The Victorian Earthquake Hazard Map

Dan Sandiford[1], Tim Rawling[1], and Gary Gibson[1]

[1]Affiliation not available

October 7, 2022

1 Summary

This report summarises the development of a new Probabilistic Seismic Hazard Analysis (PSHA) for Victoria called the Victorian Earthquake Hazard Map (VEHM). PSHA provides forecasts of the strength of shaking in any given time (return period). The primary inputs are historical seismicity catalogues, paleoseismic (active fault) data, and ground-motion prediction equations.

A key component in the development of the Victorian Earthquake Hazard Map was the integration of new geophysics data derived from deployments of Australian Geophysical Observing System seismometers in Victoria with a variety of publicly available datasets including seismicity catalogues, geophysical imagery and geological mapping. This has resulted in the development of a new dataset that constrains the models presented in the VEHM and is also is provided as a stand-alone resource for both reference and future analysis.

The VEHM provides a Victorian-focussed earthquake hazard estimation tool that offers an alternative to the nationally focussed 2012 Australian Earthquake Hazard Map (Burbidge and Australia, 2012). The major difference between the two maps is the inclusion of active fault location and slip estimates in the VEHM.

There is a significant difference in hazard estimation between the two maps (even without including fault-related seismicity) due primarily to differences in seismicity-analysis. These issues are described in the discussion section of this report, again resulting in a higher fidelity result in the VEHM. These differences make the VEHM a more conservative hazard model.

The VEHM currently exists as a series of online resources to help assist those in engineering, planning, disaster management. This is a dynamic dataset and the inputs will continue to be refined as new constraints are included and the map is made compatible with the Global Earthquake Model (GEM) software, due for release in late 2014.

The VEHM was funded through the Natural Disaster Resilience Grants Scheme. The NDRGS is a grant program funded by the Commonwealth Attorney-General's Department under the National Partnership Agreement on Natural Disaster Resilience signed by the Prime Minister and Premier. The purpose of the National Partnership Agreement is to contribute towards implementation of the National Strategy for Disaster Resilience, supporting projects leading to the following outcomes:

1. reduced risk from the impact of disasters and
2. appropriate emergency management, including volunteer, capability and capacity consistent with the State's risk profile.

2 Earthquakes, hazard and damage in Australia

2.1 Effects of Earthquakes

The effects of earthquake shaking depend on the amplitude of the motion, the frequency content, and the duration. Amplitude is determined by magnitude and distance. Frequency content is determined by the earthquake magnitude and stress change, with small earthquakes giving dominantly high frequency motion, and increasing magnitudes give an increasing proportion of energy at decreasing frequencies (longer periods). Duration of earthquake motion is determined by the earthquake magnitude, and is comparable with the rupture duration (less than 1 second for magnitudes less than 5.0 and greater than 10 seconds for magnitudes larger than 7.0).

2.2 Earthquakes in Australia

Australian earthquakes occur in a 'stable' continental region (SCR), so are infrequent compared to plate boundary settings. In a typical region an event is only felt on average each 5 to 10 years. The whole continent experiences about 600 recorded events each year, with 2 events of $M > 5$ (Leonard, 2008). Earthquakes in all regions of Australia are distributed over many faults, but with few longer than 100 km. It follows that there is relatively low maximum magnitude, probably Mw 7.2 to 7.5, limited by the thickness of the seismic zone and the length of active faults.

The record of seismicity in continental Australia is heterogeneous. A number of distinct zones of seismicity have been defined across the Australian continent. One of these, known as the South Eastern Seismic zone, corresponds broadly with the southern part of the Eastern Highlands, extending into southwest Gippsland. Compared to other areas of Australia, seismicity in this region has been consistently elevated in the previous decade, and seems to be controlled by the arrangement of dense, highly interlinked fault networks with typically short fault lengths.

Almost all Australian earthquakes are in the upper crust, from the surface to a depth of about 20 km. Moderate magnitudes can cause damage, such as Newcastle, 1989, ML 5.6, which caused about A $3 billion damage. While the orientation of the stress field in Australia is well constrained, variations in its magnitude are not as well understood. Stress is almost always horizontal compression, and reverse (thrust) faults therefore predominate. Ruptures tend to have high stress drop, giving high frequency, high acceleration and short duration motion.

2.3 Engineering and Hazard

Earthquake effects on structures and people are minimised by building to an earthquake code. In practice, this means buildings that will not collapse, even if they are badly damaged by the earthquake. Building codes use risk criteria, which usually specify the average return period of earthquake ground motion that should not interrupt the operation of the structure, and the longer period that should not cause collapse of the structure.

Many earthquake building codes, such as the Australian Earthquake Loading Code AS1170.4-2007, adopt the 500-year earthquake as the criterion. This means that a building designed to last 100 years will have a 20% chance that its design motion will be exceeded during its lifetime. This does not matter very much in active areas on tectonic plate boundaries where the 500-year earthquake is almost as large as the largest credible earthquake. However, in relatively stable continental regions such as Australia, the 500-year earthquake is quite small, and will give much lower level of motion than an earthquake with a magnitude that will recur at intervals of thousands of years. Whether the traditional PSHA approach described below, is adequate to meet these large, infrequent events is not well understood.

The 2012 Australian Earthquake Hazard Map has been recommended as a replacement to the current earthquake loading code AS1170.4-2007.

3 Probabilistic Seismic Hazard Analysis

3.1 Probabilistic Seismic Hazard overview

Probabilistic Seismic Hazard Analyses (PSHA) (Cornell, 1968; McGuire, 1995) produce estimates of the probability of exceeding various levels of ground motion (intensity measures) for a given location and time interval. The primary aims are to produce seismic hazard curves—usually drawn with the annual rates of exceedance on the vertical and increasing values of intensity measure (e.g. values of PGA) on the horizontal. Alternatively, time intervals of interest are selected (e.g. 500 years) in which case a map of expected values of the intensity measure can be made.

The standard PSH methodology estimates hazard by summing the contributions from all potentially damaging earthquakes in the region, the primary steps are as follows, e.g. (Baker, 2008):

1. Define all earthquake sources capable of producing significant events.
2. Characterize the earthquake frequency-magnitude relationship (the rates at which earthquakes of various magnitudes are expected to occur).
3. Characterize the source-site distance distribution.
4. Compute the ground motion (distribution) as a function of earthquake magnitude, distance; i.e. the conditional probability.
5. Combine all probabilities (and uncertainties) using the total probability theorem.

The application of traditional PSHA approaches requires estimation of the properties of the seismic source zones, which are often determined by subjective judgments that may be different in various studies. In low-seismicity areas such as Australia, the earthquake occurrence is often modelled as a spatio-temporal Poisson process, i.e. earthquakes are memoryless and spatially random, with rates that are completely described by the Gutenberg-Richter relationship (no 'characteristic earthquakes'). The seismicity rates and frequency-magnitude distribution (b-values) are calculated from historical seismicity or from geologically derived fault slip rates (more commonly the former). The maximum credible earthquake (M_{max}) is imposed given empirical deductions from past earthquakes and estimated maximum fault length. Given that SCRs tend to have highly clustered seismicity, it is common to subdivide the region into sub regions know as area source zones, in which it is supposed that the spatial-Poisson conditions are approximately valid.

In the last few decades, fault slip rates have increasingly been used to constrain earthquake recurrence relationships and inform hazard maps (Pace et al., 2006). In Australia, this technique has been incorporated into a couple of previous studies (Brown and Gibson, 2004; Somerville et al., 2008) . It is particularly useful in regions like Australia, however, where seismicity is relatively infrequent, historical records were likely derived from sparse networks and there are numerous geological features present that indicate recent seismic activity and that can be dated using a variety of techniques. Inclusion of fault sources represents a key point of difference between the current study and the latest national hazard map by Geoscience Australia.

Recently, PSHA has also come under criticism from a number of scientists (Klügel, 2012; Stein et al., 2012). Criticisms range from a lack of model testing, failures of the prescribed maximum credible magnitude in past PSHA (e.g. in the case of Tohoku) to the assumption of Poisson statistics, and even inherent problems with energy conservation in the PSHA method. According to Klugel (Bommer and Abrahamson, 2006), this amounts to a fundamental crisis for PSHA. Some of these criticisms may be overcome by modifications to the PSHA methodology, e.g. by using seismicity models that include short-term variations in their rates due to the time since the last large earthquake occurrence (Chan et al., 2013). (Stirling, 2013) observes that largest barrier to making PSHA effective in short term forecasting is the "inability to identify where/when major earthquakes are going to occur in areas/time periods of seismic quiescence. This is not a failing of PSHA methodology, but is one of the fundamental unknowns of seismology at the present time. " This issue expressed by Stirling is of particular relevant to SCR seismicity, where earthquakes are clustered and infrequent. In this context, PSHA is still widely believed to offer a valuable, systematic integration of earthquake occurrence models (although crude) and ground motion models (although poorly constrained).

3.2 Ez-Frisk implementation of PSHA

PSHA was performed in this study using EZ-FRISK 7.62 software (McGuire, 1995). EZ-FRISK is one of the most widely used software packages for PSHA. EZ-FRISK is an implementation of the (Cornell, 1968) method, which also relies on a number of other scaling relationships such as the (Youngs and Coppersmith, 1985) estimation of seismic activity from average slip rate.

A good summary of available software, including EZ-FRISK can be found here

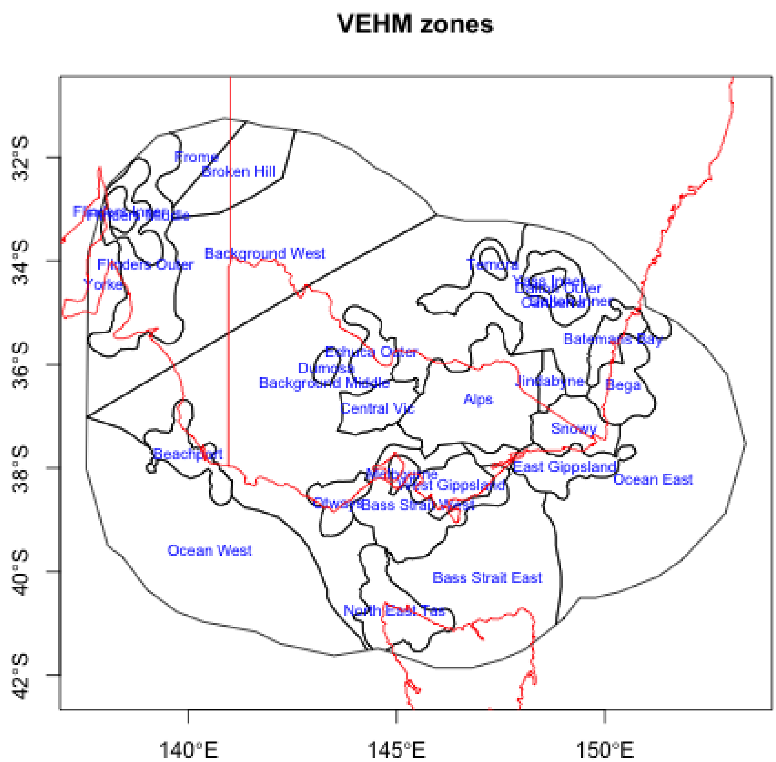

Figure 1: Area source zones for VEHM

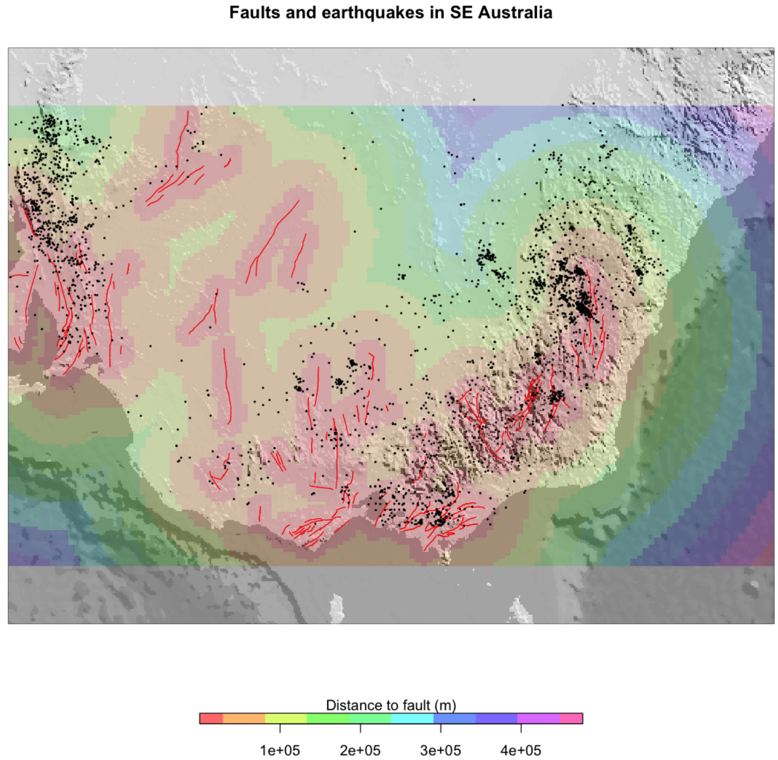

Figure 2: Active faults used in VEHM, as well as GGcat earthquakes

4 Description of Models Run

4.1 List of models and description

4.1.1 Model1: Area source zones only (also termed the reference model)

The simplest model run in this study uses area source zones only. The seismic activity within each source zone is homogenous – i.e. the seismicity is assumed to be spatio-temporally Poisson. The derivation of source zone geometries is detailed in Appendix 1. This model is also termed the reference model. In terms of inputs and approach, this model most closely follows the 2012 Australian Earthquake Hazard Map (Burbidge and Australia, 2012).

4.1.2 Model 2: 'Passive' Faults and modified area zones

The passive faults model represents a hazard model where seismicity rates are entirely informed by the historical seismicity, but where the location of the modelled activity is partly 'mapped' to active faults. For example, in a zone with a number of active faults, we first determine the percentage of earthquakes occur within a 30 km buffer of those faults. We then limit this fraction of the seismicity to occur only on those faults, providing a geographical constraint. The rationale for this model is that it may help counter earthquake-location-accuracy, by locally concentrating seismicity closer to known faults; secondly it helps distribute seismicity onto faults which may be inactive on the timescale of seismic records, but appear to be active in the current tectonic environment.

4.1.3 Model 3: 'Active' Faults plus model 1 area zones

In this model, geologically-derived fault slip rates are superimposed on a model containing only area source zones, i.e. no 'passive faults. Because the 'active faults' represent additional sources, activity rates are higher than the Model 1 values, using only area sources. In this model the higher limit of the slip rate estimates are used. By adding both recorded and paleoseismic activity rates this model is extremely conservative.

4.1.4 Final Model

The Final model assigns equal weights to the models described above. In PSHA, a preferred model is based largely on the professional judgement of the modeller. This choice of these weights is discussed below. We have not assembled a logic tree to try to quantify the uncertainty in the final model, as is common in PSHA. We are inclined to agree with (Bommer et al., 2006) who views these weights as simply ratings to reflect the relative confidence of the analyst that the most appropriate model has been selected, rather than the "scientific uncertainty".

4.2 Other comments on Models

The main difference between the models is the way in which the overall seismic activity is constrained. Models 1 2 preserve the seismic activity rate (the historical or catalogue rate) while modifying the spatial density of this rate to take into account locations of active faults. Hence for any fault where seismicity is reapportioned, the corresponding activity is subtracted from the area zone which contains the fault. This procedure is similar to that proposed by (Ninis and Gibson, 2006).

Model 3 uses 'active fault' information to modify the seismic activity. The assumption is that the long-term slip rate on active SCR faults may not be well captured by the short seismic record. In general, the seismic record may over or underestimate the long-term. This model accounts takes into account the possibility that the seismic moment rate underestimates the long-term rate, and adds published fault slip-rate information on top of the model one seismicity rate estimation.

Combining all models into 'average model', as we have in this study, means effectively weighting different hypotheses about seismicity. These can be summarised as follows:

1. Some seismicity occurs where historical/catalogue seismicity occurred and at similar rates.
2. Some seismicity occurs on geologically-indentified active faults at rates determined by historical/catalogue seismicity.
3. Some seismicity occurs on geologically-indentified active faults at rates determined by geological slip-rate estimates.

In the absence of any firm constraints about the accuracy, or relative weighting of these models (hypotheses), we assign equal weighting for the Final model.

For all models, the Ground Motion Prediction Equation implemented is (Chiou and Youngs, 2008). This model appears to agree well with Victorian data collected in recent years by Victorian AGOS seismometers (Hoult and Sandiford, in preparation). No site amplification as a result of local conditions was included. This ensures that the model is consistent with the current map in AS1170.4. Intensity measures calculated are 5 % damped response spectra at periods of 0.01 s (PGA) 0.3 s and 1 second.

5 VEHM hazard model results

Hazards values quoted are for PGA at the 500 year return period. Figures 3 - 6 show model results for PGA at 500 year return periods.

5.1 Comments on the Final Model

Figure 6 shows the VEHM, interpolated on a 0.05 degree grid. For most areas of the map the Final model is similar to the 'reference model' (area source zones only). Calculated PGA values have a strong peak in southwest Gippsland, driven by a history of high seismicity as well as the presence of a number of documented "active" faults. PGA values are generally higher in the east of the state. The peak PGA for the Final model is 0.23 g in southwest Gippsland. A number of the included active faults have a significant influence on the hazard map, the most significant being the Cadell Fault near Echuca in the central north of the map. The Melbourne CBD has a 500 year PGA value of 0.08 g. slightly less than the Aus5 model (0.09 g).

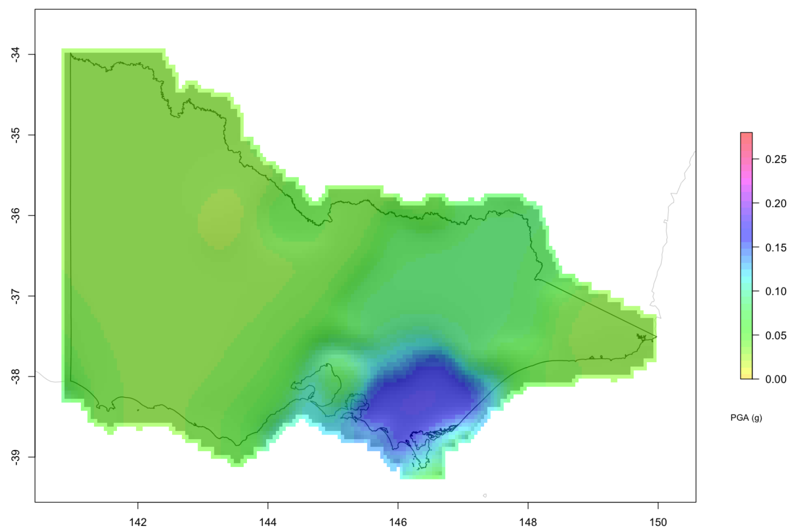

Figure 3: VEHM Model 1, 500 yr PGA, area source zones only.

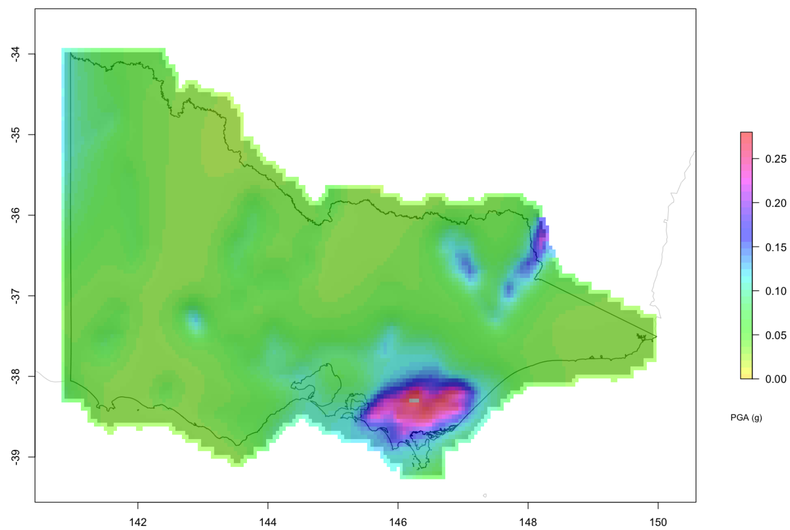

Figure 4: VEHM Model 2, 500 yr PGA, "passive faults".

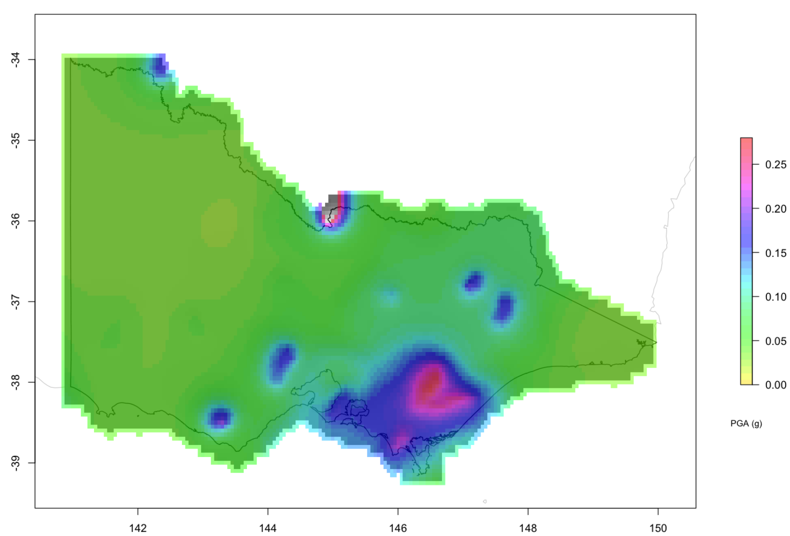

Figure 5: VEHM Model 3, 500 yr PGA, Active faults plus area source zones

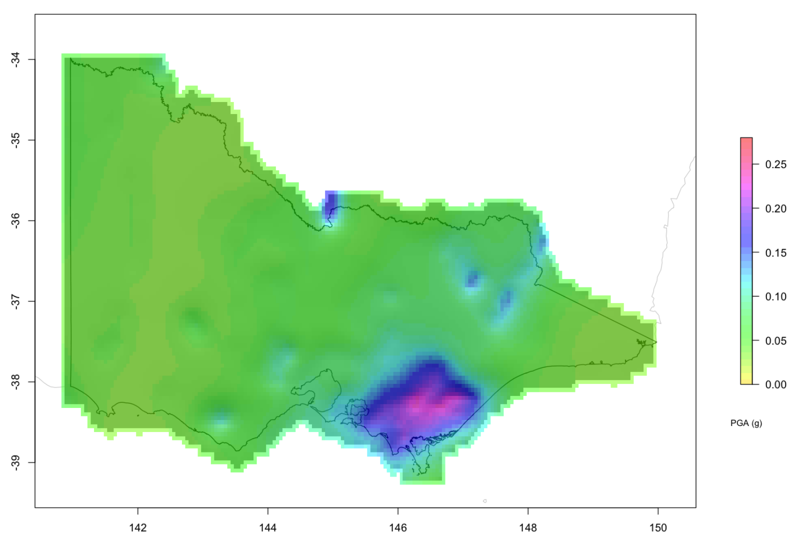

Figure 6: VEHM Final model, 500 yr PGA

6 Discussion

6.1 Summary

This report summarises the evaluation of seismic hazard for southeastern Australia in a probabilistic framework. The peak ground acceleration recurrence estimates for Victoria using the Victorian Earthquake Hazard Map inputs, (Chiou and Youngs, 2008) attenuation, a minimum magnitude of 4.0 and a maximum value of 7.5, results in slightly higher values from past fault-inclusionary PSHA studies in Australia, e.g. Aus5. The values are significantly higher than those in the AEHM from Geoscience Australia (Burbidge and Australia, 2012). The reasons for this discrepancy are discussed in Appendix 2.

6.2 Future directions

The classical PSHA approach involves the definition of seismic sources. Typically evaluation of seismic hazard requires some degree of subjective judgment. The effect on the outcome is not usually acknowledged. This was apparent in the AUS5 hazard map (Brown and Gibson, 2004). In the Victorian Earthquake Hazard Map, an approach was used that used the contours of seismicity (point density) and in principle could be automated. Yet another approach involves defining continuous distributions of seismicity parameters (Frankel et al., 1996). Such a method would also lend itself to incorporating time-dependent analysis of the same parameters. These methods seem superior to the subjective approaches of the past when dealing with seismicity, however it is still not clear how other information should be incorporated, e.g. the types of geophysical datasets discussed in Appendix 1. The earthquake hazard community has typically not developed common tools for the creation of hazard map zones and the associated earthquake statistics. To some degree this is probably a result of modellers being both outcome rather as well data-driven. Common tools would likely produce hazard results deemed unrealistic, if applied to disparate areas. Such outcome-driven factors have been contributed to hazard maps in Australia, and, indeed, in this map, primarily through the imposition of bounds on the earthquake b values.

6.3 Hazard map availability

Victorian Earthquake Hazard Map inputs and outputs are available through the Victorian Earthquake Hazard Map website. This will allow the outputs to be easily accessed by stakeholders, and the inputs to be reused by other researchers. Inputs to Victorian Earthquake Hazard Map will be made compatible for use with the Global Earthquake Model software (GEM), an open-source project that will be available late in 2014.

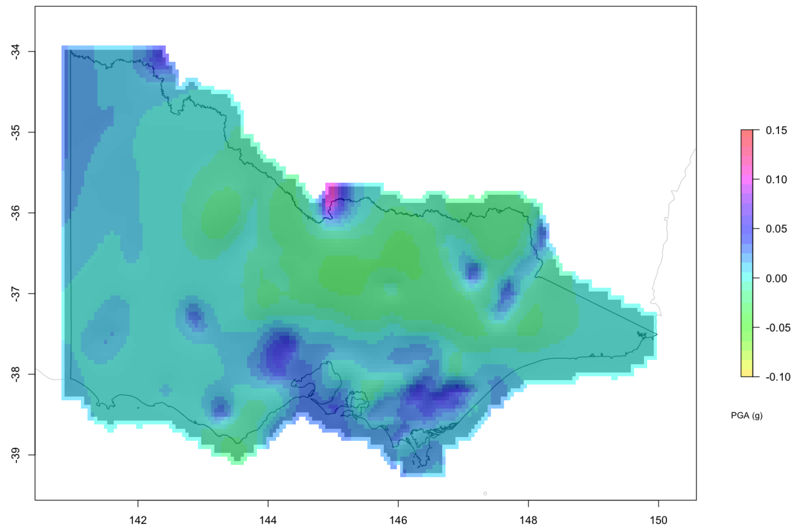

Figure 7: VEHM Final model minus Model 1, 500 yr PGA

7 Appendix 1. Hazard model inputs

7.1 Summary

The inputs to a hazard model include various types of spatial date that broadly characterises the dynamic geophysical state of the area of interest. The section below details the way in which different datasets were used to create the area source zones, one of the inputs to the EZ-Frisk PSHA.

7.2 Seismicity

Earthquakes in continental interiors happen rarely compared to those at plate boundaries. Nevertheless, such 'stable' region seismicity is the critical component of hazard in Australia, as well as in many other regions. One aspect of intra-plate seismicity is the high spatial and temporal variability of seismic activity in continental interiors compared with plate boundaries (Vasudevan, 2010). When combined with generally low seismicity, this poses a number of modelling challenges. In particular, low seismicity hampers deeper analysis of the statistical properties of seismicity. For instance, evaluation of changes in seismicity (changes in a and b-value) are difficult in many areas because of insufficient data density.

7.3 GG catalogue

Earthquakes in continental interiors happen rarely compared to those at plate boundaries. Nevertheless, such 'stable' region seismicity is the critical component of hazard in Australia, as well as in many other regions. One aspect of intra-plate seismicity is the high spatial and temporal variability of seismic activity in continental interiors compared with plate boundaries (Vasudevan, 2010). When combined with generally low seismicity, this poses a number of modelling challenges. In particular, low seismicity hampers deeper analysis of the statistical properties of seismicity. For instance, evaluation of changes in seismicity (changes in a and b-value) are difficult in many areas because of insufficient data density.

7.4 GG catalogue

The GGcatalogue (Gary Gibson, 2013, pers. Comm.,) contains 3392 earthquakes larger than M 2.5. The record includes some larger events from the pre-instrumental era.

7.5 De-clustering the catalogue and completeness

Declustering is the name given to separating earthquakes into the subcategories of foreshocks, main shocks, and aftershocks. Declustering is done to isolate 'background' earthquakes, i.e. those events that are independent of all preceding earthquakes. The declustering process used here was a simple forward-looking space time window method, without no magnitude dependence. The parameters used were 50 days and 20 kilometres, informed by the recent aftershock sequence of the 2012 Moe Earthquake. Frequency-size relations were defined using the following completeness parameters: M 5.5 up until 1960, M 3.0 for 1960-1970, M 2.5 1970-present. Completeness magnitudes (M_c) were considered homogenous across the study domain. After removing aftershocks, 2512 events remained.

7.6 Area Source zones

A key input to the PSH analysis is the choice of source zones, seismicity model and the statistical and physical parameters (a, b, M_{max}) that define these. The choice of source zones implies a seismicity model, e.g. a smoothed seismicity approach implies that seismicity is stationary (spatially and temporally Poisson). Under this assumption the historical catalogue will predict future seismicity, out to return periods that greatly exceed the catalogue duration (Leonard, 2012b). The methodology for creating area source zones is summarised beneath. The main driver for this methodology was to minimise the arbitrary 'drawing' of lines, but rather have the data create the zones itself. In principal this methodology could be fully automated. The method is similar to previous studies using spatial smoothing of historical seismicity, e.g. Somerville (2008) and the "regional source zones" in the Australian Earthquake Hazard Map (Burbidge, 2012).

1. Create a point density estimate of seismicity (here we used all seismicity above M 2.5, i.e. not a 'complete' catalogue) and contour this density estimate (performed here using standard tools on Quantum GIS, with an arbitrary 30 km smoothing kernel)
2. Work from zones of highest intensity outwards, ensuring that each zone (contour line) encloses enough earthquakes to make earthquake magnitude calculation viable (50 events was the target).
3. Draw buffers around the active faults (here a 30 km buffer on all sides was used)
4. Where active faults and area contours intersect, use the fault buffers to adapt the area source zones so that he intersection is avoided (using the principle that the initial area is most closely preserved
5. If areas have significant 'necks', i.e. where a region is made up of two 'fat' areas connected by a 'thin' corridor, then cut the regions at the thinnest point (only if this leaves enough events for EMR in each sub region.)

The area source zones created following this process are shown in Figure 1. It should also be noted that the technique used here breaks down somewhat in areas of very low seismicity, i.e. it is recognised that with the current earthquake catalogue, the technique is not suitable for Australia-wide seismic source zone definition.

7.7 Activity and b-value determination

Frequency-magnitude parameters were estimated using a method similar to Leonard (2012), the scripts are written in R., and, along with an example, can be found on the website http://vicquakehazmap.org/. Completeness magnitudes (M_c) were considered homogenous across the study domain. These were M 5.5 up until 1960, M 3.0 for 1960-1970, M 2.5 1970-present. We have only attempted to calculate earthquake magnitude relationships (EMR) where there were at least 30 independent events in the zone. If there were fewer than 30 events, the zone parameters were taken from a representative zone (”background east”).

7.8 Active faults and fault Slip Rates

Over the last couple of decades, knowledge of Australian intraplate faults has increased significantly (Clark, 2006). The location of faults is defined by field observation and geophysics/DEM analysis. The recent or ongoing activity of a fault is basically a binary decision made by the scientist on the basis of offset geology and or geomorphology. Occasionally, trenching has been performed to constrain total lip. Clark (2006) defines an ”active fault” as one which has hosted displacement under conditions imposed by the current Australian crustal stress regime, and hence may move again in the future. This implies that an active fault is one that accumulated slip in the late Neogene to present. In some cases, a fault scarp cannot be observed on the surface but folding of the landscape allows deduction of a blind fault. These are typically described as monoclines.

Fault slip rates in Australia's active faults are typically less than a 0.1 mm/y. This compares to 10s of mm/y for plate boundaries, and 1 mm/y for intermediate regions, for example, the Canterbury Plains which hosted the 2011 Darfield Earthquake (Reyners, 2013).

Active faults and fault properties were mainly taken from the Neotectonic Features Database (Clark et al., 2012), comprising 131 faults in the model domain. Some minor adjustments to these faults were made to that they had appropriate geometry for EZ-FRISK input.

Active faults added to Neotectonic Features database (12 added in total) were generally taken to be those that had some evidence Neogene activity. These were mostly sourced from literature and discussion with geologists, in particular Ross Cayley of the Victorian Geological Survey. The Neotectonic Features database is the primary input to the GEM neotectonic features (for Australia). Thus, active fault inputs to the current study should be similar to future hazard estimates performed with GEM.

Apart from high uncertainties associated with fault slip rates, a number of other assumptions in adding faults need to be made:

- All slip measured across the fault is assumed to be seismic slip (creep has not been recognised on Australian faults)
- The slip rate is an average that makes no account for short term fluctuations
- Measurements of slip rate along the surface is assumed to be representative of slip rates at seismogenic depths
- Individual faults all have a b-value equal to the b-value of the area zone that contains them.

Assuming an exponential distribution on the activity model, the activity rate, N, is constrained by the upper bound magnitude, M_{max}, the b-value for the region and the fault slip rate, S. EZ-Frisk uses the relationship derived in Youngs and Coppersmith (1985). Also needed is a model of fault rupture area as a function of magnitude. The functional form for this model is log-linear in EZ-Frisk. Here, typical values were used (e.g. Wells and Coppersmith). The equation is as follows:

$$\log_{10}(A) = A + Bm \tag{1}$$

The parameters used were $A = -4.0$, $B = 1$.

The primary GMPE used was Chiou and Youngs (2008). The SE Australia-specific relation of Allen (2012) was also tested on number of models. Although no explicit weights are attached to the models, it is noted that the 2012 Australian earthquake Hazard map weighted the above equations equally (25 % percent) along with two other equations used. Hoult (2013) shows that Chiou and Youngs (2008) provides a reasonable average of Australian-specific GMPEs, i.e. that that weightings used in the 2012 AEHM would result in an averaged GMPE close to Chiou and Youngs (2008).

7.9 Model domain

All models were calculated on a rectangular grid that enclosed the state of Victoria. Sources were defined in a polygon that extended to a 300 km buffer around Victoria. The grid resolution was 0.1 degree. While the hazard outputs extend beyond the state of Victoria (due to the ease of computing on a square grid rather than a complex polygonal grid) the results are only valid for within Victoria.

8 Appendix 2: Previous Studies

8.1 Comparisons with previous studies

Studies summarised here are the 2012 Australia Earthquake Hazard Map (AEHM) (Burbidge, 2012), the AUS5 model (Brown and Gibson, 2001) and the active fault study of Somerville et al. (2008). A description of a number of earlier models can be found in Brown and Gibson (2001).

8.1.1 Aus5

The Aus5 model was intended to be dynamic model, allowing for the updating of information as well as the addition of new discoveries as they happen (Brown and Gibson, 2001). Substantial changes in inputs and 'input methodology' mean that the VEHM is not intended as update of Aus5. In particular, this model does not follow the 'hierarchical approach' of Aus5. We have opted for a simpler approach to building zones, and only feel that incorporation of other geophysical observables (i.e. geologic region, depth to moho etc.) is only warranted if a correlation between those and seismicity can be shone. An area zone-only version of Aus5 was compiled with parameters provided by Gary Gibson for comparison. Figure 10 shows the difference between this model and Model 1 (area zones only) in the current study; Figure 9 shows the values of VEHM minus AUS5. In general, AUS5 gives higher hazard values in areas of low seismicity (Melbourne, far east). Compared to Aus5, the VEHM has anomalously high hazard predictions for areas of southwest Gippsland, and the region north of Echuca (southern NSW) due to the high slip rate assigned to the Cadell Fault.

8.1.2 2012 Australian Earthquake Hazard map

The 2012 Australian Earthquake Hazard Map has been recommended as a replacement to the current earthquake loading code AS1170.4-2007. The 2012 AEHM represents a very comprehensive study, re-examining a number of the subcomponents of PSHA including catalogue, declustering methodology, area source zone methodology, Ground Motion Prediction Equations, etc.

Apart from using different computational approaches (Monte Carlo probability distribution vs. traditional Cornell-like PSHA), the main difference between the 2012 Australian Earthquake Hazard Map and the current study is that the former does not include any information on 'active' faults. The case for either option is probably best described as intuitive, given that the relationship between "active" faults and seismicity appears ambiguous. Some studies have shown that seismic moment release rate (strain rate) is a good fit to geologically-derived uplift rates in southeastern Australia (Braun et al. 2009).

There is a significant discrepancy between hazard values in the Victorian Earthquake Hazard Map models and the Australian Earthquake Hazard Map. For the AEHM, peak Victorian PGA values are 0.1 g, for the 500 year return period, campared to 0.23 g in the VEHM. This is obviously a concern for stakeholders and is there is ongoing work between Geoscience Australia and the University of Melbourne / Australia Geophysical Observing System to reconcile the differences in calculated hazard values. Overwhelmingly though, we believe, it is the use of an 'enforced' b-value of 1.0 in 'hotspot zones' in the AEHM, (as well as the reduced M_{max} in those zones) which lowers the estimated hazard in that model.

These matters will remain a key part of ongoing work on the Victorian Earthquake Hazard Map project in 2014, along with the integration of the map with the Global Earthquake Model

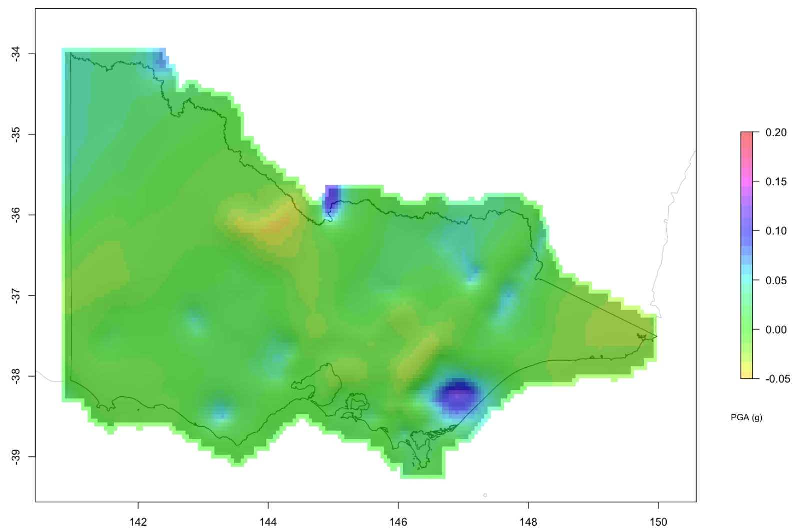

Figure 8: VEHM Final model minus Aus5 (area zones only), 500 yr PGA)

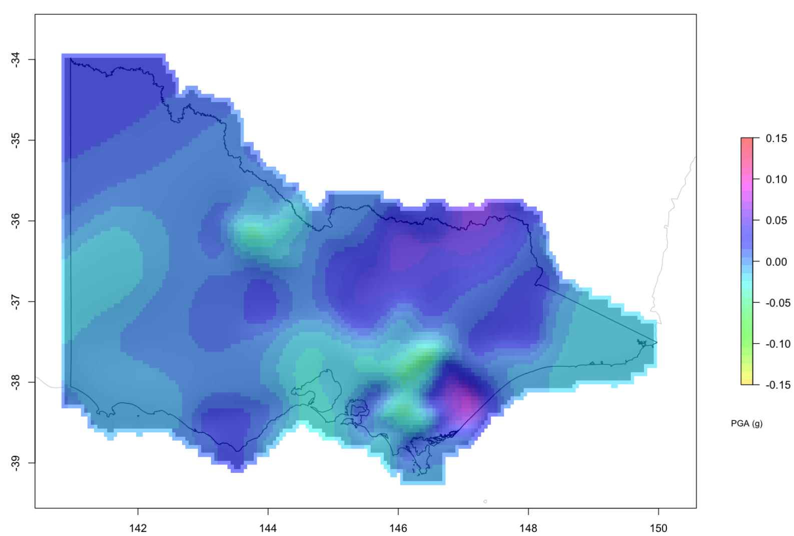

Figure 9: VEHM Model 1 minus Aus5 (area source zones only, 500 yr PGA

9 Acknowledgements

This work was funded by the Natural Disaster Resilience Grants scheme, funded by the Fedral Attorney General's Department and managed through the Victorian Office of the Emergency Services Commissioner. The authors would also like to acknowledge the support of AuScope and the Australian Geophysical Observing System for provision of seismometer equipment and aftershock kit installations. We would also like to thank Prof Mike Sandiford for his contributions to the work.

References

Jack W Baker. An introduction to probabilistic seismic hazard analysis (PSHA). *White paper, version*, 1: 72, 2008.

Julian J Bommer and Norman A Abrahamson. Why do modern probabilistic seismic-hazard analyses often lead to increased hazard estimates? *Bulletin of the Seismological Society of America*, 96(6):1967–1977, 2006.

Julian J Bommer, Stephen Oates, José Mauricio Cepeda, Conrad Lindholm, Juliet Bird, Rodolfo Torres, Griselda Marroquín, and José Rivas. Control of hazard due to seismicity induced by a hot fractured rock geothermal project. *Engineering Geology*, 83(4):287–306, 2006.

Amy Brown and Gary Gibson. A multi-tiered earthquake hazard model for Australia. *Tectonophysics*, 390 (1):25–43, 2004.

DR Burbidge and Geoscience Australia. *The 2012 Australian Earthquake Hazard Map*. Geoscience Australia, 2012.

C-H Chan, Y-M Wu, C-T Cheng, P-S Lin, and Y-C Wu. Time-dependent probabilistic seismic hazard assessment and its application to Hualien City, Taiwan. *Natural Hazards and Earth System Science*, 13 (5):1143–1158, 2013.

BrianS-J Chiou and Robert R Youngs. An NGA model for the average horizontal component of peak ground motion and response spectra. *Earthquake Spectra*, 24(1):173–215, 2008.

C Allin Cornell. Engineering seismic risk analysis. *Bulletin of the Seismological Society of America*, 58(5): 1583–1606, 1968.

Arthur D Frankel, Charles Mueller, Theodore Barnhard, David Perkins, E Leyendecker, Nancy Dickman, Stanley Hanson, and Margaret Hopper. *National seismic-hazard maps: documentation June 1996*. US Geological Survey, 1996.

Jens-Uwe Klügel. Comment on "Earthquake Hazard Maps and Objective Testing: The Hazard Mapper's Point of View" by Mark W. Stirling. *Seismological Research Letters*, 83(5):829–830, 2012.

Mark Leonard. One hundred years of earthquake recording in Australia. *Bulletin of the Seismological Society of America*, 98(3):1458–1470, 2008.

R McGuire. EZ-FRISK, User's Manual", RISK Engineering, Boulder, Co. 1995.

Dee Ninis and Gary Gibson. Developing a seismotectonic model using neotectonic setting and historical seismicity Application to central New South Wales. 2006.

Bruno Pace, Laura Peruzza, Giusy Lavecchia, and Paolo Boncio. Layered seismogenic source model and probabilistic seismic-hazard analyses in central Italy. *Bulletin of the Seismological Society of America*, 96 (1):107–132, 2006.

Paul Somerville, Peggy Quijada, Hong Kie Thio, Mike Sandiford, and Mark Quigley. Contribution of identified active faults to near fault seismic hazard in the Flinders Ranges. In *Proceedings of the Australian Earthquake Engineering Society Conference*, pages 21–23, 2008.

Seth Stein, Robert J Geller, and Mian Liu. Why earthquake hazard maps often fail and what to do about it. *Tectonophysics*, 562:1–25, 2012.

Mark Stirling. Probabilistic Seismic Hazard Modelling: A Review in Light of Recent Events. 2013.

Robert R Youngs and Kevin J Coppersmith. Implications of fault slip rates and earthquake recurrence models to probabilistic seismic hazard estimates. *Bulletin of the Seismological society of America*, 75(4): 939–964, 1985.