A Proposed PSHA Source Zone for Australia

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ABSTRACT

A novel method using Voronoi cells has been devised to group earthquakes by density without binning; no a priori assumptions of relationships with faulting, geology, or principal stress direction (Sambridge et al, 2016). Various trials were made to find the best representation of earthquake density using both Voronoi cells and Delaunay triangulation. Log-density was used because of the large range of densities observed. A Hsieh-Clough-Tocher (HCT) filter, one of the trails with 9 iterations of smoothing of the earthquake log-density map, produced artefacts in the process causing us to settle on applying a bi-linear interpolation inside the Delaunay triangulation on the nine times smoothed log-density Voronoi cells.

Finally we have created bins by imposing zone boundaries on the smoothed density plots to draw up an earthquake zone map for continental Australia. It is a requirement imposed by Geoscience Australia that source zones submitted by third parties for the next National Seismic Hazard Assessment be polygons.

We recommend that a 'b' value of 1.0 and Mmax of 7.5 be used within these zones throughout the continent. This model is submitted for a standard PSHA analysis by Geoscience Australia and discussion of its likely weighting by the seismological and engineering communities.

Few if any intraplate source models are underpinned by a physical explanation of the seismicity. The output source zones presented here are reminiscent of those produced with a physical model, the Coulomb model, based on the external stresses acting on intraplate Australia (McCue and others, 1998).

Keywords: Nearest neighbor algorithm, earthquake source zones, PSHA, seismicity

INTRODUCTION

The very first requirement for a Probabilistic Seismic Hazard Assessment at any site or set of sites is an earthquake source zone delineating the area sources and/or faults that are identified (by the seismologists) to occur in the region. This one decision impacts enormously on the results, since there is an abrupt change in hazard assessment across the boundary from the computed near-source level to that produced by the background seismicity. A circular areal source produces a circular bullseye, a linear fault produces a narrow rectangular blob in the hazard map. Smoothing will taper the hazard jump but not remove it.

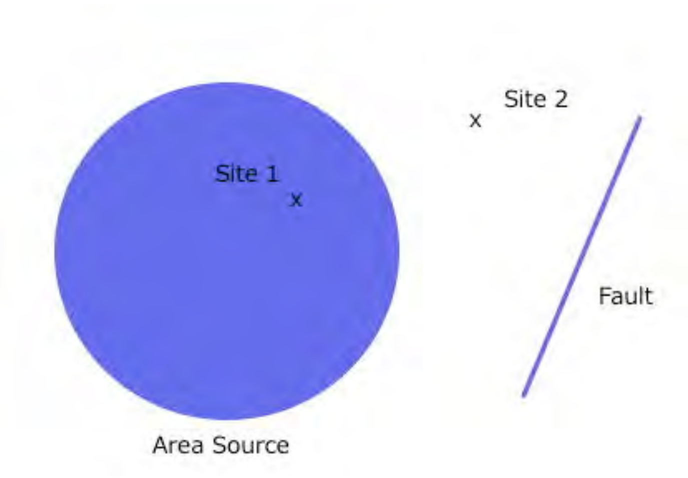


Figure 1 Typical earthquake source geometry for a PSHA at sites 1 and 2 where the hazards are quite different. To produce a hazard map a site is moved over a grid with spacing of about 20km.

There are a number of different ways of artificially smoothing the resulting PSHA boundary but considerable judgement is required to draw it in the first place and no two independent studies will agree on where it should be, especially in an intraplate environment like Australia.

The vexed issue of what constitutes an active fault divides the seismological community, simply because there is no universally agreed definition. What is acceptable in California or New Zealand would yield very few if any active faults in Australia yet seismologists agree that earthquakes occur on faults, they just don't seem to occur on large ancient faults mapped by geologists. An example is seen in Figure 2 where the epicentres are not obviously associated with one or even a few faults. It is hard to see how any individual fault could be active without them all being active and best catered for as an areal source in the PSHA. The Lake George Fault is often cited as an active fault.

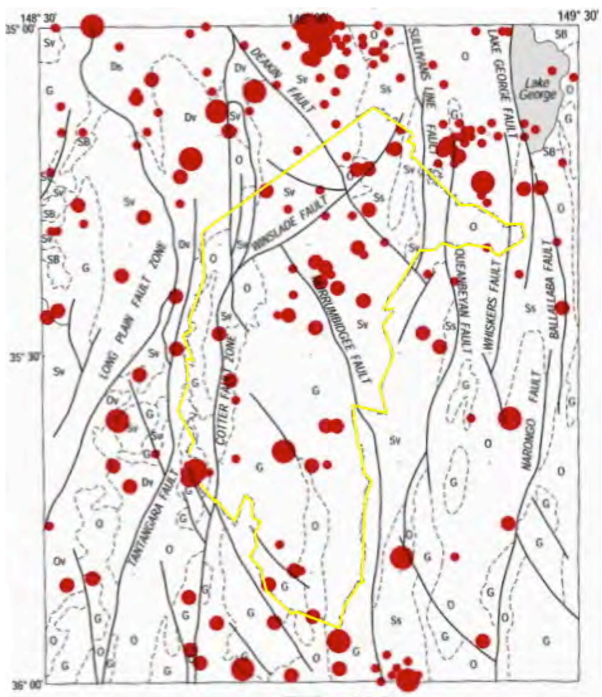


Figure 2 Epicentres (red dots) and faults (named solid black lines) in the ACT region (yellow outline).

If boundaries are drawn too tightly about past earthquakes, disappointment and dismay are experienced when strong earthquakes occur outside the boundary. On the other hand when the boundary encompasses too broad an area the density of earthquakes reduces to the point where the hazard will approach the background level. The level chosen for the background is usually 10% of that in the area source(s), a totally arbitrary choice. If the background is too high then you end up with a more uniform hazard across the country. In retrospect this might have been a sensible choice in Canterbury in the South Island of NZ, but would not yet be considered acceptable in Auckland in the North Island of NZ. Nor would town planners accept a Meckering WA level of hazard in Sydney or Melbourne, let alone Perth.

Earthquake magnitude is not a consideration at this stage of the zoning process although a lower limit may be imposed, in this case magnitude 2.5 was the cut-off for the spatial mapping with Voronoi cells.

Considerable effort has been expended by seismologists showing that earthquakes of the last 100 years or more are not uniformly distributed across continental Australia – they are not. However we don't know what we don't know, we can't generate a list of earthquakes that occurred in the last 1000 years (unlike China) or even the 100 years prior to the arrival of Europeans in Australia (unlike Europe or the USA). The normal assumption is that earthquakes will occur in the next 50 years where they occurred in the past 100 years. If we had a theory of intraplate tectonics then assumptions that differ from the past earthquake model might have some basis in theory at least.

A physical model purporting to explain the non-uniform pattern of Australian earthquakes — the Coulomb Model (McCue and others, 1998) — a stress derived model was too radical for most seismologists to be used for a PSHA though many engineers familiar with soil or rock mechanics were not so judgmental. Shear zones at approximately 45° to the principal stress direction were fitted to the epicentre plots, the resulting orthogonal zones recommended for use with a PSHA. It has withstood the test of the last 20 years, most of those earthquakes occurred within the zones, but that is deemed too short an interval on which to be judged.

Brown and Gibson (2004) published a geology-based zone map, what might be termed a rock-age and composition zone map. But large earthquakes and long faults occur in rock of all ages in Australia from the oldest rock in the Yilgarn Block WA to the youngest rock in oceanic crust off NE Tasmania, and from basaltic and granitic to sedimentary composition.

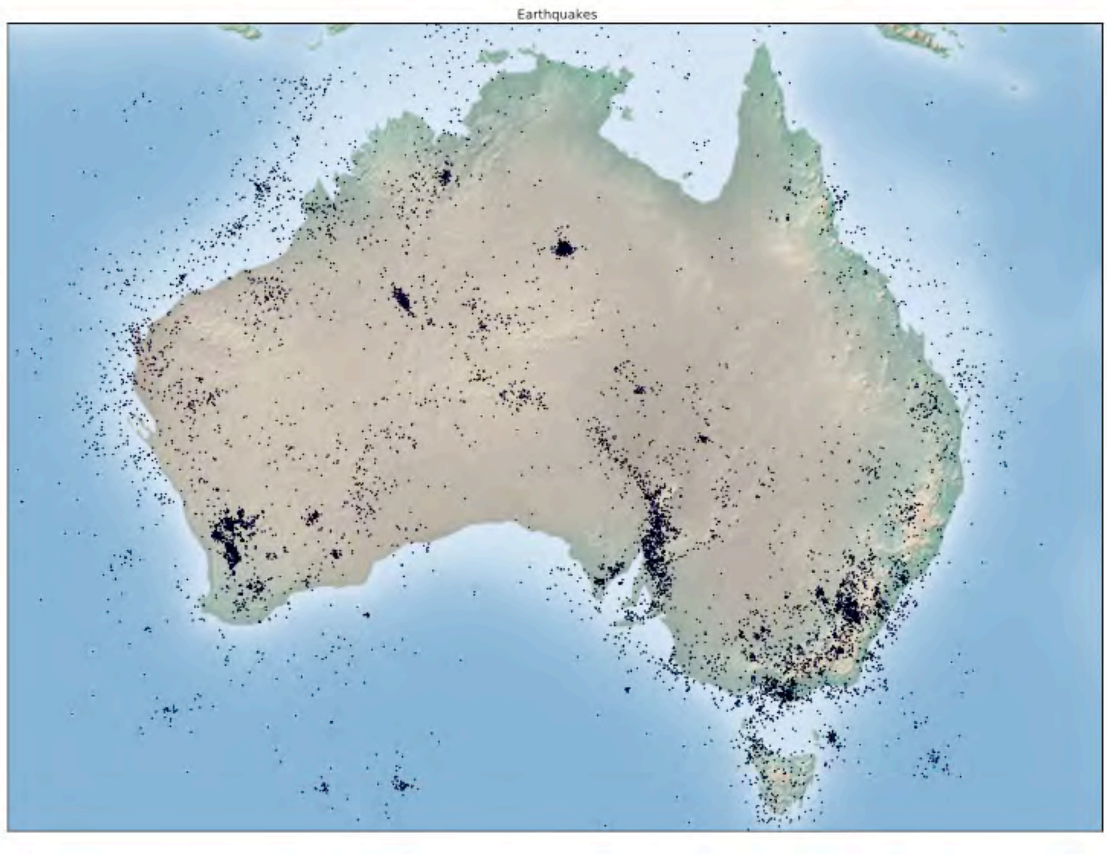


Figure 3 Seismicity of Australia (the Gibson Catalogue, 1837 – 2014, ML ≥ 2.5)

With all the uncertainty and value judgments made in the PSHA process the only sensible approach is to weight a number of 'expert' assessments at the end of the process, far better than at every step where the hazard is compounded and distorted. However we will persevere with the process on offer.

BUILDING AN EARTHQUAKE SOURCE ZONE MAP FOR AUSTRALIA

An extract of Australian earthquakes from Gibson's earthquake database (Figure 3) was agreed to be the standard on which all competing source zone models were to be developed for the next PSHA. The other steps outlined above were to follow, the first of them identifying earthquake source zones which we have done using a novel non-binning technique. All earthquakes were used including foreshocks and aftershocks. Every past event contains information on where earthquakes are likely to happen in the future.

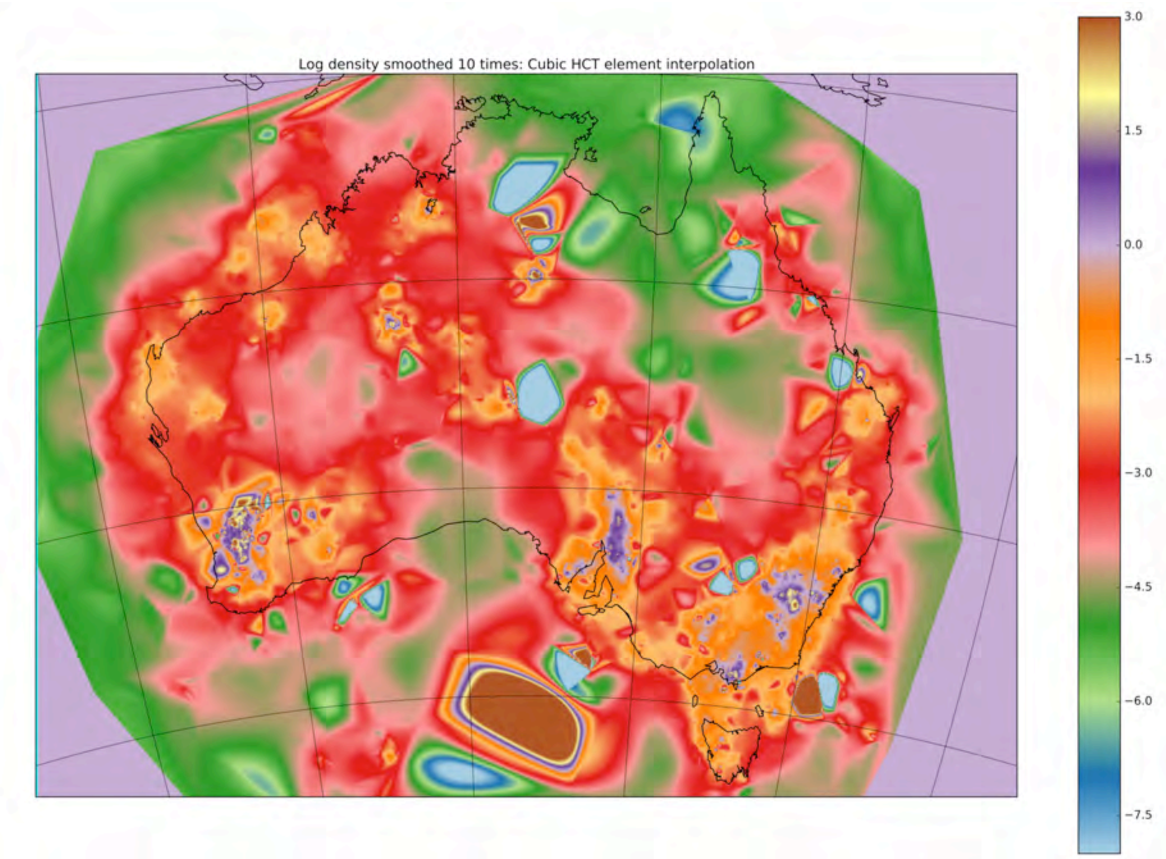


Figure 4 Voronoi diagram of earthquake log-density using a nine HCT element interpolation to smooth the map. Artefacts are seen in the image such as that south of South Australia.

What is required is a method of identifying the source zones without folding in the prejudices of those doing the analysis, minimising the subjective decisions that are normally made. That was the motivation for the authors of an accompanying paper (Sambridge and others, 2016) to experiment with a novel method of plotting earthquake densities using Voronoi cells and then experiment with various smoothing methods to use as a basis for zoning for the next loading code.

The cubic interpolation method using Hsieh-Clough-Tocher (HCT) elements to smooth the log-density map, Figure 4, (Figures 9 from Sambridge and others, 2016) was noticed by the authors and an anonymous reviewer to have unacceptable artefacts so a different strategy was chosen. Applying a linear interpolation inside the Delaunay triangulation on the nine times smoothed log-density Voronoi cells proved to be satisfactory (Figure 5) and was adopted as the basis for a zoning system (Figure 10 from Sambridge and others, 2016).

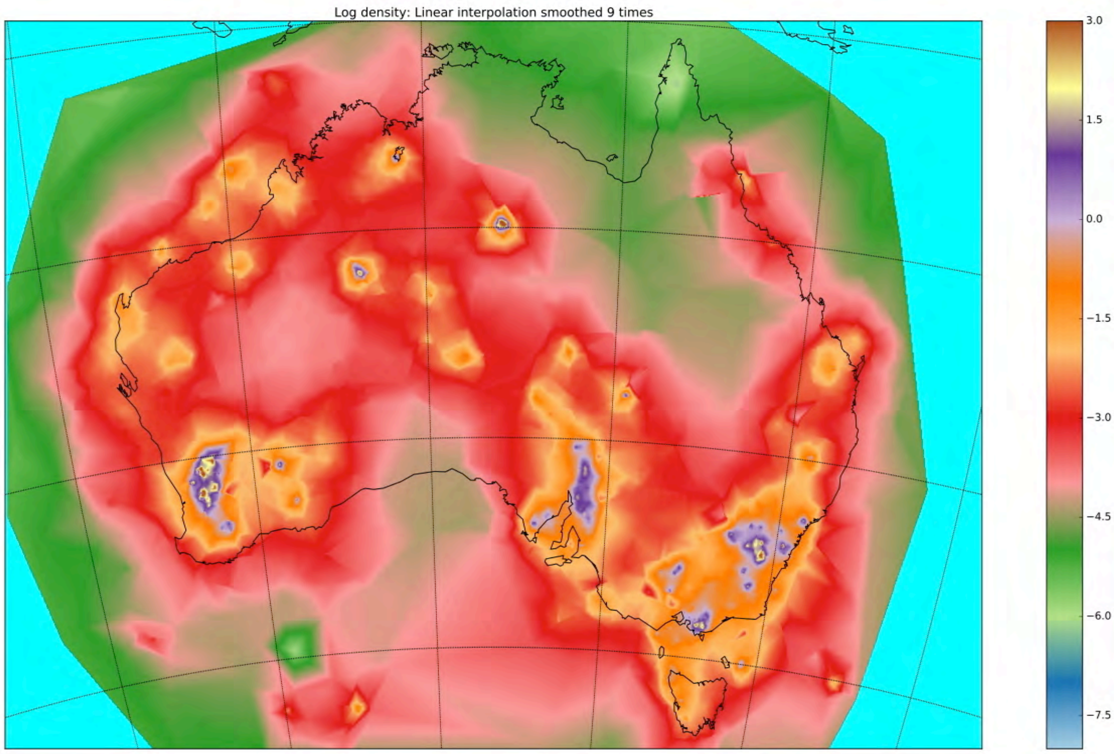


Figure 5 An interpolation of log-density proxy using linear interpolation applied to natural neighbor smoothed densities. Nine passes of the natural neighbour smoothing have been applied. There are no artefacts, the process is continuous.

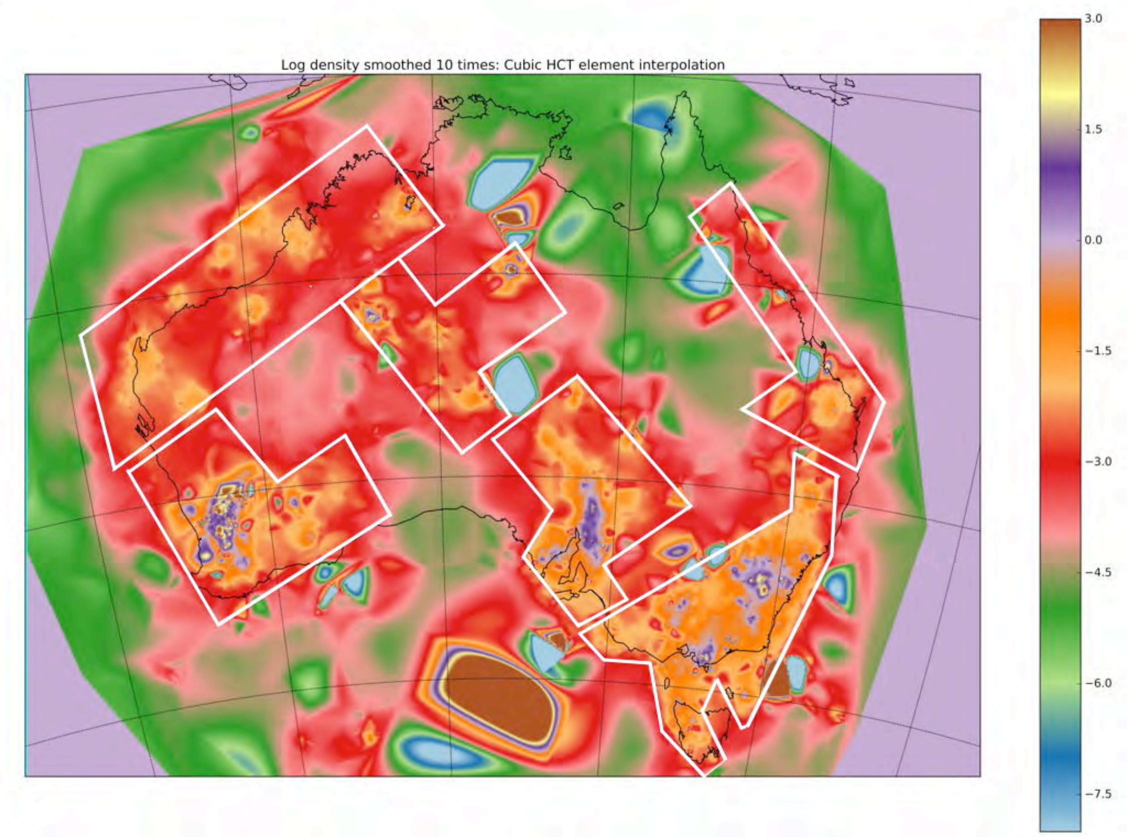
It is very clear from Figures 3, 4 and 5 that earthquake density in not uniform across Australia. Most Australia seismologists and an anonymous NZ reviewer of this paper support this interpretation.

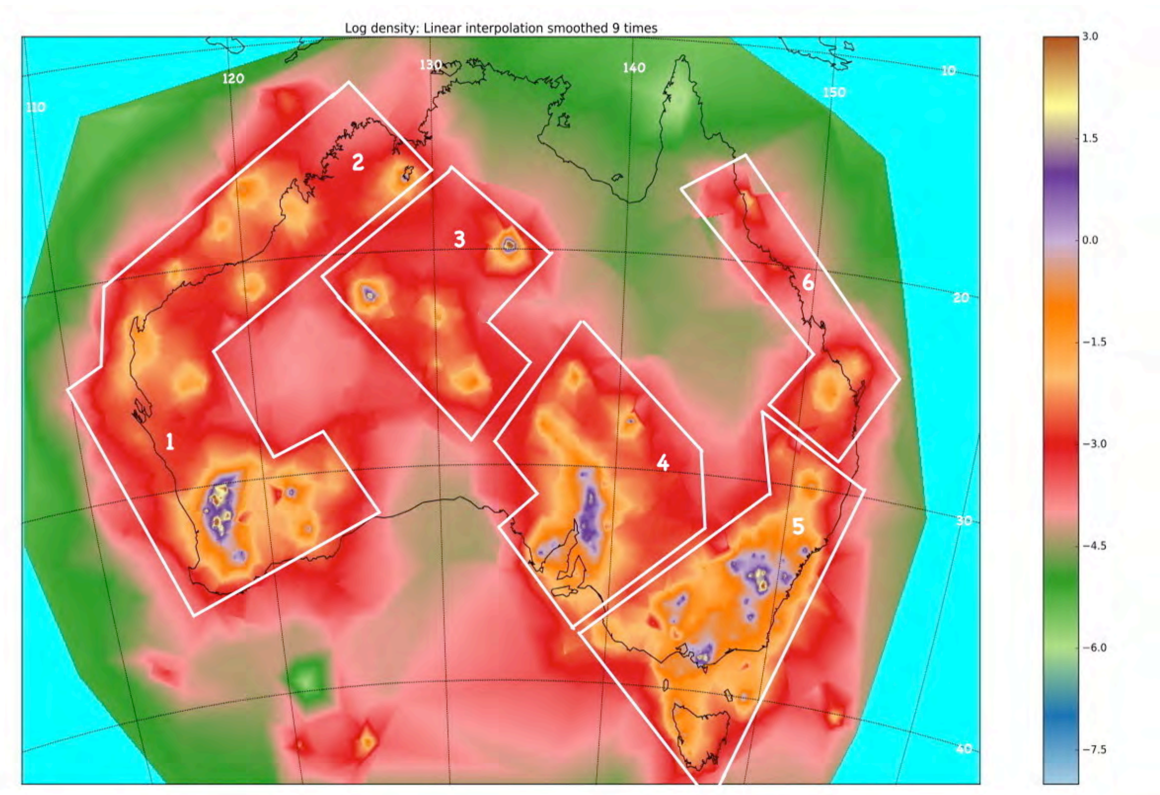
It should be noted that in this method every earthquake is assumed to be telling us something about the seismicity, no weighting has been given to earthquakes magnitude, foreshocks and aftershocks have not been removed, completeness has not been invoked to delete most of the recorded earthquakes (a common criticism of past processes).

Whether this same pattern will be observed in 200 years only time will tell. Without a physical model, the equivalent of Plate Tectonics for intraplate regions, this seems like a reasonable strategy, at least for normal buildings with an expected lifetime of about 50 years, and there is no other strategy except to add active faults if you knew where they all were, or even knew where most of them were.

The contour map must be converted into a source map that satisfies the requirements of GA's hazard analysis software – only closed polygons. To that end polygons have been superposed on the smoothed map (Figures 6 and 7) that satisfy this criterion, the white lines outlining the polygons. Both figures are included to show how little effect the change of models has on the final polygon geometry.

A contour that encloses most of the deep red was chosen to represent the zones, a balance between high and low earthquake density without covering too much of the continent so that the computed hazard would not be so low everywhere that it could be ignored. A visual integration was attempted to balance the hot and cold colours outside and inside the boundaries focussing on the onshore areas.





Figures 6 (above) **and 7** (below) White polygons and numbering outline the zones in the two different models. They are very similar. Figure 7 with no artefacts, is proposed for use in the next generation of earthquake hazard maps in the Standards Loading Code.

The sampling period is an order of magnitude shorter than what we would deem desirable to better compare our results with those of other intraplate areas like China and Western Europe that boast an earthquake history of about 1000 years, roughly double the return period associated with a 10% chance of exceedance in 50 years.

A table of coordinates of the polygon apex points is appended.

In Figure 7, five zones have been identified and marked:

1. The coastal WA zone including Perth parallels the SW and NW coasts and contains the largest onshore earthquakes in WA.
2. The NT/WA/SA zone in Central Australia includes Tennant Creek and Lake Mackay.
3. South Australian seismicity incorporating Adelaide and Warooka.
4. The eastern edge of the South Eastern Australian zone parallels the southeast coast from Southern Tasmania to near the Qld/NSW Border and into South East SA. It includes Gippsland, Dalton-Gunning and Kingston and Beachport.
5. There is a separate zone trending NW/SE along coastal Queensland from near Brisbane in the south, that takes in Rockhampton and the unusual seismic activity of 2015 - 2016 although those sequences were not in the dataset.

All of Australia's known large onshore earthquakes ($M \geq 6$), and most of the paleo-seismological features are included in one of the zones except those at the head of the Bight, and every zone includes a large earthquake.

This zoning has the effect of concatenating the NSW/Vic seismicity with that of the Kingston/Beachport area in SA and the Northeast Tasmanian hotspot off the Northeast coast which wasn't anticipated, but it would be surprising if these were indeed the only isolated long-lasting hotspots around past large earthquakes there, for all we know those earthquakes could happen anywhere within this zone. The seismicity of Gippsland or Dalton-Gunning could well be aftershocks of some pre-historic earthquake.

The zones cover about half of continental Australia and Tasmania. The hazard study will show that; the hazard coefficient of Sydney, Melbourne, Newcastle, Wollongong and Canberra are similar and slightly higher than Hobart; Lucas Heights Nuclear Reactor and the Australian Animal Health Laboratory face a similar earthquake hazard; all are higher then Brisbane; Perth and every major town in WA are equally rated. The relative hazard of Adelaide and Sydney and Perth and Sydney will be determined in the PSHA. Darwin will be rated too low because the offshore seismicity has not been included in this zoning exercise.

Rather than a sharp boundary we recommend a fuzzy boundary be used for the PSHA over a width of 100km.

The so-called Bulls Eyes around major past earthquakes have been removed in this process.

THE 'b' VALUE

The results of many studies of regional Australian 'b' values, the slope of the recurrence relation, have been published (e.g. Cuthbertson, 2006, 2014 and this conference 2016).

Various methods have been used including least squares, maximum likelihood and extreme values. These methods all give different results, even with the same dataset as shown by Cuthbertson. Variations are caused due to problems with the original data; completeness, aftershock removal and magnitude scale. We recommend the ML scale be used to 5.8 or 6 and then the Ms scale to Mmax. The least squares and maximum likelihood methods favour the low magnitude end of the distribution, whilst the extreme value method is biased towards large magnitudes, the range of engineering interest.

The 'b' value is linear over a range of magnitudes, 4 to 7, with a taper to the Mmax. The principle of the conservation of energy and source-size finiteness dictate that there must be a maximum magnitude and we have adopted the value of 7.5 in all zones. This is larger than the known largest earthquake of 1906, magnitude Ms7.2, and about the size of the largest earthquake known from paleo-seismological work (Clark and others, 2012). The slope of the recurrence relation (b-value) increases towards an infinite value at Mmax and a zero value at low enough magnitudes even when seismograph coverage is adequate.

Rather than try to defend a best value we have adopted what is sometimes termed theuniversal value of 1.0 (Rundle, 1989) for each zone in the magnitude range 4.0 to 7.0. There is no consensus for a single 'b' value (Okal and Romanowicz, 1994) but a 'b' value of 1 corresponds to a fractal dimension D of 2 which has interesting theoretical implications but outside the scope of this paper.

DISCUSSION

As agreed at the 2015 AEES annual conference, GA will compute the 'a' values for each of the zones using the Gibson catalogue. In our model we expect GA to use a 'b' value of 1.0 and compute the 'a' value only. A PSHA will then be run with this source model geometry and an Mmax of 7.5. All of the proffered models will then be weighted and a final hazard map produced, a consensus model of the seismological and engineering communities is the goal.

It is interesting that this map has strong similarities to a map produced by McCue and others nearly 20 years ago based on a completely different process. The map in this paper sought to impose no model restrictions, no binning until the last step. No correlation of earthquakes and geology, no mention of faults, intraplate stress domains or interplate actions. The authors claim no predictive capability but suggest that future earthquakes will occur near past earthquakes. By contrast McCue and others (1998) sought to impose a Coulomb stress origin on the pattern of observed earthquakes with predictive scope for future earthquakes where none had been previously observed. In both cases polygon boundaries parallel regional coastline trends or the continent/ocean boundary interface.

CONCLUSION

We have chosen one of the results of a series of novel binless mathematical experiments to recommend a binned earthquake source zone map of Australia. We have further recommended parameters 'b' and Mmax that are to be used in the PSHA to be run by Geoscience Australia for the next generation earthquake hazard map of Australia and we have discussed the likely consequences of using this map for the PSHA.

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Table Zone polygon corner points, northernmost first, clockwise, end point same as starting point.

Zone 1		Zone 2		Zone 3		Zone 4		Zone 5	
Coastal WA		Centre Australia		South Australia		SE Australia		Queensland	
12.1	125.8	16.2	130.9	23.2	137.9	26.6	148.1	15.1	145.9
16.4	130.0	20.2	136.0	28.8	144.7	29.7	154.2	24.3	155.3
23.9	118.1	23.4	132.8	32.5	145.3	45.0	146.8	28.5	152.5
29.0	120.7	25.3	135.0	37.5	138.0	37.7	138.3	26.45	148.1
28.1	123.6	28.9	131.8	32.9	133.2	30.5	149.1	23.9	150.4
32.0	126.3	20.9	124.1	31.3	135.6	26.6	148.1	16.9	142.7
35.9	114.8	16.2	130.9	28.9	133.2			15.1	145.9
24.6	109.9			23.2	137.9				
23.8	111.8								
20.2	112.6								
12.1	125.8								