret the lack of events as indicating the catalogue for that region and time was incomplete and therefore not include that time-space in its calculation of seismicity rates." In areas of high network density (i.e. Victoria and SE NSW) the method produced credible results.

To estimate M_C, Cuthbertson (2006) found the Stepp Test (Stepp 1972) excessively sensitive to changes in the catalogue difficult to automate and time consuming if done manually. Alternatively, Cuthbertson (2006) developed a method that calculated the network detection magnitude from the network configuration in space and time. Quality factors were subjectively assigned to each station based on expected sensitivity. In addition to calculating for a particular zone, Cuthbertson (2006) extended the method to a ~50 x 50 km grid. This had the advantage of measuring variability across a larger zone, but the disadvantage that each individual square has a high error. These errors were subsequently minimised by averaging. They used weighting based on the period of time above the detection threshold. For the study area, where there was both a very good earthquake catalogue and station database, the technique proved very robust. Cuthbertson (2007) applied the above method to all of eastern Australia. Unfortunately they do not give a time space breakdown of M_C across eastern Australia.

Leonard (2008) compared the magnitude-frequency statistics (log $N = a - bM$) for 10 years of data in 5 year increments. This allowed M_C to be estimated in increments of 5 years for each of the four zones of enhanced seismic activity they analysed. Leonard (2008) subsequently used the historical catalogue to estimate M_C for the pre-instrumental period. The results are shown below.

Region	*1.5*	*2.0*	*2.5*	*3.0*	*3.5*	*4.0*	*4.5*	*5.0*	*5.5*	
SWA	1990	1980	1965	1960	-	-	1880[1]	--	-	-
SA	1980	1970	-	-	1965	1960	1880[1]	-	-	-
SEA	1975[2]	1970	-	1960	-	1955	-	1880[1]	-	-
NWA	-	-	-	1980	1970	1965	1960	1960	1910	
NA[3]		-	-	-	-	1980	1970	1965	1960	1910

1 These dates are from estimates of the historical record.
2 In SEA M_C has increased to 2.0–2.5 since 1995.
3 NA is all of Australia excluding the four regions analysed in detail.

Table 1 Magnitude of completeness from Leonard (2008)

Dent (2009) took the method of Cuthbertson (2006, 2007) and applied it to western and central Australia. Dent (2009) noted that most stations in WA, SA and NT are generally more sensitive than stations considered high sensitivity in Queensland. This is likely due to the lower attenuation in western and central Australia. As such the program likely gives a slightly higher M_C than is actually the case. Dent (2009) produced a series of maps estimating the network detectibility for the years 1960, 1970, 1980 and 2005. They suggest that the M_C values proposed by Leonard (2008) are too low and their values probably reflect the best monitored portion of the zone and not the average, with the worst monitored portion being higher perhaps by 1.0 magnitude units.

None of the aforementioned authors used the earthquake catalogue now being used for the update of the national hazard map (GG_Cat). Sagar and Leonard (2007) and Leonard (2008) used the catalogue described by Leonard 2008 which in eastern and southern Australia is less complete than GG_Cat. Cuthbertson (2006) used a local Queensland catalogue which is probably of similar completeness to GG_Cat, though possibly more complete for the region. Cuthbertson (2007) used the ES&S catalogue which is probably very similar to GG_Cat in eastern Australia. Generally these differences only apply to earthquakes of magnitude less than 3.0. Dent (2009) calculated theoretical M_C using a database of seismic stations and did not use an earthquake catalogue

The techniques used herein to estimate *a* and *b* from the magnitude-frequency statistics (log $N = a - bM$) has the capacity to adjust for multiple time-magnitude windows. The space-time volumes of Leonard (2008), shown in Table 2 above, were initially used. However they were found to produce unsatisfactory results Because the cumulative occurrence curves became stepped at the boundaries of the magnitude windows. That is, the number of expected earthquakes at smaller magnitudes (<M3.0) were over estimated and the behaviour for larger magnitudes (>M5.0) was highly variable. It became apparent that the M_C for various time windows needs to be estimated individually for every source zone. To be done robustly would require at least two of the three methods discussed above (i.e. 1 - Leonard 2008; 2 – Zmap of Sagar and Leonard 2007; 3 – theoretical method of Cuthbertson 2007 and Dent 2009) to be used. This was not possible within the time frame available.

For the current draft the single M_C of M3.0 since 1965 has been used. To a large extent this is probably only the case in the SW corner of W.A., the ranges of S.A., Victoria, eastern NSW and

SE Queensland. In the northern and central regions of Australia, an M_C of 3.5 was probably achieved in the early 1970s and 3.0 in the early 1980's. So in these zones the statistics below M3.5 are variable. However, as the zones in these areas often include larger (e.g. ≥M5.0) earthquakes the least squares calculation of *a* and *b* remains robust, though the Maximum Likelihood estimates are expectedly poor. In southern and eastern Australia we ignore large earthquakes recorded prior to 1965. As discussed in the Parameterisation section these events are often extreme events so distort the least squares statistics and a method was developed which excluded these from the least squares estimation of *a* and *b*. For the Hotspots layer we used an M_C of M2.5 since 1992.

Conclusion

To match the observed statistical properties of the seismicity of Australia, 3-4 Poisson statistical source models are required. In order to account for this observation, we have adopted a three layer source zone model: 1) a *Background* layer, with three zones covering 100% of the continent, based on the distribution and characteristics of palaeo-scarps and of crustal properties; 2) a *Regional* layer, of 25 zones covering ~50% of the continent, based on the pattern of earthquake density; and 3) a *Hotspot* layer, of 44 zones covering 2% of the continent, based on the areas of sustained high seismicity.

Two values *Mmax*, based on the results discussed in Leonard and Clark (2011), Clark *et al*. (2011) and Wheeler (2009), have been adopted. *Mmax* of 7.25 is used in the non-extended cratonic areas and 7.65 elsewhere.

Though the most commonly used method (Maximum Likelihood) of estimating *a* and *b* was found not to be satisfactorily for many zones. This is thought primarily to be due to an inadequate knowledge of the variation in M_C, both spatially and temporally. The least squares method also has well known limitations for estimating *a* and *b*. A new method, which is a modification of least squares, was developed to overcome the limitation of these methods. This allowed the development of a fully automatic method for calculating *a* and *b*. For the three layers of the source zones the inputs were: 1) the *Background* layer, the declustered catalogue with an M_C of M3.0 since 1965, 2) a *Regional* layer, the declustered catalogue with an M_C of M3.0 since 1965; and 3) a *Hotspot* layer, the full catalogue with an M_C of M2.5 since 1992.

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