Chapter 5: EARTHQUAKE RISK

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5.1 Introduction

Risk assessment and its associated management is a most effective approach to addressing the impact of natural hazards on a region. It combines the hazard level with the vulnerability of the local infrastructure to give a picture of the aggregated financial consequences of a region's hazard and how this can be reduced through mitigation strategies. While the Perth metropolitan area is situated above a crustal region that exhibits low seismicity, it is located relatively close to adjacent regions that have experienced significant seismic activity during the settled history of Western Australia (WA). In this chapter the earthquake risk posed to the Perth metropolitan area is quantified by considering the seismic context of the city that contributes to its hazard and the vulnerability of its building stock. While the chapter focuses primarily on earthquake risk identification and assessment, the findings provide some basis for local government and Western Australian government agencies to review their susceptibility and preparedness.

Early attempts to quantify earthquake hazard in the southwest of Western Australia are summarised in Gaull and Michael-Leiba (1987). The first significant study was the determination of earthquake frequency in the southwest by Everingham (1968). This was followed by the estimation of ground intensity return periods for ten major centres in WA by Everingham and Gregson (1970). In 1973, McCue carried out an earthquake hazard assessment of southwest WA. Subsequently, McEwin *et al.*, (1976) made the first attempt at zoning the whole of Australia, and Denham (1976) published a preliminary Australian earthquake hazard zoning map. In 1987, Gaull and Michael-Leiba produced probabilistic earthquake hazard maps of southwest WA which were subsequently incorporated into the probabilistic earthquake hazard maps of Australia (Gaull *et al.*, 1990). It was from these maps that the earthquake hazard maps in the current earthquake loadings standard AS1170.4-1993 (Standards Australia, 1993) were derived.

The current Geoscience Australia (GA) study presents the most comprehensive and advanced earthquake risk assessment undertaken for any Australian city to date. It has focused on the economic losses associated with the building and contents damage caused by earthquake ground shaking, excluding the impacts from other secondary hazards such as soil liquefaction, fire, landslides and surface faulting. The study has adopted a probabilistic approach that makes allowances for the variability that is inherent in natural processes as well as the uncertainty in our knowledge. The study also includes an updated hazard assessment of a wider seismic region of southwestern WA which includes the more active Wheatbelt region west of Perth.

The results from this project will assist decision-makers involved in local and state government, policy development, the insurance industry, engineers, architects, and the building and finance industries to manage potential damage and loss of life from earthquakes in the Perth metropolitan region. The results also have implications for the earthquake risk facing other large Australian cities such as Sydney, Melbourne and Adelaide. This is due to a number of factors, including similarities between the earthquake hazard in Perth and that of these other state capital cities. While the Perth residential building stock is somewhat atypical due to the predominance of a single constructional form, other building types are similar to those commonly found in the other cities.

We emphasise that this report should be regarded as the best and most recent assessment of earthquake risk in Perth. However, we acknowledge that there are limitations in the models and data we have used, and that we have an incomplete understanding of the natural variability inherent in ground shaking and building response. The results, interpretations and conclusions could change with the incorporation of new data and with different model assumptions. Therefore, the reader should not take action based on information in this report alone.

In this chapter the risk methodology adopted is described. The historical seismicity of the greater region is examined and the seismic hazard quantified for both the Perth metropolitan area and the greater region. The development of an extensive building database is described, with the associated occupancy types, replacement cost models, and structural behaviour models that have been assigned to each. The risk posed by the earthquake hazard is also presented in financial terms, along with the extent of physical damage that will affect the population. Finally the implications of the results are discussed and possible mitigation strategies that could be investigated in greater detail are outlined.

5.2 Earthquake Risk Methodology

The general risk assessment philosophy adopted by the Cities Project Perth has been developed from the joint Australia/New Zealand Risk Management Standard, AS/NZS4360, (Standards Australia, 1999e). It can be expressed conceptually as follows:

Risk = Hazard × Elements at Risk × Vulnerability of the Elements at Risk

The multiplication sign does not mean a simple product but rather the convolution of the three components. For the specific case of earthquake risk assessments, this process can be described by the flowchart in Figure 5.1. A brief overview of the key risk methodology components shown in the figure is presented under separate headings below.

Earthquake hazard

The earthquake hazard in a region can be described in terms of *the level of ground shaking that has a certain chance of being exceeded in a given period of time*. It is common to describe earthquake hazard in terms of the level of ground shaking that has a 10% chance of being exceeded in 50 years. In order to calculate the earthquake hazard, three key models are needed, specifically:

- a *regional seismicity model*, which describes the chance of an earthquake of a given magnitude occurring in a year in various parts of the region;
- an *attenuation model*, which describes generally how earthquake ground shaking or intensity decreases with distance away from the earthquake source, and;
- a *site response model*, which describes how local regolith (soils, sediments and weathered rock) will affect the ground shaking experienced during an earthquake.

The regional seismicity model defines the regions that generate earthquakes. These regions are called ‘earthquake source zones’. Generally several earthquake source zones are defined with their level of activity determined from both historical seismicity and an understanding of the underlying geological structures. The level of earthquake activity is assumed uniform throughout each source zone, but differs from one zone to the next.

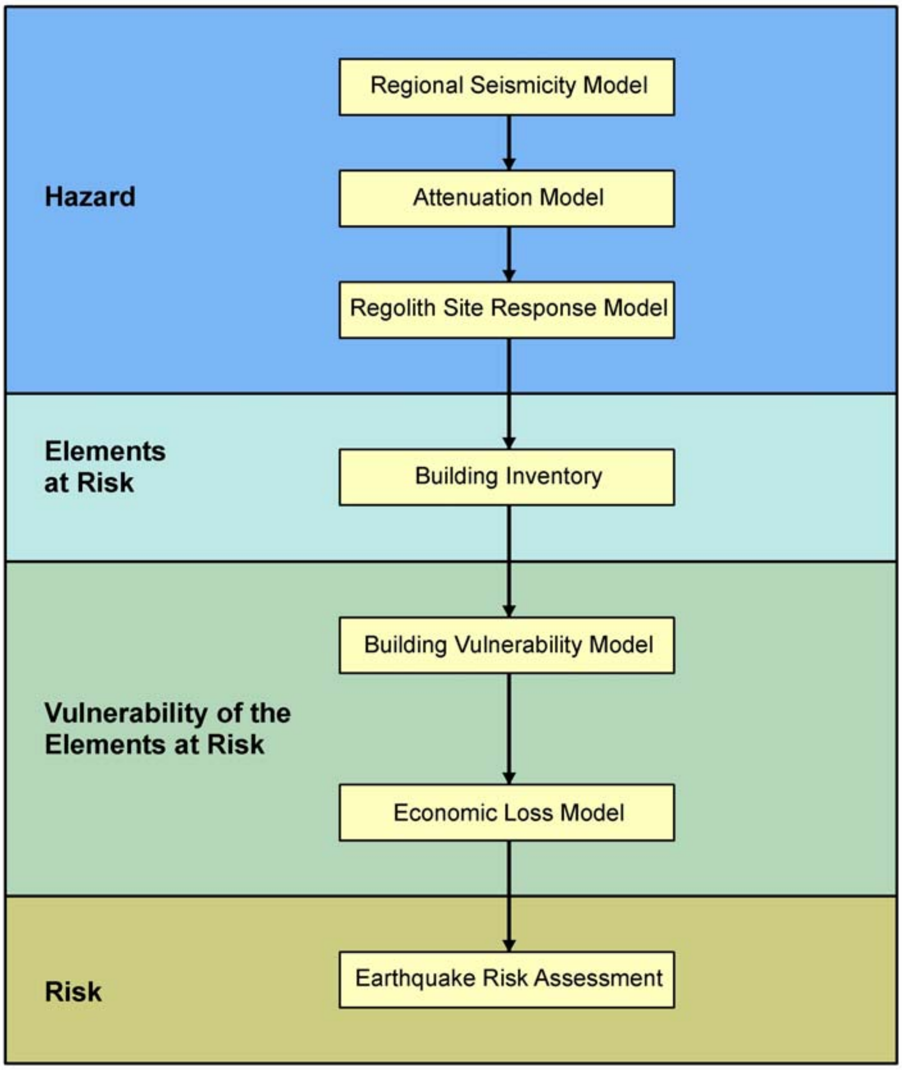


Figure 5.1: Flowchart describing the earthquake risk assessment process as applied to Perth

Attenuation models modify the earthquake waves with distance from the earthquake epicentre to give the characteristics of the earthquake vibrations below a site at bedrock level. Two attenuation models have been used in this study. The first was the model developed by Toro *et al.*, (1997) for central and eastern North America, a region of the world that is thought to have similar attenuation characteristics to Australia. The second attenuation model was that proposed by Atkinson and Boore (1995), developed for eastern North America. However, it must be emphasised that no explicit study has been conducted on the suitability of either model for Australian conditions.

The site response model adjusts the earthquake ground shaking at a site for the influence of weathered rock and overlying soils (regolith) on the propagating seismic waves. These typically amplify the vibrations, thereby causing a greatly accentuated impact upon certain building types. The Perth study region has the added complexity of an underlying sedimentary basin that attenuates components of earthquake motion in a manner not captured by the attenuation models used. The regolith model was separately developed from detailed geotechnical data, acquired primarily in Perth, which served to classify the study region into four different site classes. Subsequently these classes were incorporated into a single combined Perth sedimentary basin and regolith (soils, geological sediments and weathered rock) model that captures the influence of both on ground shaking.

Elements at risk

Risk is directly related to the *elements* exposed to the earthquake hazard. For the Perth study the range of building stock has been primarily determined using metropolitan building data held by the Perth Valuer-General's Office. This data has been supplemented with footprint data, a GA survey of 2,600 buildings using aerial photography, and a Perth flood plain field survey by GA of 2,080 buildings. Assessments of the size and associated full replacement values of the buildings and their contents were also made incorporating cost models developed through a quantity surveying consultancy (Reed Construction Data, 2003).

Vulnerability of elements at risk

Earthquake vulnerability models are used to estimate the level of damage caused by a given level of ground shaking for a wide range of building types. For the purposes of this study, building damage due to earthquake ground shaking was calculated using the method described in Kircher *et al.* (1997). This approach allows the calculation of damage on the basis of building type. For example, given a certain level of ground shaking, the damage to an unreinforced masonry structure would be different from the damage to a timber-framed structure.

Work from the Federal Emergency Management Agency (FEMA) in the United States was used to create models to convert estimates of building damage into estimates of economic loss. These models have gone through a process of modification to better represent the vulnerability of the common Australian building types. In this study, economic loss is defined in terms of the restoration cost of local buildings and their contents. In the modification process the FEMA models were calibrated, in part, using the restoration costs for Australian building types.

Earthquake risk

The earthquake risk to the study region was assessed by taking into account the earthquake hazard, the elements at risk and the vulnerability of those elements to earthquake ground shaking. In this study, these three components have been used to calculate earthquake risk by:

- conducting double computer simulations of approximately 9,400 earthquakes across the study region, each with its own magnitude and probability of occurrence based upon the regional seismicity model;
- using the attenuation and site response models to determine the level of ground shaking from every simulated earthquake at each of the surveyed buildings;
- using the vulnerability models to calculate the damage and economic loss to every building from each earthquake;
- aggregating the losses across all the buildings in the study region to produce an estimate of loss for each of the 18,800 event simulations, and;
- determining the study region earthquake risk by combining all earthquake event losses in accordance with their respective probabilities of occurrence.

The earthquake risk calculations were performed using the GA software EQRM (Robinson and Fulford, 2003) which incorporates all the computational steps described above.

5.3 Earthquake Bedrock Hazard

Introduction

An earthquake hazard model was developed for the Perth metropolitan area as a part of the Cities Project Perth. The earthquake hazard in Perth is influenced by the seismicity of the southwestern seismic zone (SWSZ) to the east of Perth, the site of some of Australia's highest historic earthquake activity. Three large earthquakes have caused considerable destruction and surface ruptures in that zone. The highest incidences of earthquake epicentres are centred on Meckering and Cadoux, where an 's'-shaped zone extends from 180 km northeast to 110 km southeast of Perth. The epicentres south of Meckering correlate strongly with structural trends inferred from aeromagnetic data and a more general north-northwest trend of the major gravity gradient.

Development of the hazard model requires knowledge of the historical earthquakes and potentially active faults over a broad region centred on Perth. A workshop was held at Geoscience Australia on the 2nd December 2002 with the purpose of defining an appropriate model of seismicity for southwestern WA. It was attended by expert Australian seismologists and structural geologists and was followed by later rounds of discussion and determination of results. The workshop participants proposed a seismicity model with the following earthquake source zones (shown in Figure 5.8):

- Zone 1, the SWSZ, modified from Gaull *et al.* (1990) to include the Burakin events;
- Zone 2, east of the Darling Fault, with boundaries modified from Gaull *et al.* (1990) to align with the Darling Fault and regional structural trends;
- Yilgarn Zone, extending across the remainder of the Yilgarn Craton;
- Zone 3, an offshore zone extending to the continental margin, modified from Gaull *et al.* (1990); and
- Background Zone, including the Perth Basin.

Seismicity parameters were determined for each of the source zones from statistical analyses of historic earthquakes. Alternate source zone models had maximum magnitudes ranging from 7.0 to 8.0 (seismic moment magnitude). The earthquakes were assumed to occur in the top 20 km of the crust, while their mechanisms were assumed to be predominantly reverse faulting with the principal stress axis normal to the regional north-northwest structural trend.

The seismicity models were used to generate earthquake hazard estimates and hazard maps for metropolitan Perth and later combined with models of soil site amplification. Subsequently, earthquake risk was estimated through considerations of likely damage and replacement costs.

Principal results indicate that the new seismicity model produces higher estimates of the Perth earthquake hazard in terms of peak ground acceleration for than those in the current Australian earthquake loadings standard (Standards Australia 1993). However, estimated spectral accelerations were found to be similar suggesting that the current design standard hazard is adequate and, in some instances, conservative. The most significant factor in the hazard calculations was the choice of an attenuation function for earthquake ground shaking. The earthquake strong motion recorded from the Burakin 2001 sequence helped in the preliminary selection of the appropriate regional attenuation relations.

Geology and geophysics

The characteristics of the SWSZ were addressed in the context of Western Australian geology. The exact boundaries of the zone are not precisely defined, but it lies within the Yilgarn Craton, which is part of the Archaean Shield structure – an area of very ancient rocks. (Figure 5.2). The southwest Yilgarn Craton was previously subdivided by Gee *et al.* (1981) into the Western Gneiss Terrane (WGT), and two granite greenstone provinces to the east, the Murchison and Southern Cross Provinces. Boundaries between the provinces were only approximately located but inferred to separate crust with contrasting geological attributes: particularly the relative abundance of older gneissic belts in the WGT, and the structural orientation and lithological content of greenstone belts in the Murchison and Southern Cross Provinces.

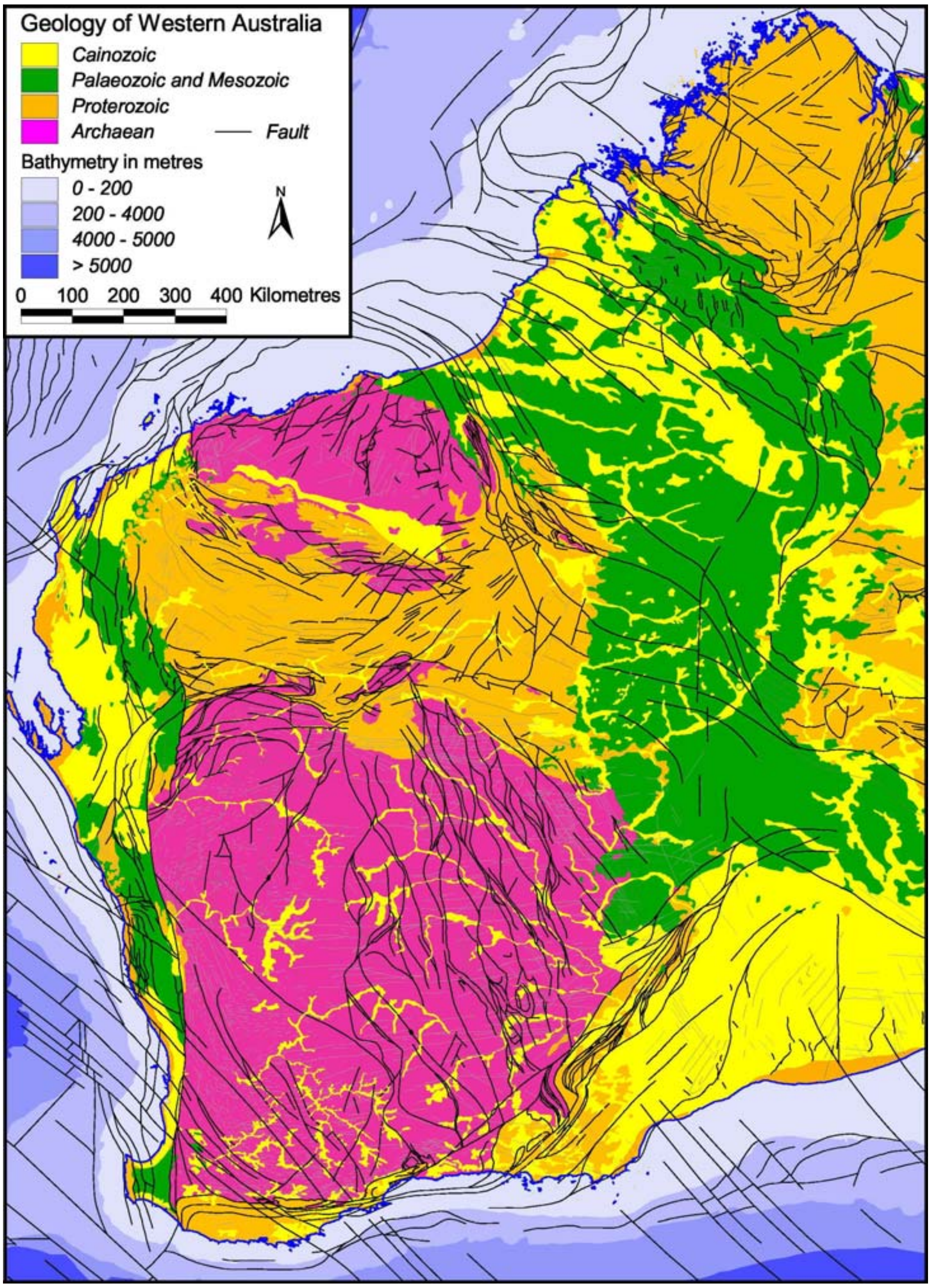
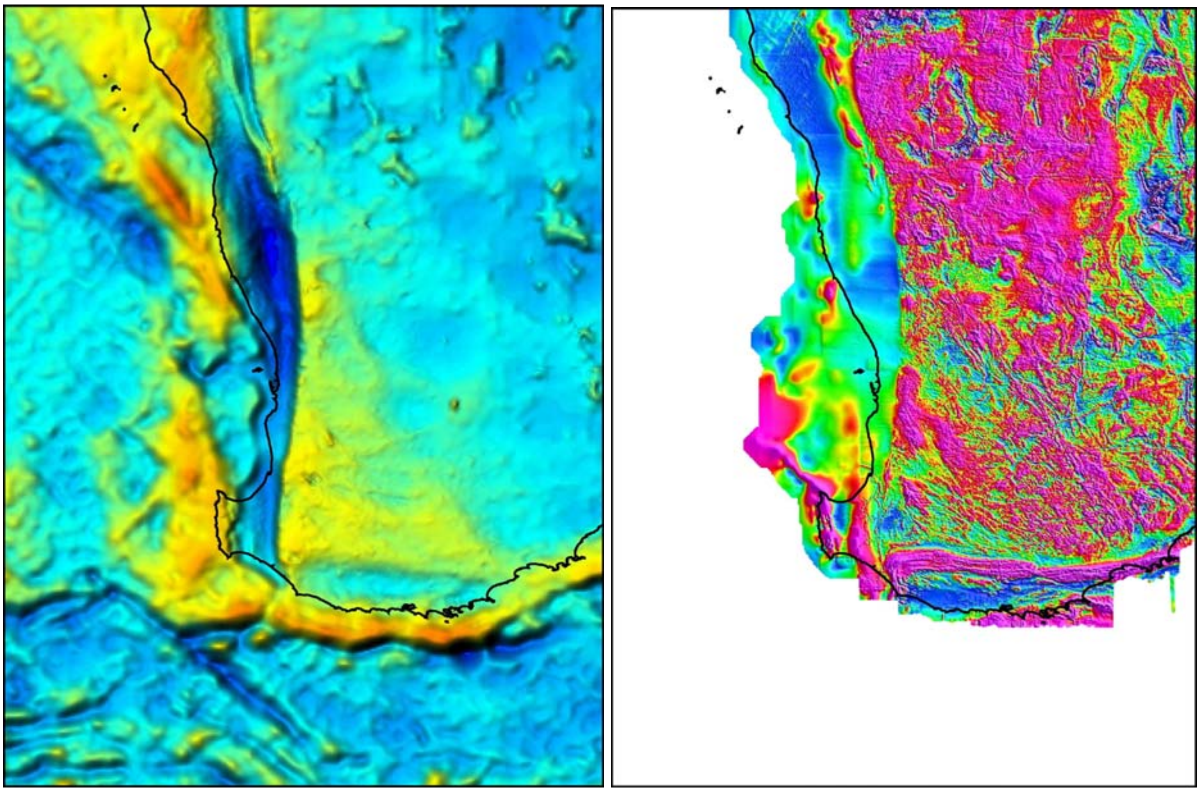


Figure 5.2: Geology of Western Australia. The Cainozoic rocks and sediments are the youngest. The Archaean rocks are some of the oldest on Earth

The absence of outcrop suggests the use of regional geophysical datasets for mapping large scale units and structures in the area (Figure 5.3). These data have also been supplemented by higher resolution surveys undertaken for mineral exploration.

The region has been subdivided a little differently on the basis of more recent aeromagnetic interpretation (Whitaker, 1992; Whitaker and Bastrakova, 2002). In this model the Murchison domain in the north extends westward to the Darling Fault, the western boundary of the Yilgarn Craton, and is separated from the South West domain to the south by the north-northwest-trending Toodyay–Lake Grace domain. The Southern Cross domain bounds the Murchison and Toodyay–Lake Grace domains to the east.



(a) (b)

Figure 5.3: Gravity (a) and magnetic (b) anomaly maps of southwest WA

The gravity data of southwestern Australia consist of the national 11 km grid in-filled by government and industry surveys, to about a 5 km average spacing, in a 200 km wide corridor abutting/paralleling the western coast line. These data provide complementary but significantly lower resolution information than the regional aeromagnetic coverage. The combined gravity and magnetics anomaly images are given in Figures 5.4 and 5.5.

Much of the Murchison and Southern Cross domains have an average Bouguer gravity anomaly in the order of –450 μm/sec^2. Local gravity highs to –100 μm/sec^2 in this region correlate with greenstone belts. A major north-northwest trending gravity gradient (the Yandanooka–Cape Riche Lineament of Everingham, 1968) with high values to the southwest transects the South West domain and the northwest of the Toodyay–Lake Grace domain. The high gravity to the south west of the gradient has been linked with crust of higher average thickness and a thick, high seismic velocity, high density basal layer relative to crust to the east (Mathur, 1976). Certainly there is no inferred change in surface geology across the position of this lineament as inferred from interpretation of aeromagnetic data. However, Wilde *et al.* (1996) have interpreted/mapped a zone with abundant migmatite immediately east of the gravity lineament.

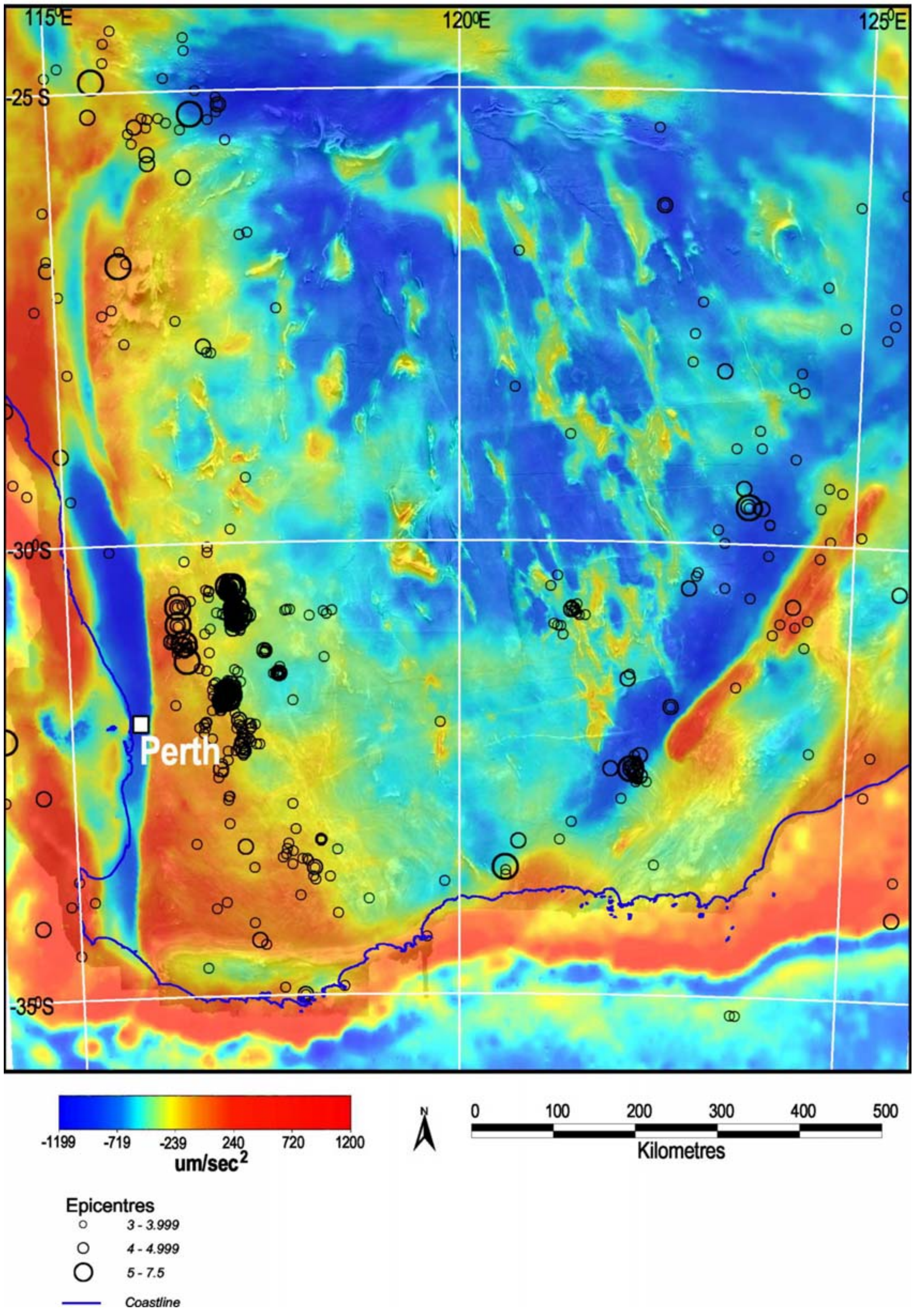


Figure 5.4: Combined gravity/magnetics image with seismicity (earthquake epicentres) for southwest WA. The Richter magnitudes of the earthquakes are indicated by the circle size as shown in the key.

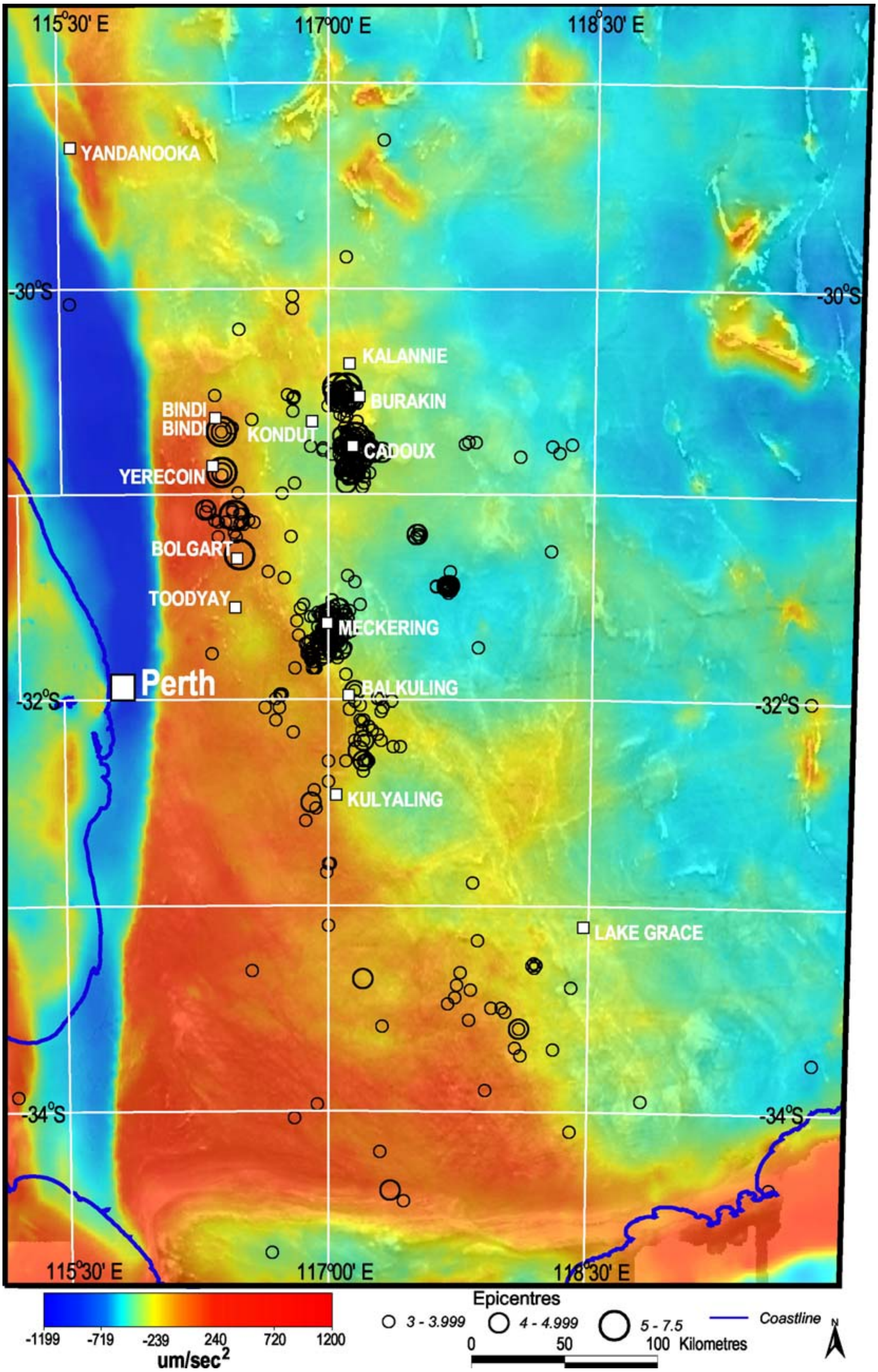


Figure 5.5: Combined gravity/magnetics image with seismicity (earthquake epicentres) around Perth. The Richter magnitudes of the earthquakes are indicated by the circle size as shown in the key.

The highest incidences of earthquake epicentres in the region are centred on Meckering, within the Toodyay–Lake Grace domain, and Cadoux in the southern Murchison domain, as shown in more detail in Figure 5.5. A zone of relatively high epicentre incidence, which includes these two areas of highest incidence, describes an ‘s’-shaped form (Cadoux–Kondut–Yerecoin–Bolgart–Meckering–Balkuling–Kulyaling) from 180 km northeast to 110 km southeast of Perth. The epicentres from Meckering to Kulyaling correlate strongly with structural trends of the Toodyay–Lake Grace domain as inferred from interpretation of aeromagnetic data. This area also correlates very well with a local curve and more general north-northwest trend of the major gravity gradient (Yandanooka–Cape Riche Lineament) through the area. Further south, earthquake epicentre incidence is relatively abundant across the South West domain but particularly so between the Yandanooka–Cape Riche Lineament and the southwestern boundary of the Toodyay–Lake Grace domain.

More generally, the incidence of epicentres in the southern Murchison and South West/Toodyay–Lake Grace domains drops off extensively east of the western boundary of the Southern Cross domain. Epicentre abundance also drops significantly north of an east-northeast-trending gravity lineament that passes through the central Murchison domain near the towns of Bindi Bindi, Damboring, and Kalannie. Figure 5.6 represents the southwest of WA in more detail where epicentres are superimposed on the fault structures as defined by the geological map of the Geological Survey of Western Australia (Myers and Hocking, 1998).

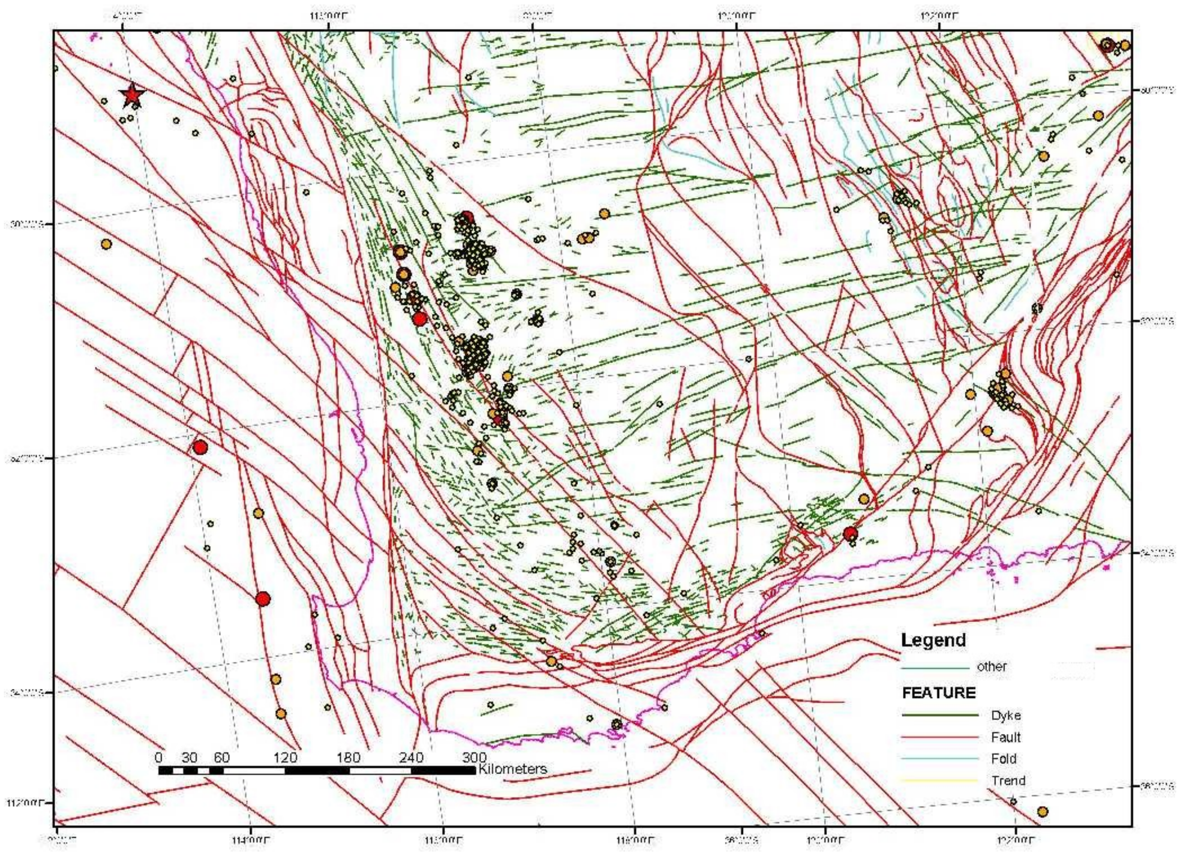


Figure 5.6: Seismicity and faults in southwestern WA

Regional seismology

The seismological data comprised subsets of Geoscience Australia’s QUAKE Earthquake Database for Australia for the region around Perth (Figure 5.7), isoseismal maps for the larger events and their fault plane solutions.

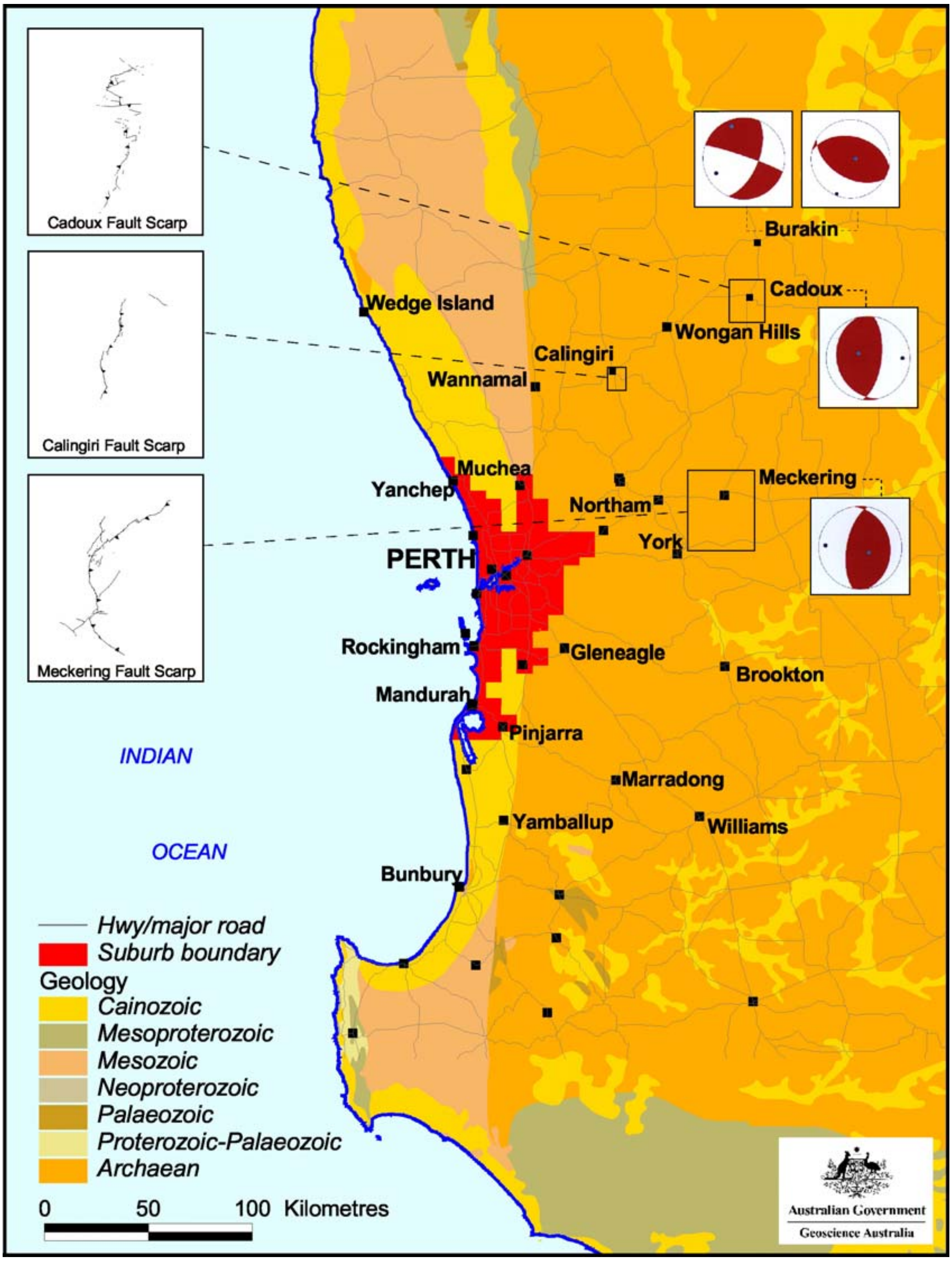


Figure 5.7: Geology of the wider Perth region showing fault scarps for the three largest earthquakes, Meckering, Cadoux and Calingiri. Fault plane solutions are shown for Meckering, Cadoux and the two Burakin 2001 earthquakes.

Seismicity parameters have been estimated only for those times in which the seismic network has been able to consistently record all earthquakes above the specified magnitude threshold (Sinadinovski, 2000) on the Australian continent. In the preliminary analysis for this study the numbers of earthquakes were counted for the declustered dataset of various magnitude ranges in magnitude intervals of 0.2 which is about the uncertainty. The declustered data set has the same magnitude ranges but the identifiable foreshocks or aftershocks are removed. A quake was considered to be a foreshock or an aftershock if it was within a certain distance of the main shock in a procedure described by Sinadinovski (2000).

Three large earthquakes have caused considerable destruction and surface ruptures in the SWSZ. They are the Meckering 1968 earthquake, magnitude 6.9, the Calingiri event of 1970, magnitude 5.9 and the Cadoux earthquake of 1979, magnitude 6.2.

The original formation of the earthquake source zones was based on the work of Gaull *et al.* in 1990. The epicentral data in the current GA catalogue appear to fit the source zones chosen by Gaull *et al.* (1990) reasonably well, even though an estimated 50% of the events have occurred since they were originally defined. Some modifications were done to the original source zone boundaries, namely the northern border of the Cadoux–Meckering zone, to include the most recent activity in the Burakin area.

The adopted model is presented in Figure 5.8 and is comprised of:

- Zone 1, the SWSZ, modified from Gaull *et al.* (1990) to include the latest Burakin events;
- Zone 2, the larger zone east of Darling Fault, with modified borders from Gaull *et al.* (1990) to follow closely the Darling Fault and the orientation of the main geological structures;
- Yilgarn Zone, covering the remainder of the Yilgarn craton;
- Zone 3, an offshore zone, extending to the continental margin, modified from Gaull *et al.* (1990); and
- Background Zone, or Perth Basin, as part of the continental shelf, modified from the EPRI 1994 report and Gibson and Brown's model (AUS5) discussed at the Australian Earthquake Engineering Society conference in 2002.

The other recommendations for the seismic parameters to be used in the hazard calculation program are summarised below:

- ***Maximum magnitude:*** Two options were anticipated
  - Option-I where maximum moment magnitude of M_W 7.5 was assigned to all of the zones, including the background;
  - Option-II where maximum moment magnitude of M_W 7.0 was assigned to Zones 1 and 2, and M_W 8.0 to Zone 3 and the background (Perth) zone.
- ***Event depth:*** Two distributions of earthquakes were anticipated
  - Distribution-I depths between 0 and 20 km for areas east of the Darling Fault;
  - Distribution-II depths between 0 and 15 km for areas west of the Darling Fault.
  - The probabilistic distribution for the depth dependencies were not defined more specifically by the group of experts. GA is considering using a distribution with maxima in the top 5 km and decreasing with depth.
- ***Fault type:*** Two types of faults were anticipated
  - Reverse faults - 80% of the earthquakes will occur on reverse faults aligned with the structural trend NNW-SSE; and
  - Strike slip - 20% of the earthquakes will occur on strike slip faults.
  - Variation of +/- 30° around these principal fault orientations was allowed.
- ***Fault dip:*** Two positions of fault dips were anticipated
  - Position-I - 50% of the earthquakes occur on faults dipping 35^{o} East; and
  - Position-II - 50% of the earthquakes occur on faults dipping 35^{o} West.

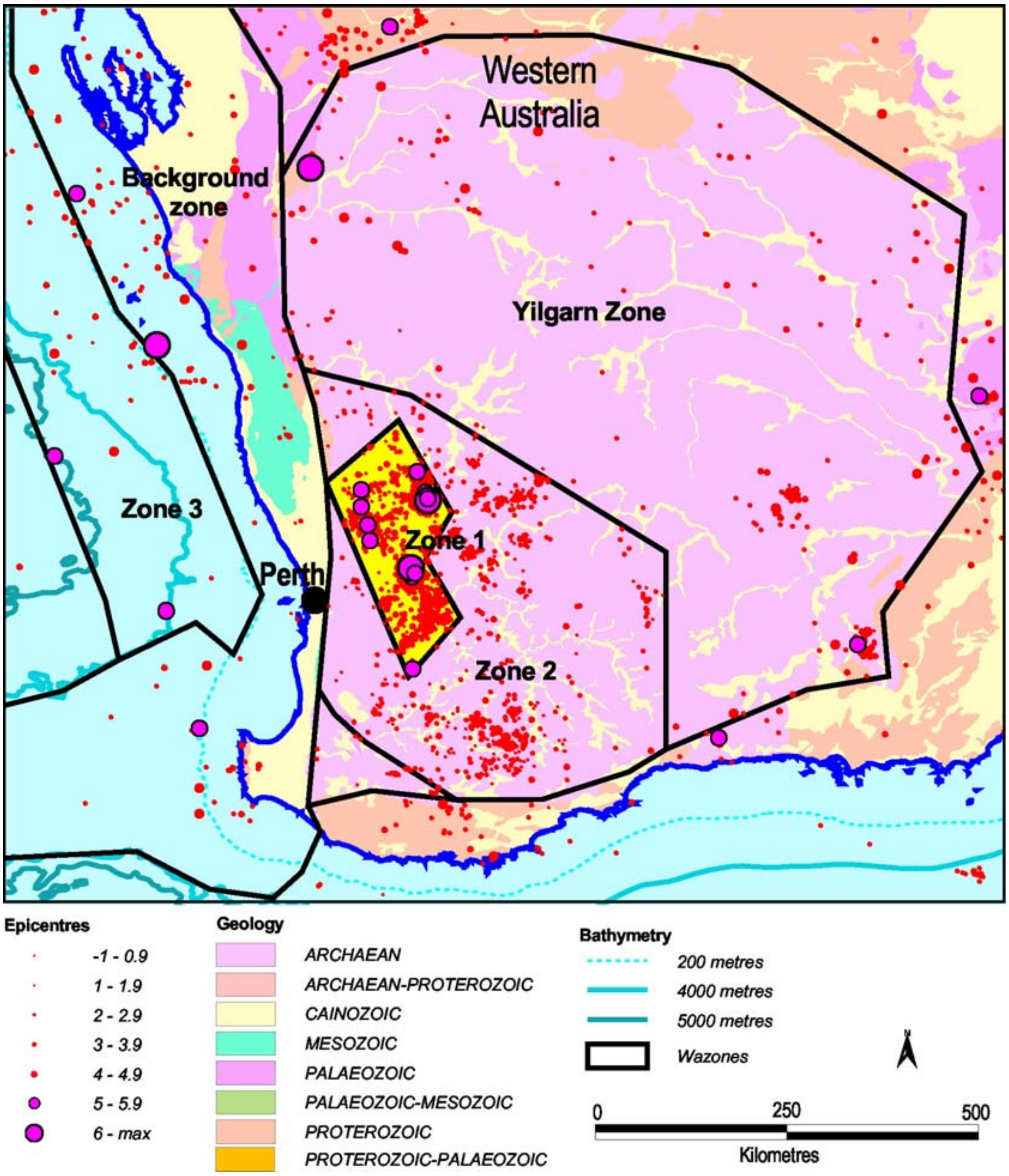


Figure 5.8: Seismic source zones of southwest WA. The Richter magnitudes of historical earthquakes are indicated by the range of circle sizes shown in the key.

Earthquake hazard

Recurrence relationship

The relationship between the number of earthquakes and their magnitude is routinely approximated by the Gutenberg–Richter (GR) empirical formula (1949), represented by a single straight line in log-linear coordinates

$$\log N = a - bM \qquad \textbf{Equation 5.1}$$

where N is usually the cumulative number of earthquakes, greater than or equal to magnitude M, per year, M is the local or Richter magnitude and a, b are constants related to the total number of earthquakes above a certain size and the frequency relation between small and large earthquakes. Data are treated by grouping of N according to the magnitude range.

Because earthquake size is characterised by seismic moment, a relationship between the Richter and moment magnitudes is required. This relationship may be developed empirically, but in the absence of quality data from large Australian earthquakes, a curvilinear relationship was adopted (Electric Power Research Institute (EPRI), 1993) which converts local magnitude M_{Lg} to moment magnitude M_W for earthquakes of magnitude greater than 5.25:

$$M_W = 3.45 - 0.473M_{Lg} + 0.145M_{Lg}^2 \qquad \textbf{Equation 5.2}$$

The local magnitudes measured in Australia, M_L, are mainly derived from earthquake body waves. The more sophisticated local magnitude measure, M_{Lg} as used in Equation 5.2, is based on a combination of earthquake wave types. For the purposes of this research the M_L values available to this study have been substituted in Equation 5.2, thereby assuming both magnitude parameters are equivalent.

The coefficient *b* usually takes a value around 1. In general this relationship fits the data well on a global scale, but not for particular tectonic regions. Various authors have discussed the spatial variation in *b*. In his work Kárník (1971) mentioned that in some cases for the weakest and the strongest earthquakes, the (log *N*, M) distribution deviated significantly from linearity. Recently, some other approximation formulae for that deviation have been applied (for example Utsu, 1999).

For use in prediction and comparative mechanism studies, standard errors of *b* must be supplied for statistical tests. Because earthquakes follow stochastic processes and the *b* value is a random variable, the probability distribution and the variance of *b* are essential in studying its temporal and spatial variation. The *b* value can be calculated by the least-squares method (LSM), but the presence of even a few large earthquakes influences the resulting *b* value significantly. As an alternative, the maximum likelihood estimate (MLE) can be used to calculate *b* because it yields a more robust value when the number of infrequent large earthquakes is considered. Weichert (1980) discusses in detail the advantages and disadvantages of the various methods.

The data used for this study comprised a subset of GA's earthquake database for Australia. Analysis was restricted to only those time intervals in which the seismic network was able to consistently record all earthquakes of the specified magnitude. On our assessment, the periods of completeness were: 1901–2003 for $M \geq 6.0$, 1959–2003 for $M \geq 5.0$, 1965–2003 for $M \geq 4.0$, and 1980–2003 for $M \geq 3.2$ (Sinadinovski, 2000). Principal values of *a* and *b* coefficients for our preferred model with maximum magnitude M_W 7.5 in Western Australia using seismic data up to the end of 2002, are presented in Table 5.1.

Table 5.1: Seismic parameter values for zones closest to Perth

Source zone	Area (km^2)	M_{min}	M_{max}	b	A_{min}
Zone 1	25 365	3.9	7.5	1.00	3.266
Zone 2	134 344	3.9	7.5	1.00	0.252
Zone 3	330 916	3.9	7.5	1.00	3.617
Background	373 291	3.9	7.5	1.00	1.649
Yilgarn	460 465	3.9	7.5	1.00	1.970

M_{min} is the minimum moment magnitude, M_{max} is the upper bound magnitude, and A_{min} is the number of earthquakes per year with $M \geq M_{min}$ (intercept of Equation 5.1 at $M = M_{min}$)

The level of seismicity normalised to 10,000 km^2 for the areal zones is shown in Figure 5.9. This new configuration increases seismicity in the Zone 1 at the expense of decrease of seismicity in Zone 2, when compared with the earlier model of Gaull *et al.* 1990.

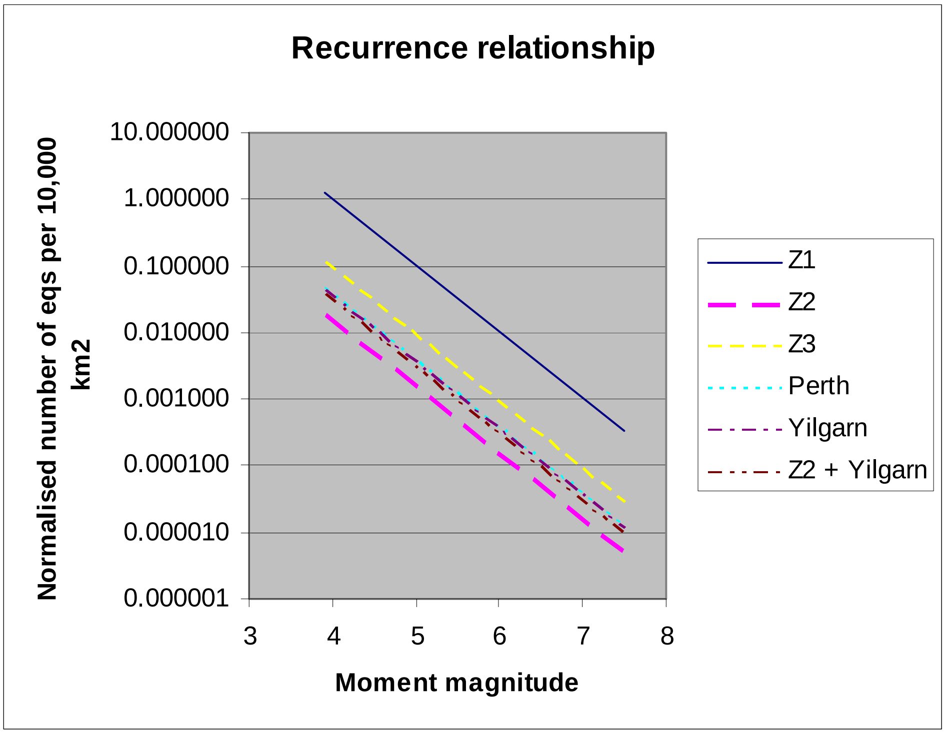
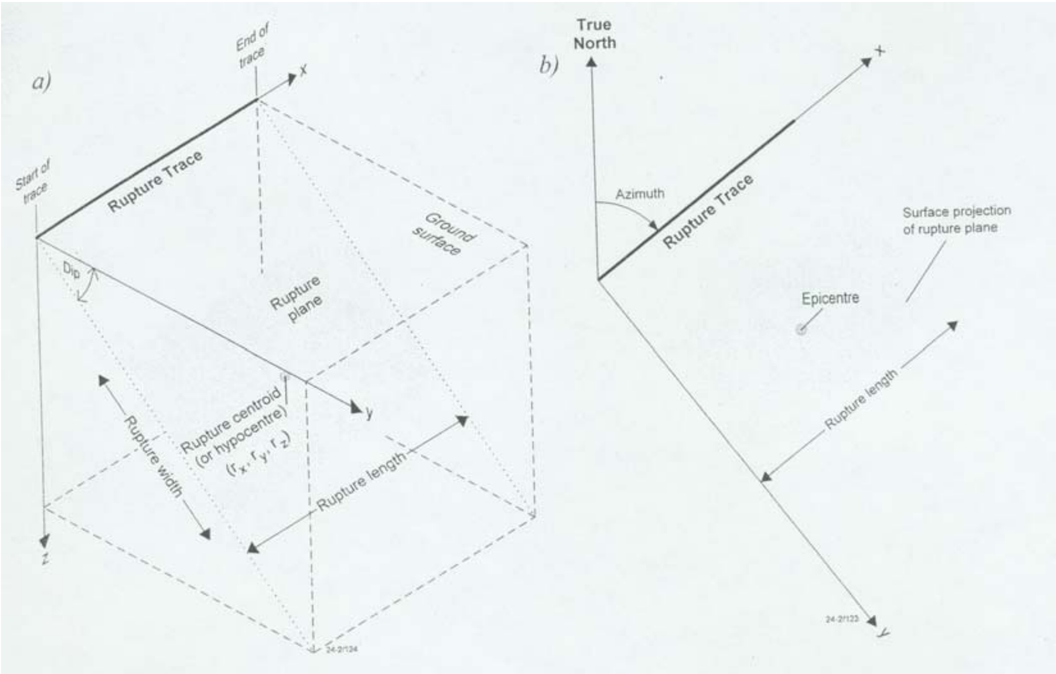


Figure 5.9: Recurrence relationship for the areal seismic zones

Simulation of earthquakes

The computation of hazard relies on the simulation of earthquake events within each of the source zones. The earthquakes are modelled to occur on 'virtual' rupture planes within the Earth. A brief outline of the process used to simulate the events is given below.

1. *Define the number of desired events in each zone.* The number of desired events within a zone depends on the influence of that zone on the overall hazard in the study region. The desired number of events for each of the zones was defined to be the minimum value which, when increased, does not significantly change the hazard. These values were determined through a separate sensitivity analysis and are 10,000 in the zone immediately below Perth and 2,000 in every other zone.
2. *Define a characteristic dip angle for the seismic zone*. A characteristic dip angle of 35 degrees was used for the source zones as recommended by the workshop participants in 2002.
3. *Randomly assign a rupture location for each of the desired events*. The location represents a latitude and longitude for the start of the rupture trace (see Figure 5.10).
4. *Assign a moment magnitude for each event*. The software adopts an approach that forces uniform sampling across the range of magnitudes. In other words, the number of simulated magnitude 5.2 earthquakes in each zone is roughly similar to the number of simulated magnitude 4.6 earthquakes. This ensures that earthquake events with a range of moment magnitudes contribute to the estimated hazard without requiring excessive computation of small events.



a **b**

Figure 5.10: The orientation and dimensions of the rupture plane in (a) 3D space, and (b) plan view

5. *Compute a likelihood (or probability) of occurrence for the magnitude of each simulated event*. The likelihood of occurrence accounts for the uniform sampling mentioned above, i.e., the number of actual magnitude 5.2 events in each zone is not the same as the number of magnitude 4.6 events. The probabilities are computed using the bounded Gutenberg–Richter probability density function (BGR–PDF), defined by the Gutenberg–Richter parameters in each zone (Kramer, 1996). Note that the BGR–PDF is closely related to the BGR relationship.
6. *Randomly assign an azimuth for each of the events.* These are selected uniformly in the range from 0 to 360 degrees from true north.
7. *Compute the geometry (or dimensions) and location (including depth) of each event.* The motion experienced at a point on the Earth's surface depends on the distance to the rupture plane, not the distance to the plane's centre (hypocentre). Therefore it was important that the position of the rupture plane was modelled as accurately as possible. The important rupture parameters are its dimensions (i.e., area, length and width) and the location of the hypocentre. These are computed using empirical relationships based on magnitude.
8. *Compute the end point of each rupture trace.* The end point is computed using the start of the rupture trace, the azimuth and the rupture dimensions. This information is useful for diagnostics such as Figure 5.11, which gives an overview of the geographical distribution of the simulated events. The location of the rupture trace is also required for Step 9.
9. *Adjust the azimuth of each event* to force, where possible, the rupture trace to lie within the source zone. Zone 1 is defined to favour north-northwest–south-southeast orientation as recommended by the workshop participants in 2002.

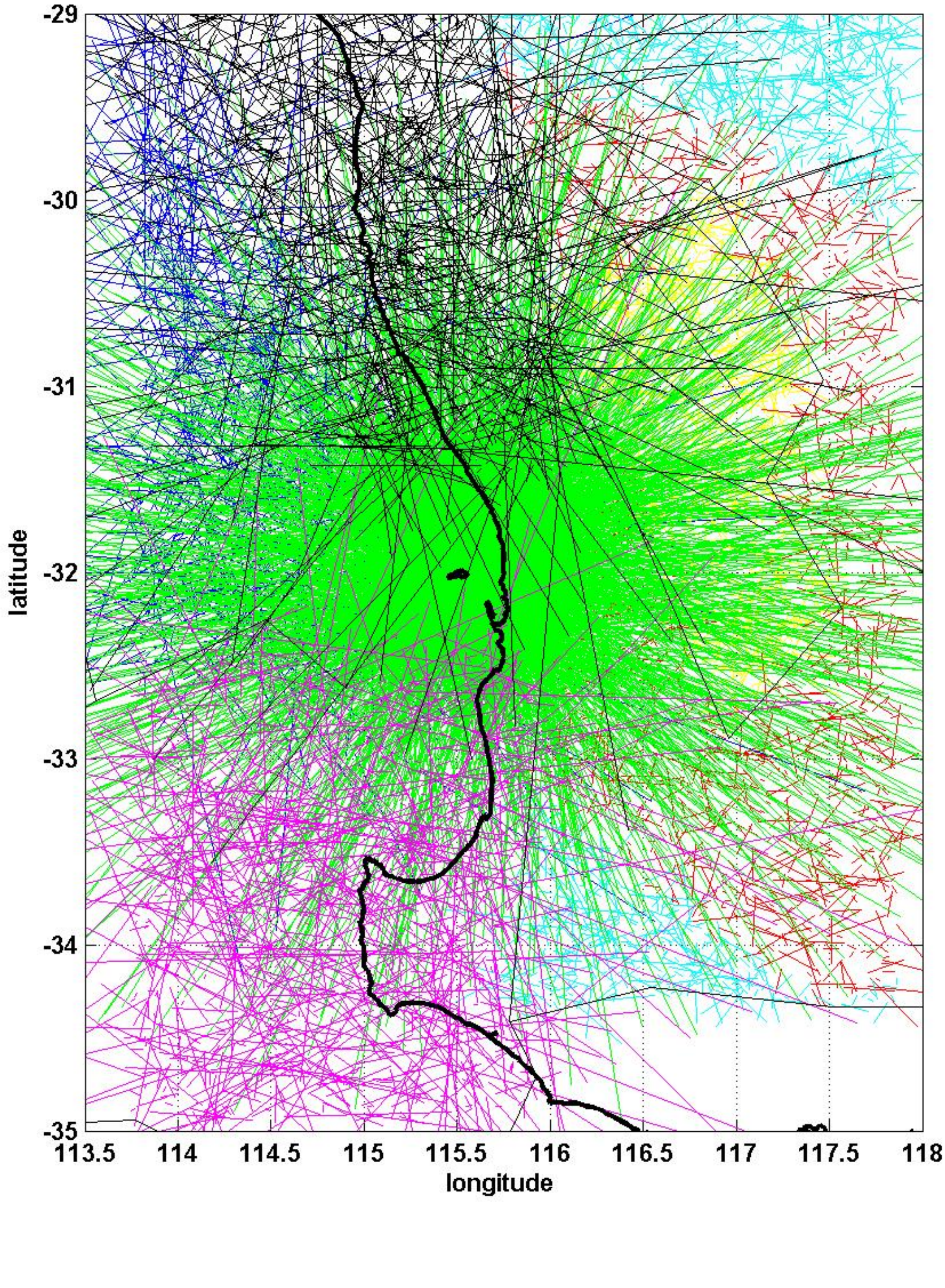


Figure 5.11: The fault traces of simulated events. The colours identify the different origin zones (see Figure 5.8 for seismic zone boundaries)

Attenuation model

Attenuation models describe how the intensity of ground shaking decreases with increasing distance from an earthquake. When few data exist, attenuation relations for Modified Mercalli Intensity can be developed and then converted by empirical formulae to equivalent peak ground accelerations (PGAs, which are expressed as a fraction of the gravity constant g). This approach was employed in the development of the Australian earthquake hazard maps (Gaull *et al.*, 1990), which were largely adopted in the 1993 Australian earthquake loadings standard (AS1170.4, Standards Australia, 1993).

GA's research of the Burakin data has provided some quantitative support for the use of attenuation models from central and eastern North America (CENA) over models developed for western North America (Dhu *et al.*, 2004). The CENA attenuation models were adopted because. the 'intraplate' tectonic environment in central and eastern North America is thought to be generally similar to the environment in southeast Australia. They describe the attenuation of response spectral acceleration (RSA) as well as PGA, and they include both a median attenuation model and a measure of the model variability due to the randomness inherent in natural processes.

In this report we incorporated two different CENA attenuation functions into the estimates of earthquake hazard, namely Atkinson and Boore (1995) and Toro *et al.* (1997). These functions were all derived using similar crustal velocity structures, and they may contain different assumptions about source and path effects. At this stage CENA models are equally weighted when used for Australian conditions.

A comparison of the CENA and the Gaull *et al.* (1990) attenuation models for PGA is presented in Figure 5.12. The Atkinson and Boore model has the highest PGA values and the Toro *et al.* model attenuates the fastest. The Gaull *et al.* model gives the lowest PGA values out to epicentral distances of 100 km but has the lowest rate of attenuation. It should be emphasised that this model used source depths of 10 km and is based on local magnitudes. We calculated our moment magnitudes from the local magnitudes using the Johnston relationship (G. Gibson, personal communication) for all events larger than 5.25.

These assumptions result in different predicted RSAs for any given magnitude-distance combination. The various predicted RSAs for a magnitude 5.5 event at 100 km distance are shown in Figure 5.13 in order to demonstrate the differences in these functions for an earthquake typical of the SWSZ that would be expected to affect Perth.

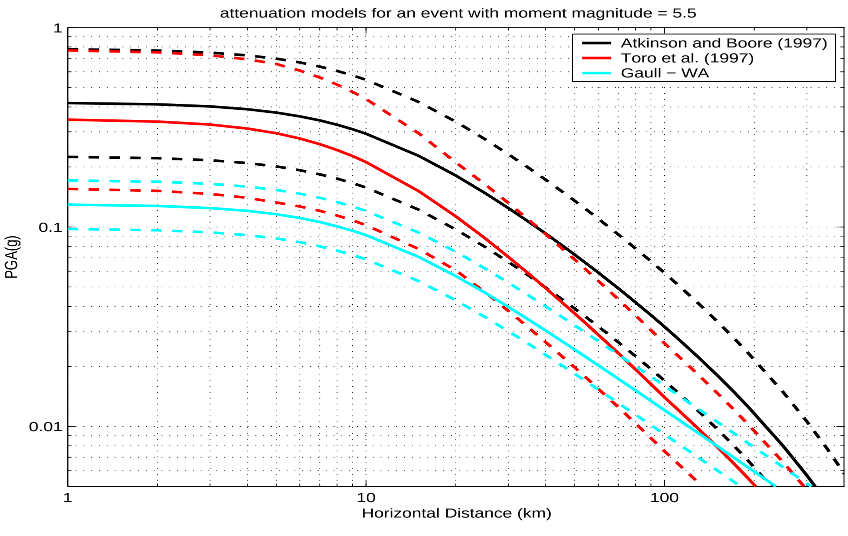


Figure 5.12: Comparison of attenuation models for M_w = 5.5 event at 100 km. Mean model predictions shown along with plus and minus one standard deviation.

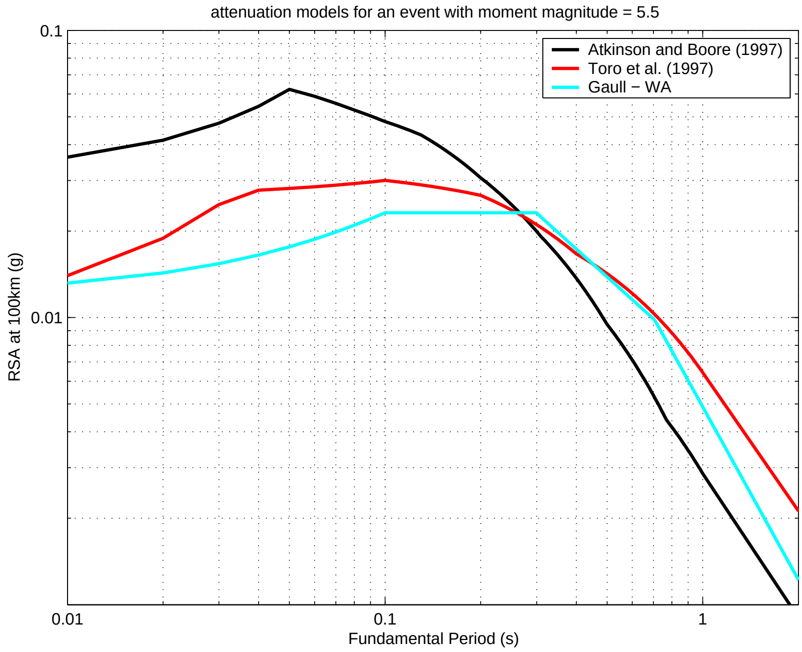


Figure 5.13: Predicted RSA for a magnitude 5.5 event at 100 km for the attenuation functions considered in this report

The Toro *et al.* predictions are approximately half of the values predicted by the Atkinson and Boore model for periods less than 0.2 s, and the Gaull *et al.* values are lower still. The models predict similar RSAs for periods between 0.2 s and 0.4 s. However, the Toro *et al.* model predicts the largest RSAs for periods of 0.5 s or greater.

The models used in this study have two different approaches for incorporating uncertainties. Toro *et al.* (1997) incorporates two distinct types of variability; that associated with the randomness in the natural process (aleatory) and the variability associated with the attenuation relationship in modelling the process (epistemic). In comparison, the Atkinson and Boore (1995) relationship only captures aleatory uncertainties. As mentioned previously, this study has used the two selected attenuation functions independently and then averaged their respective hazard estimates. Consequently, only the aleatory component of uncertainty has been used when combining the two models.

Calculated earthquake hazard on rock

For depicting earthquake ground motion severity, the predictive empirical relationships for intensity, PGA and spectral amplitudes at typical periods (between 0.3 and 1.0 seconds) and for different site classes need to be considered. For this report the PGA and spectral accelerations on rock corresponding to 10% and 2% probability of exceedence in 50 years are presented.

In the previous sections the source and attenuation models developed for the Perth region were described. In order to calculate the earthquake hazard it is necessary to amalgamate these models. The approach taken in this study is outlined below.

- A spacing of 500 m was used to create a uniformly spaced grid of sample points at which the hazard was calculated.
- Earthquakes were generated using the method described in the ‘Simulation of earthquakes’ section.
- For each earthquake – sample point combination, an attenuation function was selected by choosing a random variation from the median attenuation model.

- For a given level of hazard the maximum RSA that has at least that chance of being exceeded in the given time frame was stored. For example, given a hazard level of 10% probability of exceedence in 50 years, the hazard at a sample point is defined as the maximum RSA that has at least a 10% chance of being exceeded in 50 years

The Australian earthquake loadings standard, AS1170.4-1993, presents earthquake hazard in terms of an 'acceleration coefficient' that has a 10% chance of being exceeded in 50 years. This acceleration coefficient shown in Figure 5.14 is considered to be equivalent to the PGA.

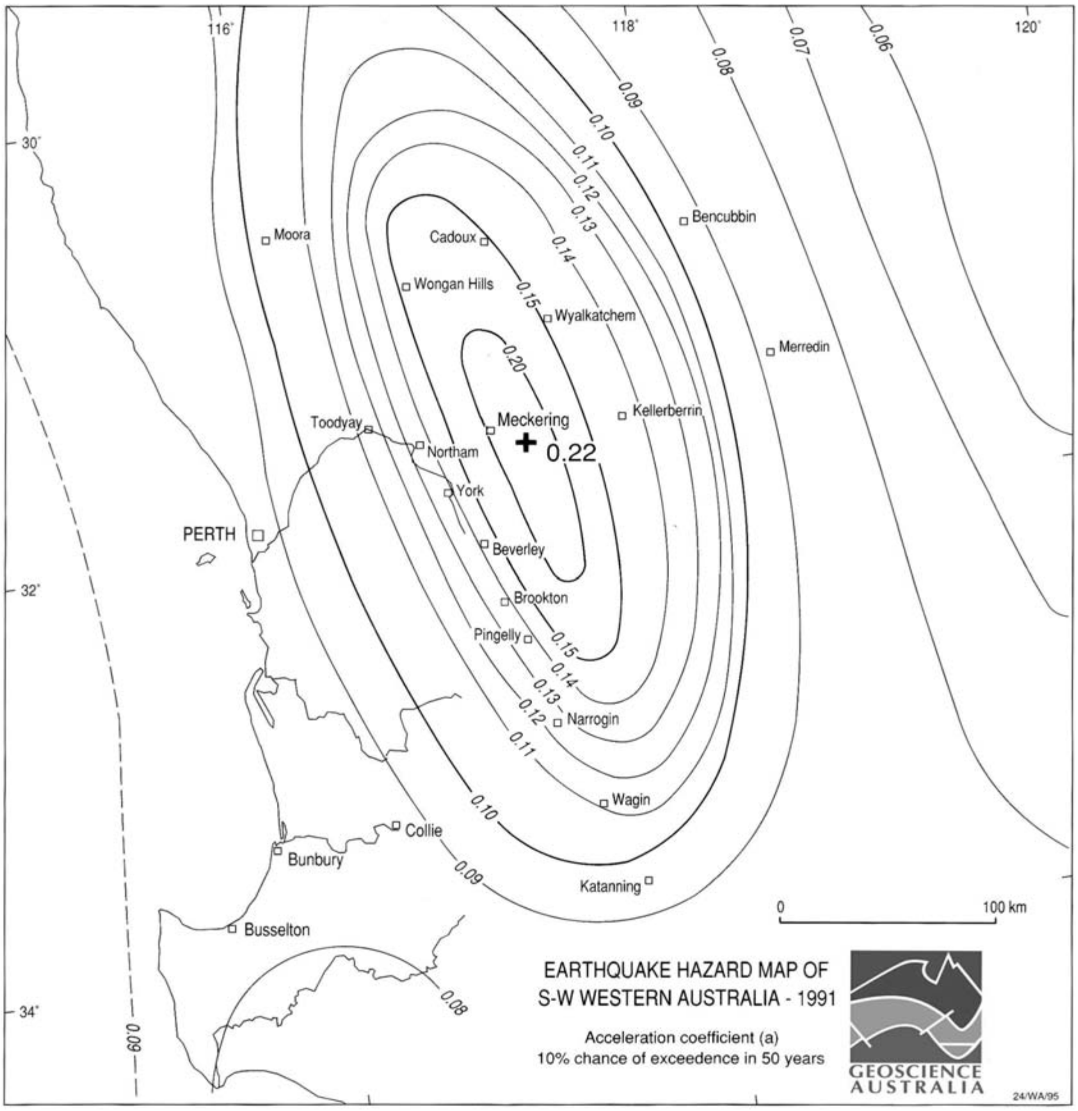


Figure 5.14: Earthquake loadings standard (Standards Australia, 1993) hazard map of WA

While hazard definition often centres on the PGA, building damage is influenced by the spectral period that corresponds with its natural period of vibration. For example, low to medium-rise structures are typically more vulnerable to ground shaking that has a period of vibration of approximately 0.3 s. Medium to high-rise structures are typically more vulnerable to ground shaking that has a period of vibration of approximately 1 s. The importance of spectral values as opposed to PGA is of particular note given that the high PGA values used for Perth in this study have little structural significance. Spectral acceleration values at 0.3 s and 1.0 s have been included in the hazard results presented below.

Whilst the Australian earthquake loadings code describes hazard in terms of the level of ground shaking that has a 10% chance of being exceeded in 50 years (i.e. for events with a return period of 475 years), it is often important to consider the possible effect of less likely but more damaging events. Consequently, this study has also determined the earthquake hazard that has a 2% chance of being exceeded in 50 years. This probability of being exceeded corresponds to events with a return period of approximately 2,500 years.

Perth study region hazard

There is currently no quantitative evidence to support the preferential use of either of the CENA attenuation models. Consequently the hazard was predicted using both, combining them with equal weighting. The hazard was calculated using the same simulated catalogue of earthquake events in conjunction with either Atkinson and Boore or Toro *et al.* relationship. The approach is illustrated in Figure 5.15, which presents the separate and combined PGA bedrock hazard for a 475-year return period. All maps have the same trend of increasing hazard towards the northeast of the study region due to the defined seismic activity in Zone 1. The two attenuation model results have notable differences in the hazard range predicted across the study region, mainly because of differences in the rate of RSA decay with distance. The PGA calculated within the majority of the Perth metropolitan area is typically double the hazard presented in the Australian earthquake loadings standard. The significance of this will be discussed later.

The hazard calculation process was repeated for all three spectral periods and the two return periods of interest. The plots are presented together in Figure 5.16 for comparative purposes. The hazard for all three parameters increased by a factor of approximately 2.2 in moving from a 475-year return period hazard to a 2,475 year. This factor is similar to, though slightly larger than, the 1.8 probability adjustment factor proposed in the draft standard (Standards Australia, 2004). The values of the hazard parameters for a 475-year return period at three key locations in the Perth metropolitan area are also presented in Table 5.2.

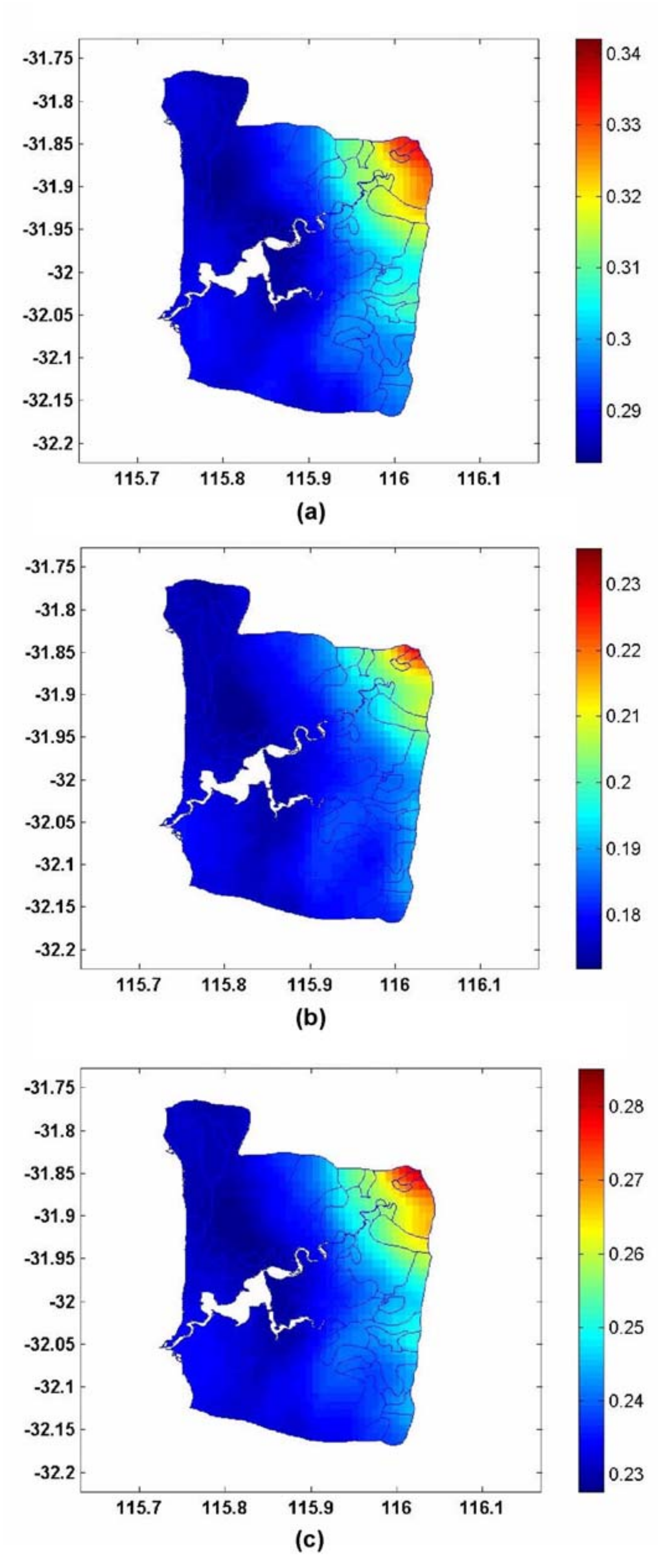


Figure 5.15: Earthquake hazard on rock in Perth with 10% probability of exceedence in 50 years, PGA(*g*). **a**) Atkinson and Boore attenuation model results. **b**) Toro *et al.* attenuation model results. **c**) Combined with 50/50 weighting to the Atkinson and Boore model and Toro *et al*. model

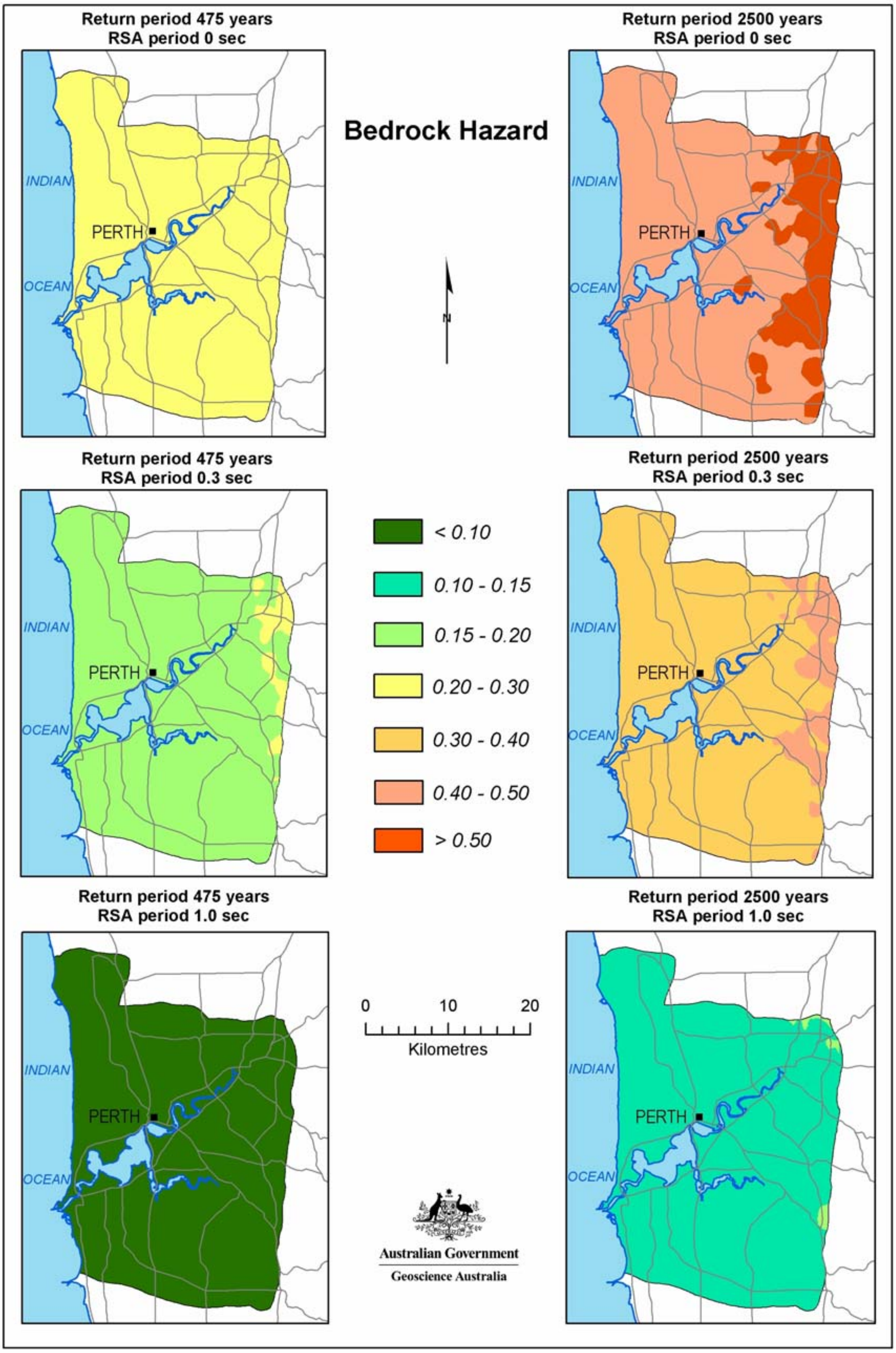


Figure 5.16: Perth metropolitan study region earthquake hazard on bedrock. All accelerations are presented as a fraction of the acceleration due to gravity (g).

Table 5.2: Perth region bedrock hazard for a 475-year return period of exceedence

Location	Both standards[1]	AS 1170.4 - 1993		DR 04303 - 2004	
	PGA(*g*)	S_A at 0.3 s(*g*)	S_A at 1.0 s(*g*)	S_A at 0.3 s(*g*)	S_A at 1.0 s(*g*)
Perth metro.					
Midland	0.093[2] [0.261][3]	0.233 [0.226]	0.116 [0.070]	0.273 [0.226]	0.082 [0.070]
Perth CBD	0.089 [0.232]	0.223 [0.205]	0.111 [0.065]	0.262 [0.205]	0.078 [0.065]
Fremantle	0.088 [0.229]	0.220 [0.202]	0.110 [0.064]	0.259 [0.202]	0.077 [0.064]
Perth region					
Moora	0.103 [0.401]	0.258 [0.321]	0.129 [0.090]	0.303 [0.321]	0.091 [0.090]
Cadoux	0.160 [0.620]	0.400 [0.474]	0.200 [0.123]	0.470 [0.474]	0.141 [0.123]
Meckering	0.200 [0.615]	0.500 [0.484]	0.250 [0.130]	0.588 [0.484]	0.176 [0.130]
Northam	0.136 [0.536]	0.340 [0.422]	0.170 [0.116]	0.400 [0.422]	0.120 [0.116]
Brookton	0.138 [0.593]	0.345 [0.456]	0.173 [0.118]	0.406 [0.456]	0.121 [0.118]
Pinjarra	0.088 [0.218]	0.220 [0.188]	0.110 [0.058]	0.259 [0.188]	0.077 [0.058]

Notes: (1) Bedrock peak ground acceleration (PGA) unchanged from AS 1170.4 (1993) in DR 04303.
(2) Hazard values have been interpolated from hazard maps in standards to capture variation across the study region.
(3) Values derived from this study are shown in square brackets.

Perth regional bedrock hazard

The bedrock hazard for the larger Perth region was determined using the same methodology to that described above. The 475-year return period hazard results are presented in Figures 5.17–5.19 and the hazard values at several key Western Australian towns are summarised in Table 5.2. The elevated hazard in the Wheatbelt region is clearly evident with the common trend of reducing hazard in a westerly direction towards the Perth metropolitan area.

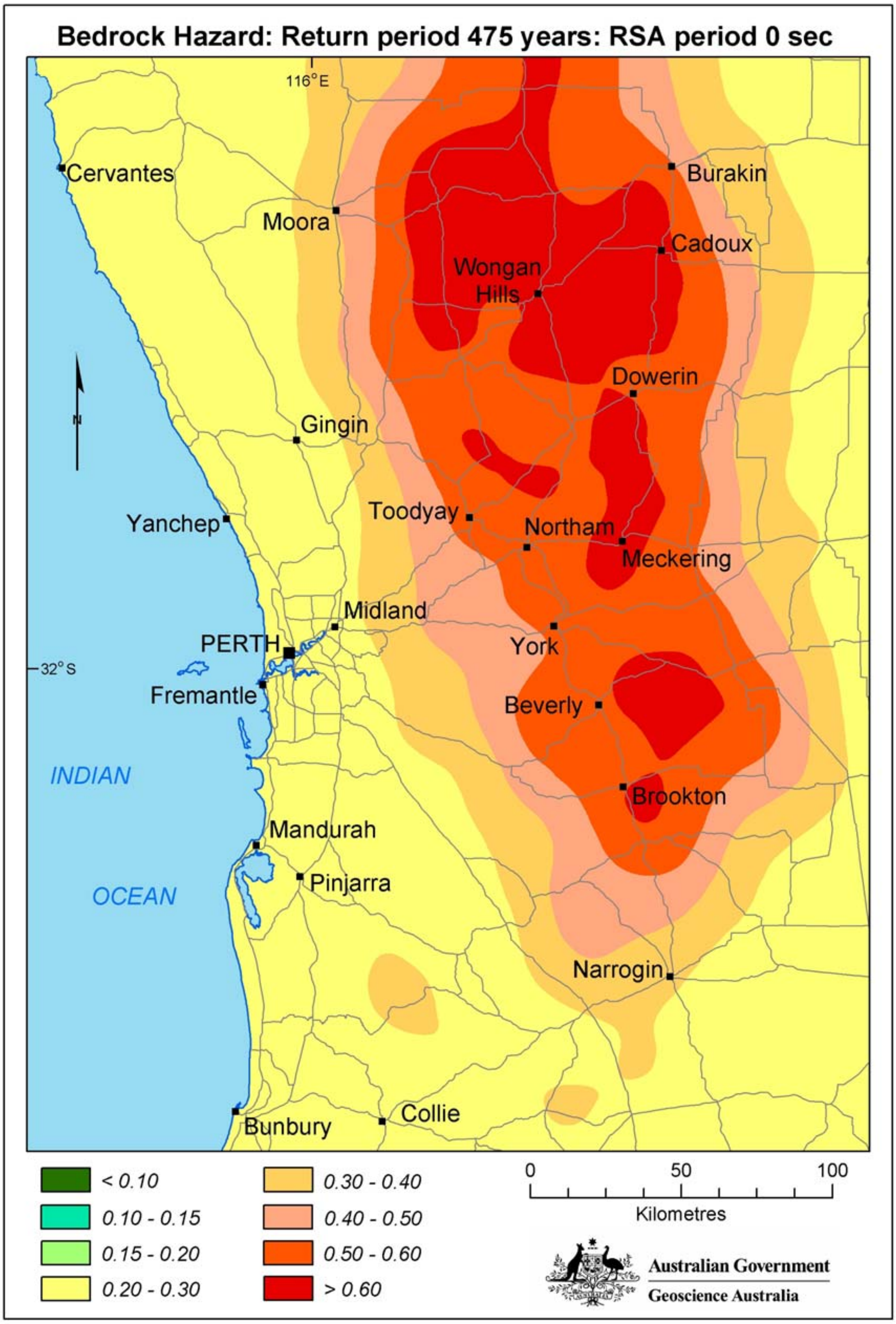


Figure 5.17: Perth region PGA on bedrock for 475-year return period

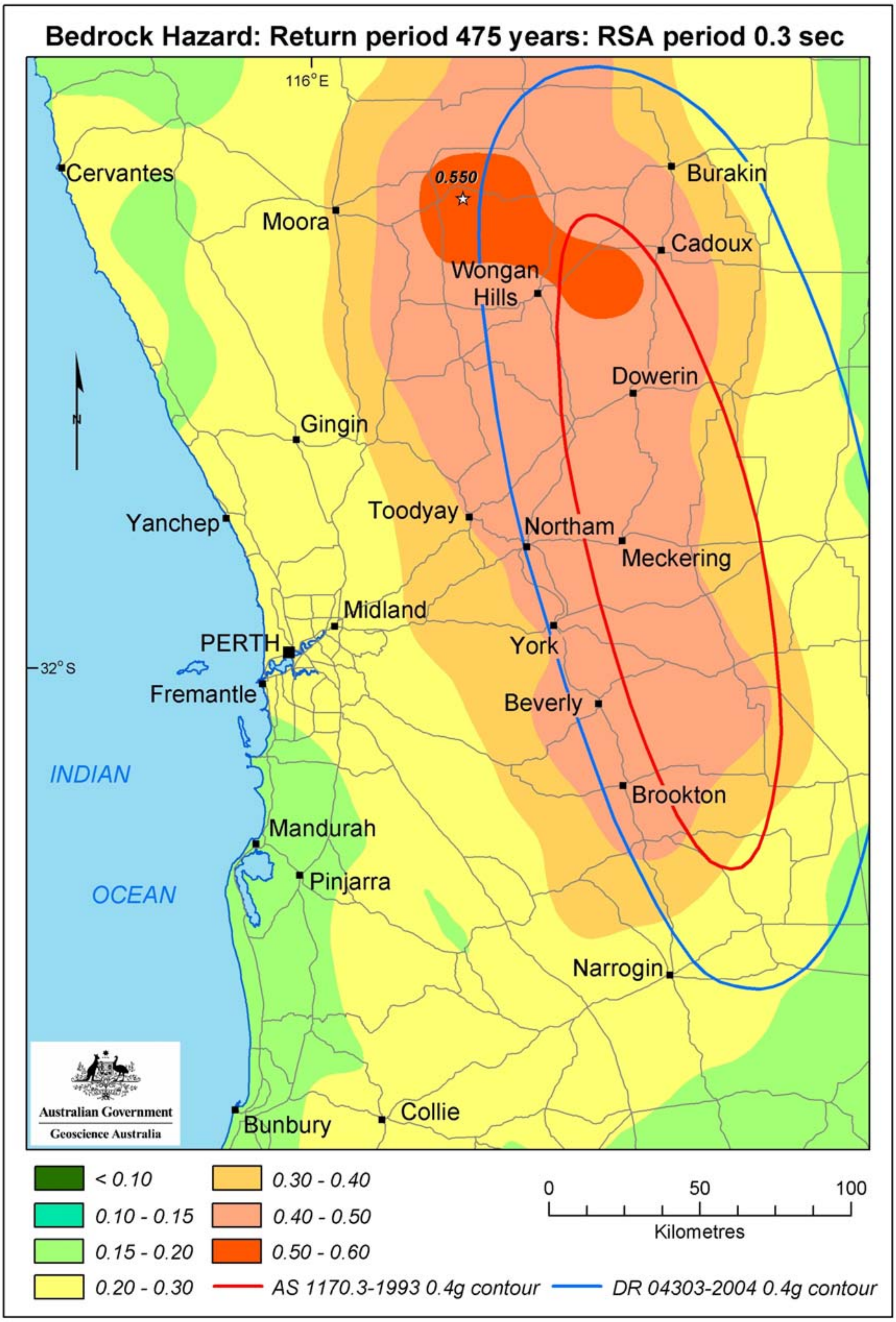


Figure 5.18: Perth region 0.3 s spectral acceleration on bedrock for 475-year return period

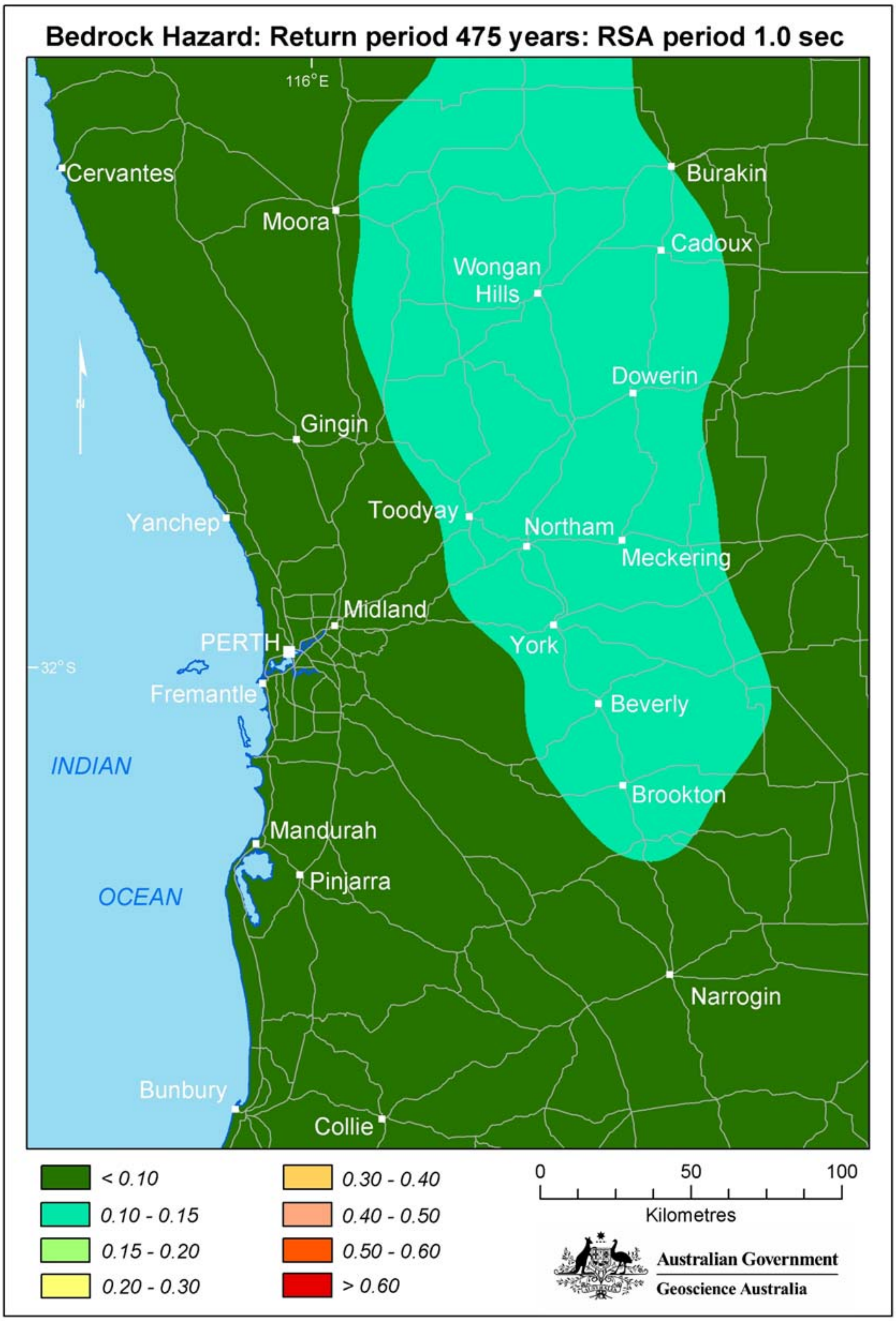


Figure 5.19: Perth region 1.0 s spectral acceleration on bedrock for 475-year return period

Comparison with current loadings standard definition of bedrock hazard

The hazard in Perth is significantly influenced by the Cadoux–Meckering zone which is located, at its closest, approximately 100 km northeast of the study region. The estimated hazard decreases with distance towards the southwest. This suggests that the PGA with a 10% probability of being exceeded in 50 years is probably being driven by small-to-moderate sized earthquakes at distances of around 100 km or more.

The averaged hazard results tend to be higher than the level prescribed by the Atkinson and Boore (1995) model. They explicitly stated that their model 'grossly over-predicted… amplitudes of small-to-moderate earthquakes at distances greater than 30 km'. This was a deliberate compromise of their model to ensure that their simple functional form adequately described spectral shapes that displayed complicated magnitude dependence. Similarly, Toro *et al.* (1997) focused on accurately describing larger earthquakes that were seen to be important to the earthquake hazard in CENA. Their model does not claim to grossly over-predict small-to-moderate earthquakes and predicts notably lower hazard than that predicted by Atkinson and Boore (1995).

Table 5.2 permits a comparison between the currently used definition of Perth hazard as presented in the earthquake loadings standard (Standards Australia, 1993), how that hazard definition is expected to change by the substitution of the draft standard (Standards Australia, 2004) and that determined by this study. A number of observations can be made from the table.

- The PGA predicted by this study greatly exceeds the PGA values in the standards but has little structural significance. These elevated values do not mean that the Perth regional hazard needs to be increased and should not be substituted for the 'a' or 'Z' values in the design standards.
- The spectral values at a 0.3 s period are very similar to the current and draft code values. The re-assessed hazard for the study tends to be slightly lower, particularly when compared to the draft standard (20% lower). This drop is less evident for the Perth region where the hazard shows some increase from that in the current standard and is comparable to that in the draft. The larger earthquake catalogue used for this study that includes the Burakin swarm events is, in part, responsible for the upward shift.
- The spectral values at a 1.0 s period are significantly lower than those derived from the current standard but are similar, though slightly lower, than those proposed in the draft.
- The bedrock hazard values for the Perth study region are expected to be generally conservative as they do not capture the attenuating effect of the Perth sedimentary basin. This effect has been later captured in the predictions of earthquake hazard on regolith.

The spatial extent of the elevated hazard in the Wheatbelt can be seen in Figure 5.18. The area of highest hazard has moved from the Meckering area to the vicinity of Cadoux and Wongan Hills. The S_A = 0.4g contour as determined from the current and draft standards have been superimposed on Figure 5.18. Significantly, the area of elevated hazard is more extensive than previously identified being wider in an east–west direction, extending further northwards and located closer to Perth. While the draft standard will define the area of elevated hazard slightly better than the current, neither will capture the full spatial extent of the elevated hazard determined by this study.

Assumptions and uncertainties of the earthquake hazard models

The earthquake hazard results in this work are based on numerous assumptions and idealisations ranging from the empirical relationships used to determine rupture dimension through to the use of an equivalent-linear methodology for modelling site response. The majority of these are thought to have minimal impact on the results presented in this chapter. However, there are some assumptions and uncertainties that are thought to strongly influence the presented results and these are discussed below.

Earthquake source model

There are two key issues relating to the earthquake source zones that have had a significant impact on the earthquake hazard results, specifically:

- The GR relationships defined for the southwest WA zones are based on datasets that have some uncertainty associated with the consistency of the catalogue of earthquakes and their magnitude computation. Variations in the GR relationships for the closest zones could affect the hazard estimates.
- The definition of the source zones in the region has been based on the expert opinion of the participants in the workshop of 2002 and represent GA's current knowledge of the complex structures and processes in the area. Nevertheless, a discovery of some active fault system may influence the seismic parameters defined in the region and consequently could change the present hazard calculations.

Attenuation model

The attenuation model used in this study is one of the most important inputs to the earthquake hazard analysis. Every estimate of earthquake ground shaking is based on this model's prediction of earthquake attenuation. Consequently, a change in the attenuation model could potentially cause a significant change in the estimated hazard. As mentioned previously, the attenuation model of Toro *et al.* (1997) is based on the tectonic and geological conditions of central and eastern North America. To date there has been only one detailed analysis of the applicability of this model to Australian conditions – in Newcastle (Dhu *et al.*, 2002), and consequently questions exist as to the appropriateness of this attenuation model. The Atkinson and Boore (1995) attenuation model has not been tested as to its applicability to Australian conditions. Preliminary work on strong-motion data recorded from the 2001–02 Burakin, WA earthquake swarm suggests that the Fourier spectral amplitude models (eg, Atkinson, 2004a, 2004b) that form the basis for this attenuation model may underestimate ground shaking at hypocentral distances less than approximately 70 km (Allen *et al.*, accepted). This is particularly apparent for periods between 0.3 s and 1.0 s.

5.4 Localised Ground Motion Model

The Perth study region is located on the sediments of the Perth Basin. This basin consists of some 10–15 km of sedimentary material ranging in age from ~430 Ma to <500,000 years, overlying Proterozoic basement rock. The upper sedimentary sequences in the study region are characterised by 30–80 m of Quaternary sands, muds and limestone. Appendix D describes the regional geology in more detail, however two key points are summarised below.

- The Perth Basin has poorly constrained shear-wave velocities, however the limited available data suggests that the top 5 km of the crust has shear-wave velocities significantly slower than the central and eastern North American (CENA) crust assumed by Toro *et al.* (1997) and Atkinson and Boore (1997).
- The regions regolith tends to have shear-wave velocities on the order of 100–300 ms^{-1}, however the material thickness and spatial distribution is extremely variable.

This geological environment (i.e., a deep sedimentary basin overlain by significant regolith material) is distinctly different from the environment assumed by Toro *et al.* (1997) and Atkinson and Boore (1997). These two attenuation models both predict ground motions at the surface of what is effectively hard, crystalline basement. Consequently, a modification was required to account for the effect of the slow crust and regolith material.

Ground motions recorded during a sequence of earthquakes that occurred near Burakin in 2000–2002 (Leonard, in prep.) have been used to create an empirical correction for the two CENA attenuation models used in this risk assessment. Specifically, two ground motions recorded from the magnitude M_w 4.4 Burakin earthquake, located approximately 200 km northeast of the Perth CBD (Figure 5.20), have been used. The recording at PIG4 is located within the Yilgarn Craton, and hence is assumed to be unaffected by the crust and regolith that will modify the ground shaking in the study region. In contrast, the recording at EPS is located in the centre of the study region and is assumed to incorporate the effects of the region's geology.

The process for creating an empirical correction factor for Perth is detailed below.

1. The two recorded response spectra were smoothed using an 11-point Savitsky–Golay smoothing filter (Press *et al.*, 1992) (Figure 5.21a).
2. The EPS recording was corrected for its 34 km offset from the PIG4 recording. This was done by simulating response spectra at 168 km and 204 km using various attenuation models and determining a distance correction from these models (Figure 5.21b).
3. Each of the distance corrected EPS recordings were divided by the PIG4 recording in order to generate three different empirical corrections.
4. The mean and standard deviation of the three empirical corrections were derived as a function of period (Figure 5.21c).

The final correction factor has significant de-amplification of ground shaking for all periods less than 0.1 s. This is at least an intuitive result, as it suggests the slow crustal materials within the Perth Basin are de-amplifying ground motions when compared with the faster crustal materials of the Yilgarn Craton. There is a small amount of amplification for periods of motion greater than 0.1 s. The peak amplification of 1.5 occurs at a period of 0.5 s. This amplification is most likely caused by the surficial regolith material.

There are some obvious problems with the creation of an empirical correction in this fashion. In particular, the derivation of a correction factor from only two recordings is a point of concern. An alternative would be to use detailed numerical modelling to try to better model how the region's geology would affect ground shaking. However, the lack of quantitative geological and geotechnical data from the Perth Basin currently makes this alternative less reliable than an empirical model.

Another issue is that the correction factor has been derived from a small magnitude event, but will be applied to ground motions from significantly larger events. One possible issue from this is that larger ground motions may induce non-linear effects in the region's regolith and hence reduce the amount of amplification seen at higher periods. However, this work has taken the conservative approach of adopting the one correction factor for all earthquakes. This is again due to the lack of quantitative data available for modelling the change in amplification for larger earthquakes.

The appropriateness of these models has been checked to some degree by the validation of the EQRM against historical events, as described at the end of Section 1.2, 'Earthquake Risk Methodology'. This validation is described later in this report; however, it is important to note that the validation is for the model as a whole and does not guarantee the accuracy of any individual component.

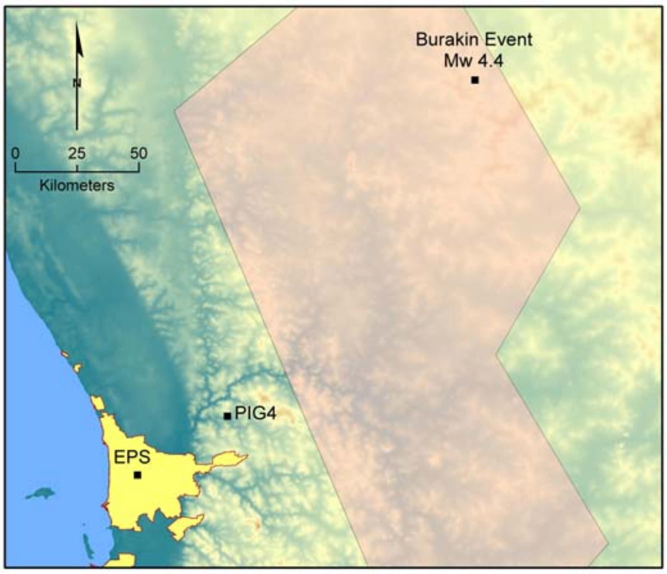


Figure 5.20: Location of the Burakin earthquake and ground-motion recorders used to derive the geological correction factor for Perth.

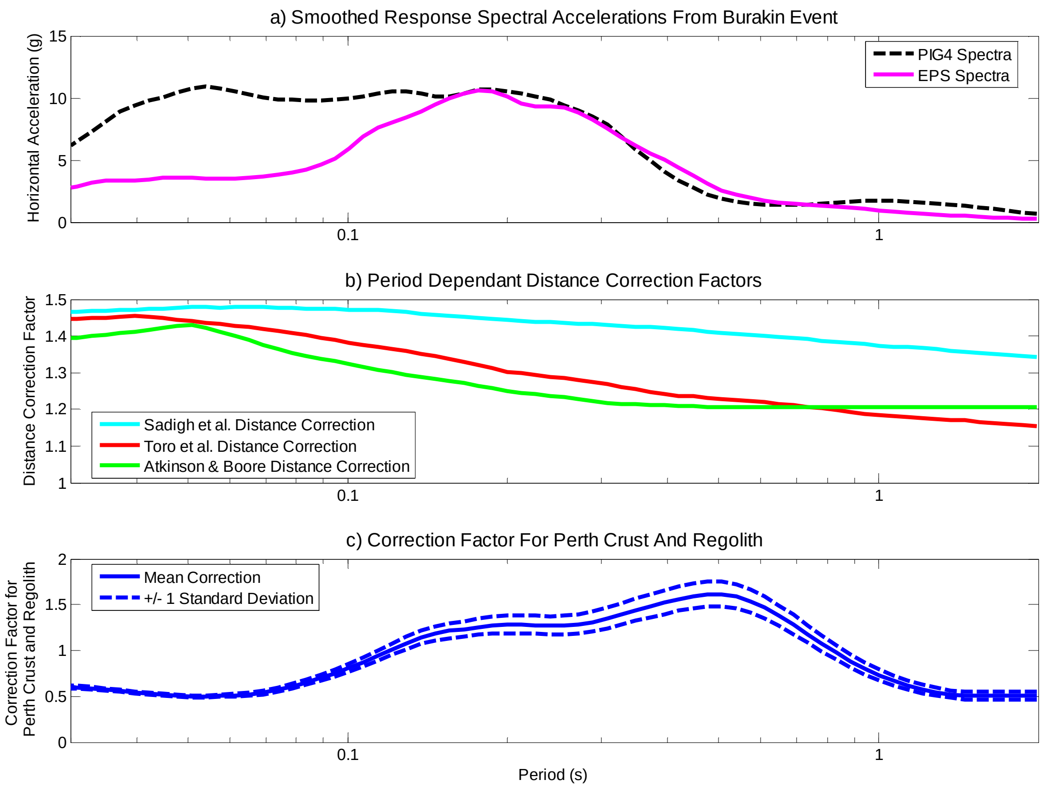


Figure 5.21: Data used for the development of a geological correction factor to account for the crust and regolith in the Perth study region. **a**) Response spectra recorded from the Burakin event. **b**) Period dependant distance corrections derived from Sadigh *et al.* (1997), Toro *et al.* (1997) and Atkinson and Boore (1997). **c**) Final correction including variability

5.5 Earthquake Regolith Hazard

As described earlier, the Perth study region is situated on significant regolith and crustal geology that is markedly different from the hard-rock models used to produce the previous bedrock hazard. The regolith hazard was determined for two exceedence return periods and at three spectral periods of interest. The two return period results have been presented alongside each other in Figure 5.22 for comparative purposes. In most plots the westerly reducing hazard characteristic of the bedrock hazard can be observed on the regolith. The variable influences of changes in regolith across the study region which could not be captured in this hazard assessment would add further localised features to the plots in the Figure. The 475-year exceedence return period hazard values at a number of key study region locations are also presented in Table 5.3.

The presence of regolith tends to decrease the bedrock earthquake hazard at very short spectral periods such as PGA (compare Figures 5.16 and 5.22, and Tables 5.2 and 5.3). This reduction in PGA hazard will have little effect on the potential for structural damage in Perth as essentially all structures have longer natural periods of vibration.

The ground shaking at a period of 0.3 s will tend to affect the medium to low-rise structures that are prevalent in the Perth study region. A comparison between Tables 5.2 and 5.3 demonstrates that the Perth Basin and regolith tends to slightly increase (approx. 20%) the bedrock hazard at this structural period. Clearly, the regolith in Perth will tend to increase the risk to the residential structures in the study region.

Longer periods of motion tend to have marginally lower hazard than on bedrock (compare Table 5.2 and 5.3). This is predominantly due to the effect of the crustal geology in the Perth Basin which tends to de-amplify most periods of ground shaking. This suggests that medium to high-rise structures will be offered some measure of protection from earthquake damage due to the attenuation of ground motions in the Perth Basin.

Table 5.3: Perth study region regolith hazard for a 475-year return period of exceedance

Perth metropolitan location	**Both standards**[1]	**AS 1170.4 - 1993**		**DR 04303 - 2004**	
	PGA(*g*)	S_A at 0.3 s(*g*)	S_A at 1.0 s(*g*)	S_A at 0.3 s(*g*)	S_A at 1.0 s(*g*)
Midland	0.093[2] [0.159][3]	0.233 [0.277]	0.145 [0.047]	0.342 [0.277]	0.116 [0.047]
Perth CBD	0.089 [0.139]	0.223 [0.248]	0.139 [0.043]	0.328 [0.248]	0.111 [0.043]
Fremantle	0.088 [0.132]	0.220 [0.243]	0.138 [0.042]	0.324 [0.243]	0.110 [0.042]

Notes: [1] Bedrock peak ground acceleration (PGA) unchanged from AS 1170.4 (1993) in DR 04303.
[2] Hazard values have been interpolated from hazard maps in standards to capture variation across the study region.
[3] Values derived from this study are shown in square brackets.

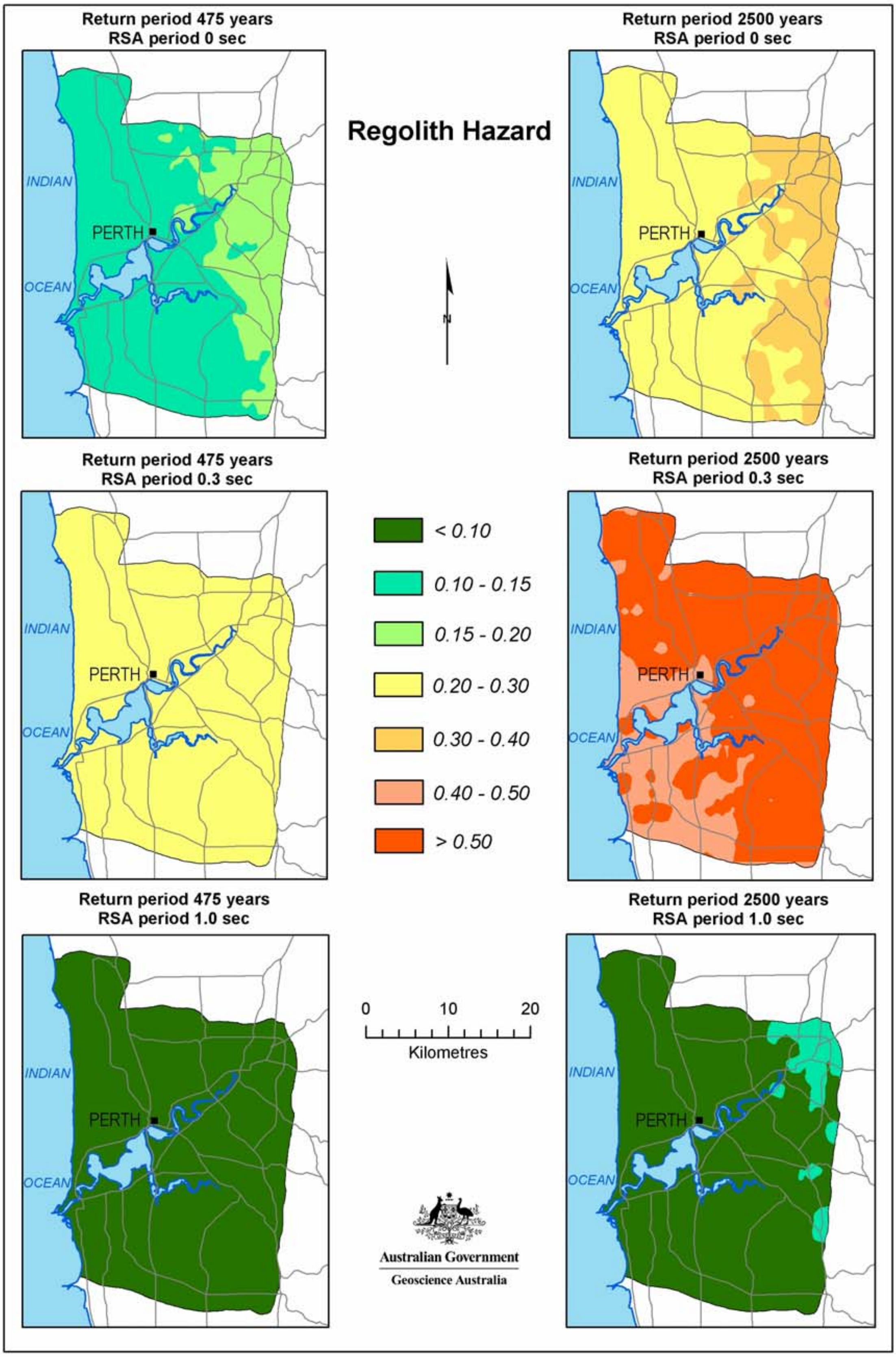


Figure 5.22: Perth study region earthquake hazard on regolith. All accelerations are presented as a fraction of the acceleration due to gravity (g).

5.6 Elements at Risk

The assessment of seismic risk requires a definition of both the hazard and the infrastructure exposed to it. For this Perth study the exposure is limited to the building stock (and contents) in the study region that has been defined as to its distribution, individual building size and construction type. The methodology used to do this is described under separate headings below.

Distribution of building stock in study area

Perth's beginnings date back to Captain James Stirling, who arrived in 1829 with a handful of settlers to establish a new colony on the banks of the Swan River. The development of the city to its present sprawl has comprised periods of rapid growth interspersed with more gradual development. The residential component of Perth's development over time within the study region is presented in Figure 5.23 and is based on spatial data supplied by the WA State Government (Department of Planning and Infrastructure, 2004). It can be seen that construction was initially centred on Fremantle and Cottesloe/Claremont at the mouth of the Swan River and both north and south of the Swan in the proximity of the current CBD. Consequently the older building stock in these areas of early development is expected to be more vulnerable as a result of the less regulated standards of construction in earlier years and the building deterioration that takes place with time, particularly near the coast. Subsequently this initial development has in-filled along with a radial spread from the river. More recently residential development has extended in a northerly/southerly coastal spread confined by the Indian Ocean to the west and the Darling Scarp to the east. Ribbon development has also taken place along the Great Western Highway, reaching almost as far as Northam with the suburbs exposed to incrementally increased seismic hazard. This later easterly development into the Wheatbelt region is outside the study region.

Perth metropolitan building data were obtained from the Perth Valuer-General's Office (VGO, 2002, 2003) for the years 2002 and 2003. Complementary footprint data were used to provide the area of each building (see Appendix B for details of databases). The building stock included in the Perth study and its usage types are depicted in Figure 5.24. There are about 350,000 built structures in the study area and approximately 50% of them are in the LGAs of Stirling, Joondalup, Melville, Cockburn, and Canning (see Table 5.4). For outer LGAs – Wanneroo, Swan, Northam, Mundaring, Kalamunda, Armadale, and Cockburn – only a portion of the total building stock is incorporated. The building database is not comprehensive, as the base VGO data does not include all non-rateable public buildings. Notwithstanding this limitation, the database does represent the most complete exposure data that could be assembled using available resources.

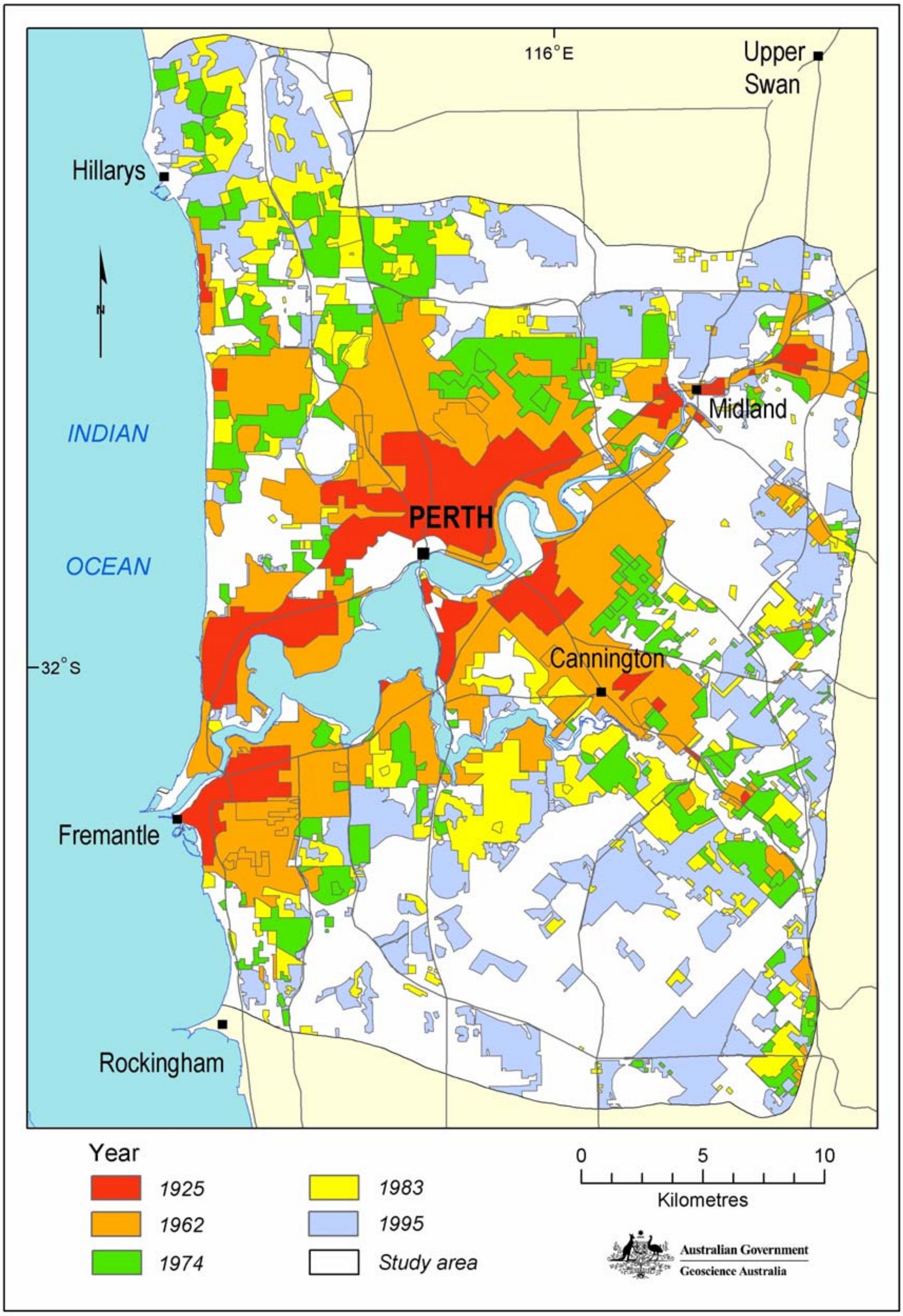


Figure 5.23: Extents of Perth residential development with time within the study region

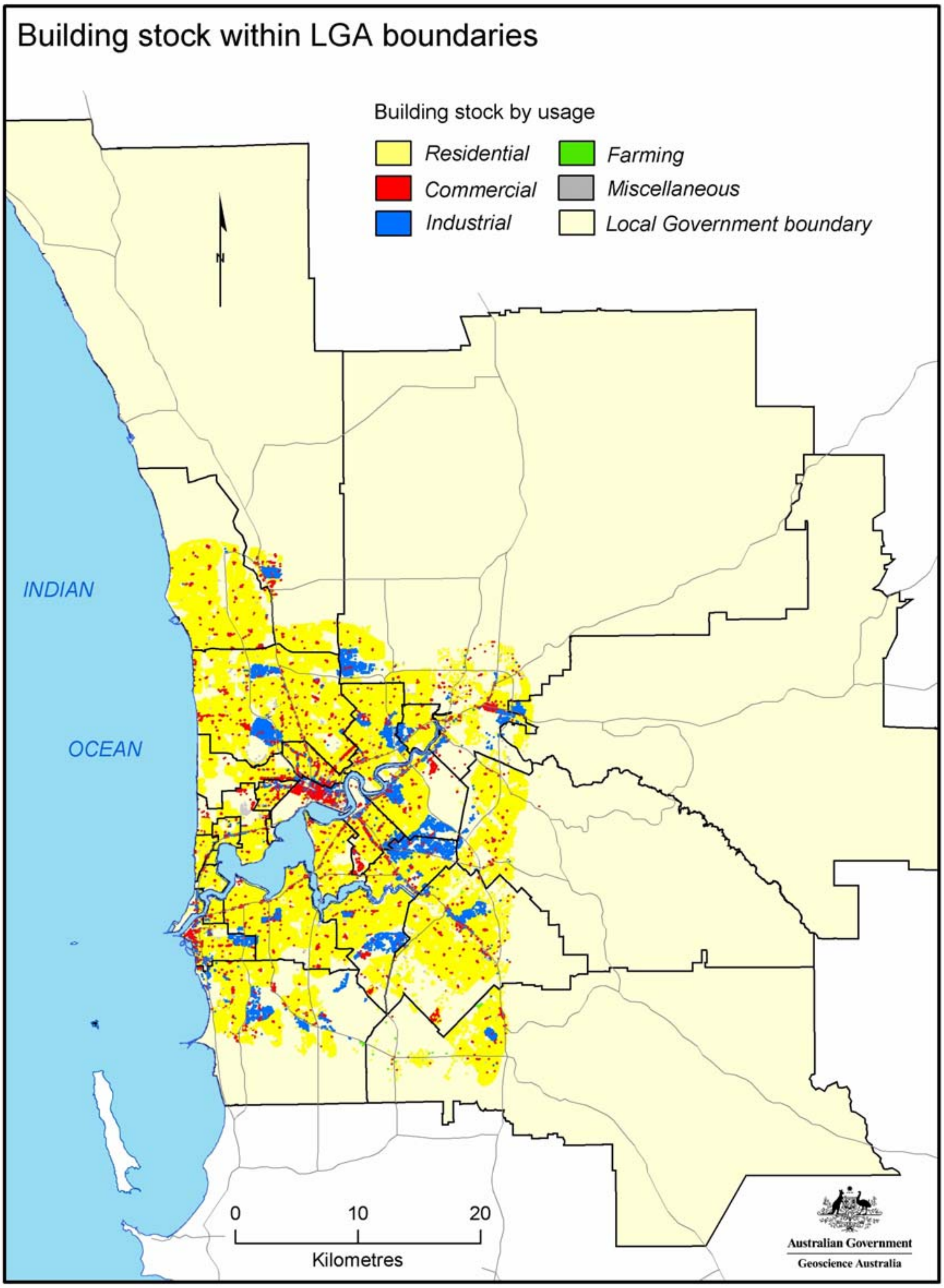


Figure 5.24: Building stock within LGA boundaries

Table 5.4: Building count by LGA

LGA	Number of buildings	% Study area
Stirling	56 016	15.82
Joondalup	36 410	10.28
Melville	32 928	9.30
Cockburn	28 868	8.15
Canning	28 320	8.00
Gosnells	26 452	7.47
Bayswater	16 323	4.61
Fremantle	12 088	3.41
Belmont	12 064	3.41
Swan	11 525	3.25
Armadale	10 658	3.01
Kalamunda	9 907	2.80
South Perth	9 328	2.63
Cambridge	8 483	2.40
Wanneroo	7 972	2.25
Nedlands	7 611	2.15
Victoria Park	7 544	2.13
Vincent	6 895	1.95
Perth City Council	4 483	1.27
Subiaco	4 122	1.16
Cottesloe	2 386	0.67
Mundaring	2 331	0.66
Mosman Park	2 282	0.64
East Fremantle	2 199	0.62
Claremont	2 133	0.60
Bassendean	1 746	0.49
Peppermint Grove	477	0.13
TOTAL	354112	100

The building stock is broadly classified by usage type – residential, commercial, industrial and government – and structural type. The usage types have been further sub-divided according to the Functional Classification of Buildings (FCB), developed by the Australian Bureau of Statistics (ABS) (see Table 5.5).

Residential buildings make up over 95% of the total building stock of the Perth study area, 90% of which are detached houses (see Table 5.6). Industrial and commercial building stock represents less than 5% of the total building stock in the study area. Of the commercial buildings, 53% are offices and 36% are retail outlets. Factories make up about 75% of the industrial building stock.

Table 5.5: Functional classification of buildings

FCB	Building usage
	Residential buildings
111	Separate house
113	Transportable house
121	Semi-detached – 1 storey
122	Semi-detached – 2 or more storeys
131	Flat – 1or 2 storeys
132	Flat – 3 storeys
133	Flat – 4 or more storeys
134	Building attached to a house
	Commercial buildings
211	Retail/wholesale trade
221	Passenger transport
223	Car parks
224	Transport buildings (not elsewhere classified)
231	Offices
291	Commercial (not elsewhere classified)
	Industrial buildings
311	Factories and other secondary production
321	Warehouses
391	Industrial buildings (not elsewhere classified)
	Other non-residential buildings
411	Education
421	Religion
431	Aged-care facilities
441	Hospitals
442	Health
451	Entertainment and recreation
461	Self contained short-term apartments
462	Hotels, motels, boarding houses, hostels or lodges
463	Other short-term accommodation (not elsewhere classified)
491	Non-residential (not elsewhere classified)

Source: Australian Bureau of Statistics, 2001a

Table 5.6: Perth metropolitan building stock by usage type

FCB	Building usage	No. of buildings	
	Residential buildings	**95.5%**	***% Residential buildings***
111	Separate house	301 187	90
121/122	Semi detached – 1 to 2 storeys	26 034	7.7
131-134	Flats	7 890	2.3
	Commercial buildings	**3.4%**	***% Commercial buildings***
231	Office	6 228	53
211	Retail/wholesale trade	4 298	36
291	Other	777	6.5
223	Car park	330	3
221/224	Passenger transport	178	1.5
	Industrial buildings	**1.3%**	***% Industrial buildings***
311	Factories and other secondary production	3 466	75.5
321	Warehouses	1 085	23.5
391	Other	40	1
	Other non-residential	**0.8%**	***% Non-Residential buildings***
442	Health	633	24
451	Entertainment and recreation	619	23.5
431	Aged care facilities	334	13
491	Other	331	13
462/463	Hotels, motels, boarding houses, short term accommodation	304	12
411	Education	288	11
441	Hospitals	48	2
421	Religion	25	1
461	Self contained short term apartments	14	0.5

Source: VGO, 2002

Definition of the size of building structures

Building vulnerability models furnish the damage loss as a percentage of the full replacement cost of the structure concerned. Consequently the replacement value for each exposed building is required and was determined using an estimated total floor area for each building and the cost models described in Section 5.7. The floor area estimation methods adopted for the range of building usages are described below.

Discrete residential homes

Free-standing discrete residential homes represent 86% of the total building stock (Table 5.6). Several data sources were utilised to determine their floor areas with a source accuracy hierarchy established. These are described below.

Building footprints

In total 525,000 Perth roof-plan footprints were available with 320,000 falling within the study region. Most were supplied by the WA Department of Land Information (DLI) through the Western

Australian Land Information System (WALIS), though the set was supplemented with additional footprints created by GA. These polygons represent a direct measure of the house size but include attached garage, eaves areas and other peripheral roof areas such as verandas. These were considered the most accurate measure of building floor area after correction for the non-enclosed areas.

VGO room number data

The VGO database includes equivalent floor areas for 490,000 building occupancies, some of which were part of multi-occupancy dwellings such as blocks of flats and apartments. The area is expressed as a room number that is related to the rateable floor area. Each room has a notional area of 18.5 m^2, incorporating secondary floor areas such as hallways and bathrooms. The area does not include garages and non-enclosed roof areas. With corrections this was considered to be the second most reliable indicator of house size.

ABS building permit data

The ABS processes building permit data and publishes the average annual size of newly constructed homes (ABS, 2004). The floor area given is that enclosed by walls and so includes attached garages. The area does not include eaves areas or peripheral roof areas. This was considered the default floor area when the preceding area measures were unavailable but building age could be assigned.

Area adjustment factors

Correction factors for all three sources of building area were derived using data obtained from two surveys of Perth buildings and one from Victoria. The first was a Perth survey (August/September 2003) of 2,600 buildings located in three Perth suburbs (Clarkson, Winthrop and Duncraig). The survey utilised aerial photography and recorded roof areas and building plan shapes, matching these to the corresponding VGO data. The second was a Perth floodplain foot survey (December 2003) of 2,080 buildings that provided a measure of the variation of eaves width with age. Finally, a peripheral roof area survey of 188 Bendigo, Victoria, homes (Edwards *et al.*, 2004a) was used as an indicator of typical peripheral roof areas for Perth homes. The application of this data is summarised in Figure 5.25. Firstly, the 2,600 aerially surveyed Perth roof areas are reduced for eaves width using the eaves width size data but with no adjustment made for other non-enclosed roof areas. The areas obtained are plotted as construction year averages in the figure. Secondly, the linear regression of this area data is adjusted using the Bendigo data for the other non-enclosed roof areas to obtain the enclosed roof area also shown. The resultant line compares very closely with the mean ABS permit data floor areas (shown as triangles in the Figure 5.25), even though the approach did not consider the proportion of two-storey homes with living areas on the ground floor. Finally, the adjusted areas are factored up on the basis of construction cost data to obtain an area that would give a reconstruction cost for the entire house, including verandas and carports. The corresponding VGO data areas are also shown in Figure 5.25 and correction factors are also derived for adjustment to the target area shown. The suite of adjustment factors obtained was sequentially applied to the full residential building database.

The steps in deriving the representative floor areas for each house, which reflect the accuracy hierarchy discussed above, were:

1. Where the building footprint area is known, correct to target costing area.
2. Where the VGO area based on room number is known, correct to the target costing area.
3. Where only the construction year is known, use the ABS floor area for that year and correct for non-enclosed roof areas.
4. Where nothing is known about the house, take the mean of the known house ages in suburb and use the ABS floor area for that year, correcting it for non-enclosed roof areas.

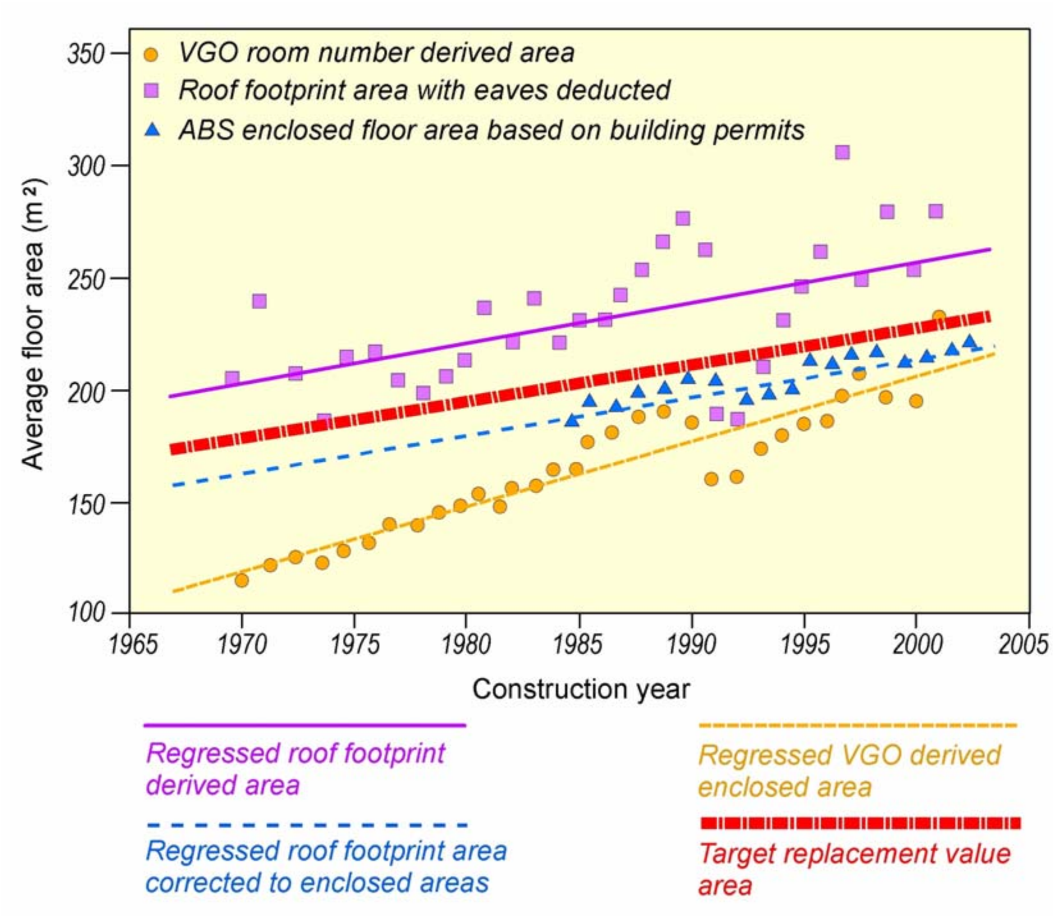


Figure 5.25: Verification of residential home floor area determination

Multi-dwelling residential buildings

Multi-dwelling residential structures represent a further 9.6% of the total building stock (Table 5.6). These were identified in the VGO database where several leaseable occupancies were assigned to a single land parcel. The separate occupancies were aggregated into a single multi-level residential building using the footprint area, the total VGO derived occupancy areas, and the assumption that the residential occupancies are equally distributed on all floors. Eaves areas and peripheral structures were assumed to be negligibly small.

Commercial

The storey number and the total building area were determined using a similar methodology to that used for multi-dwelling residential structures.

Industrial and other non-residential

Where the VGO database included a floor area for the building this was adopted. Where no floor area was available the building was assumed to be single story with limited eaves width and the building footprint area used.

Construction types

For the risk-simulation modelling the 350,000 buildings that comprise the building data base were classified into sub-groups of building construction types. The assignment influences both the level of building response to each simulated earthquake event (accelerations and displacements) and the damage degree probabilities associated with the response. The classifications used follow those of the methodology used by HAZUS (National Institute of Building Sciences, 1999) with the inclusion of several additional building types developed to better represent the vulnerability of Australian structures. The VGO base data included fields for roof material type and wall material type. It was found that only a small proportion of fields were unpopulated (12,000 wall types and 32,000 roof types of 500,000 study region occupancies) and defaults were nominated for the small 'unknown' percentage. The construction type was assigned using a combination of the FCB and the roof and wall types with mappings provided to cover a minimum of 95% percent of the building stock in each building usage category. The mappings of structural models for residential structures are presented in Table C4 in Appendix C.

The construction types used in the Perth database are listed in Table 5.7 below. Not all 36 HAZUS types were present in Perth and so are not presented below. Some of the types were subdivided into sub-classes based on wall and roof type to better reflect the building stock vulnerability. For a full list of the HAZUS construction types see the *HAZUS99 Technical Manual* (National Institute of Building Sciences 1999, Chapter 5). Table 5.7 shows the percentages of each construction type in the Perth building database. The most common are unreinforced masonry followed by timber frame. The primary types are described further below.

Table 5.7: Building types, codes and percentages for Perth

Construction types	HAZUS/EQRM type codes	Total buildings (%)
Steel framed buildings	S1L	0.05
	S2L	0.59
	S3	0.04
	S5L	1.85
Timber framed	W1BVTILE	2.54
	W1BVMETAL	0.44
	W1TIMBERTILE	3.19
	W1TIMBERMETAL	2.22
Reinforced and pre-cast concrete buildings	C1LMEAN	0.05
	C1LNOSOFT	0.006
	C1MMEAN	0.007
	PC1	0.19
Unreinforced masonry	URMLTILE	87.83
	URMLMETAL	1.00

Unreinforced masonry buildings
This type of buildings is very common in Perth and is the most common construction form for new residential structures. A wide range of buildings (including houses, terraced houses, shops, schools, churches and hospitals) are constructed of unreinforced masonry. Infill walls in reinforced concrete framed buildings are also commonly constructed of unreinforced masonry.

Unreinforced masonry buildings have historically performed poorly in earthquakes, as demonstrated by the 1989 Newcastle earthquake (Melchers, 1990). While these types of structures can perform satisfactorily if designed and constructed according to current building standards, buildings which are old, decayed, of poor design or construction may perform poorly during an earthquake.

A common deficiency in this type of construction is a lack of ties between the two leaves of double-brick cavity wall construction. This deficiency may be the result of corrosion or either the lack of ties or their incorrect placement. Soft and eroded lime mortar joints also contributed to structural weakness and to widespread corner failures in the Newcastle 1989 earthquake (Melchers, 1990). These deficiencies commonly manifest themselves in the failure of parapets, gable roof ends, corners, chimneys and the transverse failure of walls. Cracking due to racking is another common type of damage, although this result is less dependent on construction quality.

Continuity of the structure and ductile behaviour are keys to good seismic performance. The latest Australian standard for masonry structures, the 3rd edition of AS3700 (Standards Australia, 2001b), gives recommendations for design, including requirements to take seismic effects into consideration to achieve adequate performance levels. This standard replaced the second edition issued in 1998. In general, Australian Standards for buildings are enacted by federal parliament into the Building Code of Australia. The latest version of AS3700 is referenced by BCA Amendment 3 and was published in November 2001.

Timber frame buildings

In Perth timber frame housing is often identified by brick veneer, timber and sometimes fibreboard cladding. Brick veneers, which can easily be confused with unreinforced masonry buildings, are becoming more popular in Perth, though they still represent a smaller portion of new construction due to economies in double brick construction. Timber frames are largely limited to smaller buildings such as houses.

Timber frame buildings generally perform very well in earthquakes, although non-structural and contents damage can be significant. Brick veneer cladding, brick chimneys, plasterboard linings and cornices are commonly damaged by earthquake shaking. However, serious structural damage is perhaps most likely in the subfloor and foundations, particularly where there is a lack of subfloor bracing or if there is a lack of continuity.

Timber frame housing must be designed according to AS1720.1 (Standards Australia, 2002) or AS1684.1–4 (Standards Australia, 1999a, 1999b, 1999c, 1999d), though consideration of lateral loading is dominated by discussion of wind loading in these documents. The consideration of seismic effects has had practically no effect on the construction practices for this category of structure. Despite non-structural and contents components of these building types being more vulnerable than the structural components, little attention has been paid to improving their performance, and this is reflected by a lack of requirements in Australian Standards.

Reinforced and pre-stressed concrete buildings

Concrete buildings form a significant percentage of the large buildings in Perth. These buildings are used for a wide range of purposes, including commercial, car parking, industrial, residential, educational and government purposes. These concrete buildings may be normally reinforced and/or prestressed, cast *in situ* and/or precast, consisting of slabs, moment frames and/or shear walls.

Concrete construction performs well when detailed to ensure continuity and ductility and if structural irregularities are avoided. A vertical structural irregularity, often called a 'soft' or 'weak' storey is particularly susceptible to collapse. These soft/weak storeys are common where car parking or large open spaces are located on the ground floor of a multi-storey building. Irregularities in building plan are equally undesirable since torsional effects can amplify the response for torsionally eccentric components. Soft storey construction can also be an issue for types of construction other than concrete.

The presence of unreinforced masonry infill walls in multi-storey frame buildings can inadvertently cause structural irregularities. Also, the failure or cracking of such walls in racking or out-of-plane response can be costly in terms of repair and also in terms of the hazard they present as falling debris. Falling debris from other failed non-structural components, such as glass windows, can be equally hazardous.

'Tilt-up' forms of pre-cast concrete construction have become more popular in recent decades. However, this construction method has not been well tested by real earthquake events in Australia.

The current Australian Standard for concrete structures, AS3600, issued in 2001 (Standards Australia, 2001a), requires special seismic design and detailing only in special cases and has not been modified from the 1994 version. Previous versions had no such requirements. In general, however, requirements for seismic effects have had practically no influence on construction practice. Non-structural and contents components are expected to be more vulnerable, although, as previously mentioned, few requirements exist in Australian Standards for these components.

Steel framed buildings

Steel framed buildings make up a significant proportion of large light commercial and industrial buildings in Perth. These buildings are mainly in the form of large shed-type structures and include buildings used for recreational purposes.

Although steel is a ductile material, the connections between steel members can have limited ductility, particularly when poorly designed and/or constructed welds are used. Structural irregularities, and non-structural elements and contents are the sources for the greatest concern, as they are for concrete buildings.

Both editions of the Australian Standard for steel structures, AS4100, first published in 1990 and revised in 1998 (Standards Australia, 1998), contain requirements for seismic effects, whereas previous versions lacked them. As with concrete structures, generally the requirements for seismic effects have had practically no influence on construction practice.

5.7 Direct Economic Loss Models

Estimations of economic losses from natural hazards can be used for a number of purposes, including risk assessments, appraisals of community vulnerability, evaluation of mitigation options, and the determination of levels of disaster assistance. In this chapter, a risk assessment approach for estimating direct damage losses from earthquakes is described. The method used is based on the HAZUS economic loss framework (National Institute of Building Sciences, 1999).

Definition of economic losses

Economic losses resulting from natural hazards are typically classified into tangible losses (items and services that can be costed using existing market prices) and intangible losses (items and services that are not traded directly in markets and so require proxy prices for estimation: eg, environmental damage). Tangibles and intangibles can be further sub-divided into direct and indirect losses (see Figure 5.26). For the Perth risk assessment tangible losses only have been considered.

Direct losses

In general, direct losses, or more specifically, direct damage losses, refer to losses resulting from the physical impact of a hazard event. Direct tangible losses include physical damage to capital stocks such as buildings, contents, infrastructure, and vehicles. In most loss assessments, tangible direct damage losses are measured in terms of the replacement value of the damaged property at a single point in time. It is worth noting that in an economic analysis, the losses would usually be calculated in terms of the changes in *flows* of goods and services over time rather than at a single point in time.

Buildings, inventories and public facilities are treated as capital investments that produce income, and the value (or loss) of the building and inventory would be the capitalised value (or loss) of the income produced by the investment that created the building or inventory.

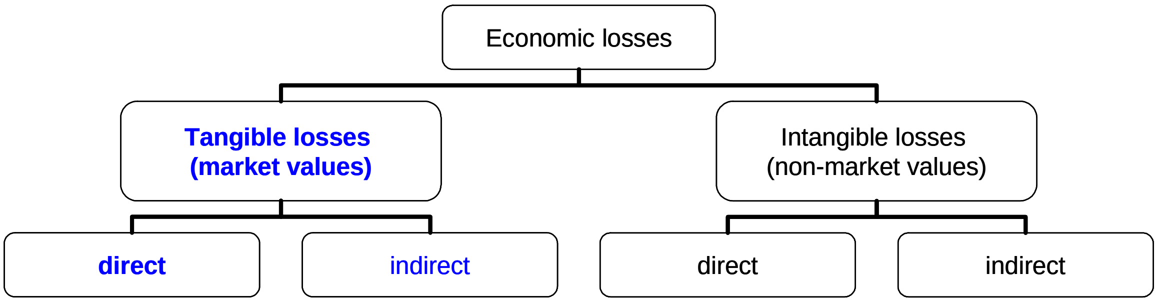


Figure 5.26: Classification of economic loss

Some loss assessments classify the cost of disruption to businesses directly affected by the hazard event as direct tangible losses (National Institute of Building Sciences, 1999). Here, a distinction needs to be made between financial losses (i.e., losses to individual entities) and economic losses (losses to society). Financial losses may be incurred by entities where the normal functioning of businesses is not possible due to the hazard event. However, if other producers in the region can provide the goods and services at no additional cost to the consumer, then there will be no disruption to the flows of goods and services and hence no economic loss is incurred. By including the losses to all affected entities in an economic loss assessment, economic losses would be overestimated.

Indirect losses

Natural hazard events not only disrupt households and businesses directly impacted by the event but may also produce dislocations in economic sectors 'downstream'. The extent of these indirect losses depends on the availability of alternative suppliers and customers for the goods and services as well as the length of the production disturbance. Indirect losses have not been calculated for this study but will be available for the Perth region in the future.

Availability of post-disaster data for economic loss assessments

In Australia, economic loss data are not systematically and consistently collected following a natural hazard event. Under the five-year Disaster Mitigation Australia Package (DMAP), administered by the Department of Transport and Regional Services (DOTARS), efforts are being made to collect more consistent and comprehensive data for damage and recovery post-disaster economic loss. These data would allow a broader assessment of economic losses over time, particularly with the inclusion of household and business disruption and recovery data. For the Perth study, no attempt was made to capture losses that occur after the immediate impact of the event. Estimates of the injury or death tolls due to earthquakes are also not included.

Direct loss model for Perth

The direct loss model for metropolitan Perth is a first step in developing an economic loss model for the impacts of natural hazard events on Australian communities. Given the complexity of the problem and the present lack of post-disaster data, the direct losses are only measured in terms of the tangible losses derived from direct building and contents damage. Losses from infrastructural damage – such as road, water and electricity networks – are not included. The direct economic loss model essentially converts the structural and non-structural damage state information, derived from the engineering vulnerability models, into repair and replacement costs of the building stock and contents. Direct costs are therefore measured in terms of the current value of resources required to rebuild and repair the damaged stock. In using building replacement costs to value building damage, a number of simplifying assumptions have been made. It is assumed that damaged buildings will be repaired and rebuilt in accordance with the current building codes and to the identical size and structural type of their pre-disaster state. In addition, it is assumed, irrespective of the hazard event, that damaged buildings were not due for demolition, and hence will be rebuilt after the event.

Building cost models

Initial estimates of replacement costs of buildings were developed by Reed Construction Data (2003) and provided in 2003 dollars. For the Perth metropolitan area, 86 building cost models were developed to capture at least 95% of the building stock of the metropolitan area. In Appendix C the replacement costs per square metre of representative buildings are tabulated for each usage type (Tables C.1–C.4). Since the residential cost models were developed for different sized buildings, the costs per square metre estimates were regressed to provide a continuum of cost estimates for the full range of house sizes.

In costing residential buildings, the age of the building was also considered and closely aligned to the structural type. For all other usage types, contemporary replacement cost models were assumed. The age classifications for residential buildings are as follows:

- Victorian: 1840–1890;
- Federation: 1891–1913;
- War period: 1914–1945;
- Post-war: 1946–1959; and
- Contemporary: 1960 to present.

Given the significant cost variations for each building type, the cost estimates are only indicative of the potential building losses and considered most useful for larger rather than smaller spatial analysis.

Calculation of building losses

To calculate the cost of replacing a building damaged by an earthquake, the building value is divided into three components: structural, non-structural (acceleration-sensitive) and non-structural (drift-sensitive). Acceleration-sensitive components include hung ceilings, mechanical and electrical equipment, and elevators. Drift-sensitive components include partitions, exterior wall panels, and glazing. The percentage component breakdown is based on US figures and is estimated for each building usage classification (Jackson, 1994) (Table 5.8).

Damage costs are expressed as a percentage of the complete damage state. However, it is recognised that once a certain level of damage is reached, it is usually more cost-effective to demolish the building and rebuild the entire structure rather than replace the damaged components. This is often the case with older houses, especially where buildings may not be built to the current building codes. In terms of the model, once the upper limits of 'extensive damage levels' are reached for older structures it is classified as 'complete damage'. The relationship between damage states and repair/replacement costs for both structural and non-structural components are presented in Table 5.9 and is consistent with those used in HAZUS.

Table 5.8: Percentage breakdown of building replacement costs by FCB and structural and non-structural components

FCB	Structural (%)	Non-structural, drift-sensitive (%)	Non-structural, acceleration-sensitive (%)
111	23.44	50.00	26.56
112	23.44	50.00	26.56
113	0.00	50.00	50.00
121	23.44	50.00	26.56
122	23.44	50.00	26.56
131	13.75	42.50	43.75
132	13.75	42.50	43.75
133	13.75	42.50	43.75
134	23.44	50.00	26.56
191	23.44	50.00	26.56
211	29.41	27.45	43.14
221	16.18	33.82	50.00
222	16.18	33.82	50.00
223	60.87	17.39	21.74
224	16.18	33.82	50.00
231	19.18	32.88	47.95
291	16.18	33.82	50.00
311	15.69	11.76	72.55
321	32.35	26.47	41.18
331	46.15	7.69	46.15
391	15.69	11.76	72.55
411	18.92	48.65	32.43
421	19.77	32.56	47.67
431	18.42	40.79	40.79
441	14.05	34.71	51.24
442	14.44	34.44	51.11
451	9.90	35.64	54.46
461	23.44	50.00	26.56
462	13.58	43.21	43.21
463	13.58	43.21	43.21
491	15.32	34.23	50.45

Source: National Institute of Building Science, 1999.

The repair cost (loss) for each building is the weighted sum of the probable damage costs to each of the three building components. For a given usage type and each of the defined damage states, building repair and replacement costs are estimated as the product of the floor area of each building within the given usage type, the probability of the building structural type being in the given damage state, and repair costs of the building type per square metre for the given damage state, summed over all building structural types within the usage class (National Institute of Building Sciences, 1999).

Contents losses

Estimated contents damage from earthquake events has been calculated based on the building acceleration, structure and usage. In costing the contents damage, it is assumed that the losses increase as the level of damage to the building increases. It is also assumed that some of the contents will be salvaged even where 'complete damage' of the structure is assumed (see Table 5.10).

Table 5.9: Percentage building losses by damage states (percentage of complete replacement cost)

Damage state	Structural	Non-structural drift	Non-structural acceleration
No damage	0	0	0
Slight damage	2	2	2
Moderate damage	10	10	10
Extensive damage	50	50	30
Complete damage	100	100	100

Table 5.10: Percentage contents losses by damage state

Damage state	% Replacement cost
Slight damage	1
Moderate damage	5
Extensive damage	25
Complete damage	50

Residential contents losses

For metropolitan Perth, estimated contents values were only available for residential buildings. They differ according to the location and size of the residence. The contents category (average, quality or prestige) was assigned to an LGA based on average weekly income (ABS, 2001b) (see Table 5.11). For a contents value classification of each LGA in the study area, see Appendix C, Table C.5. The residential contents values were also assigned to each building according to the size of the structure (see Table 5.12).

Table 5.11: Value of contents by average household income

Average weekly household income ($)	Contents classification
500–899	Average
900–1,350	Quality
Over 1,350	Prestige

Table 5.12: Estimated residential contents costs by house size

Area of building (m^2)	Average ($)	Quality ($)	Prestige ($)
120	44 000	97 000	249 000
200	54 000	118 000	285 000
275	73 000	161 000	392 000
350	85 000	190 000	468 000
Unit (low rise)	54 000	120 000	289 000
Apartment (high rise)	25 060	55 690	134 220

Source: RCD 2003

Contents losses for non-residential buildings

For commercial contents values, estimates were only available for a select number of usage types (see Table 5.13). For the remaining commercial usage types in the study area, the value of contents was assumed to be the equivalent of the building replacement cost, consistent with the assumption made in HAZUS (National Institute of Building Sciences, 1999). With respect to industrial buildings, where contents values were not available, the value of contents was assumed to be 1.5 times greater than the cost of replacing the building (National Institute of Building Sciences, 1999). This assumption was also made for religious, entertainment, short term accommodation, education and hospital buildings.

Table 5.13: Contents costs by usage type

FCB	Sub-category	Average cost of contents per m^2 ($)
211	Supermarket	430
211	Shopping centre	290
211	Arcade	390
211	Restaurant	1 055
211	Take-away outlet	1 135
231	Commercial office – low rise	710
231	Commercial office – mid rise	1 770
231	Commercial office – high rise	1 765
291	Garage/workshop	260
291	Service station	530
321	Depot/yard	80
442	Health buildings	119
461	Hotel	630
461	Club (RSL type)	345
462	Hotel – small	780

5.8 Risk Model Verification Against Historical Earthquake Losses

There is a paucity of documented Australian earthquake damage data that can be drawn upon to verify earthquake risk models. However, it has been possible to make use of two damaging WA earthquakes to test the realism of GA's combined ground motion, exposure and damage models that comprise the risk model used. The events selected were the M_w 6.6 Meckering 1968 event and the M_w 6.1 Cadoux event of 1979. Both events were simulated 1,050 times using the EQRM software (Robinson and Fulford, 2003) in order to capture the variability in ground motion and damage models. The results and the assumptions made to obtain comparable study region losses (structure and contents combined) are presented below.

Meckering

The Meckering scenario simulation predicted a mean study region loss of 0.27 % with a standard deviation of 0.06 % (Figure 5.27). Peele (1993) claims that the Meckering event caused approximately $700,000 (1968 dollars) of insured residential loss in the Perth metropolitan region. This number must be converted into the percentage loss to both uninsured and insured structures in order to be comparable with GA's simulated results. However, there is no published information on the 1968 Perth ratio of insured to uninsured structures, nor on the total number of structures in the region.

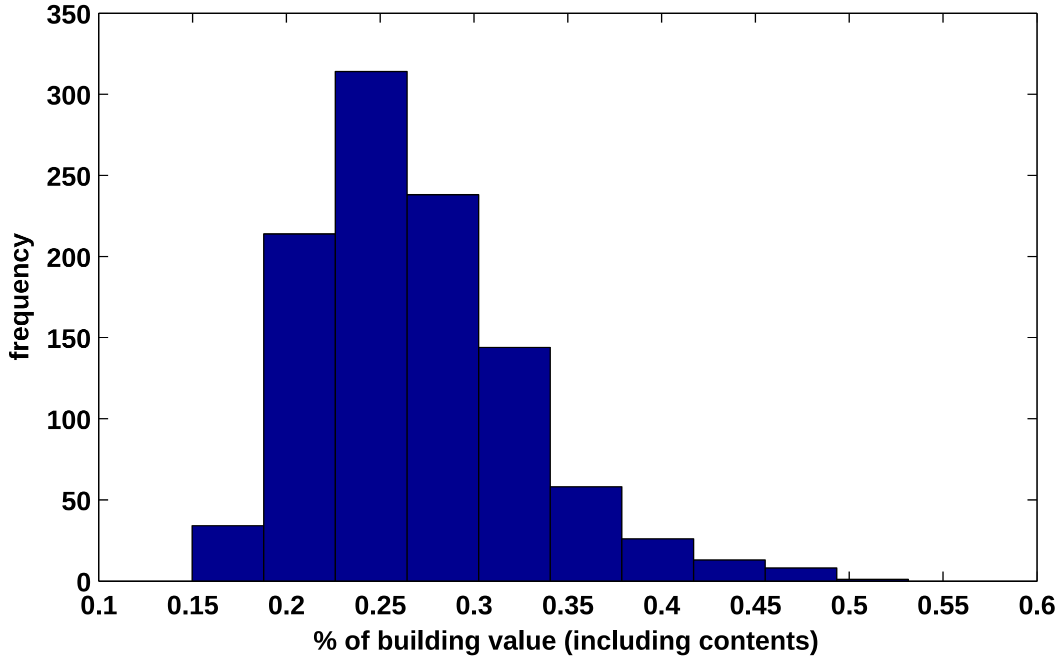


Figure 5.27: Estimated study region loss from the Meckering 1968 earthquake

Consequently, the comparison with GA's simulated event required a number of assumptions, specifically that:

- 40 % of structures in Perth were insured in 1968;
- the number of structures in Perth in 1968 was 52 % of the number of structures present in 2001, and;
- the replacement value of insured structures in Perth in 1968 can be derived from 2003 cost models discounted using the consumer price index.

Based on these assumptions the Meckering event is thought to have caused less than 0.1 % damage with a best estimate of 0.05 % of the total value of buildings and contents in the Perth region in 1968. The estimate is only an indicative value due to uncertainties in the ratio of insured to uninsured structures and the total number of structures in Perth in 1968. However, this estimate is similar to the insured loss of 0.05–0.075 % estimated by Dr George Walker of Aon Re (pers. comms 2004).

Cadoux

The Cadoux simulation gave a mean estimated loss of 0.0046% for the event (Figure 5.28). The extremely small loss predicted for Cadoux is considered to be at the threshold of damage and is consistent with observations that no damage was reported in Perth due to that event.

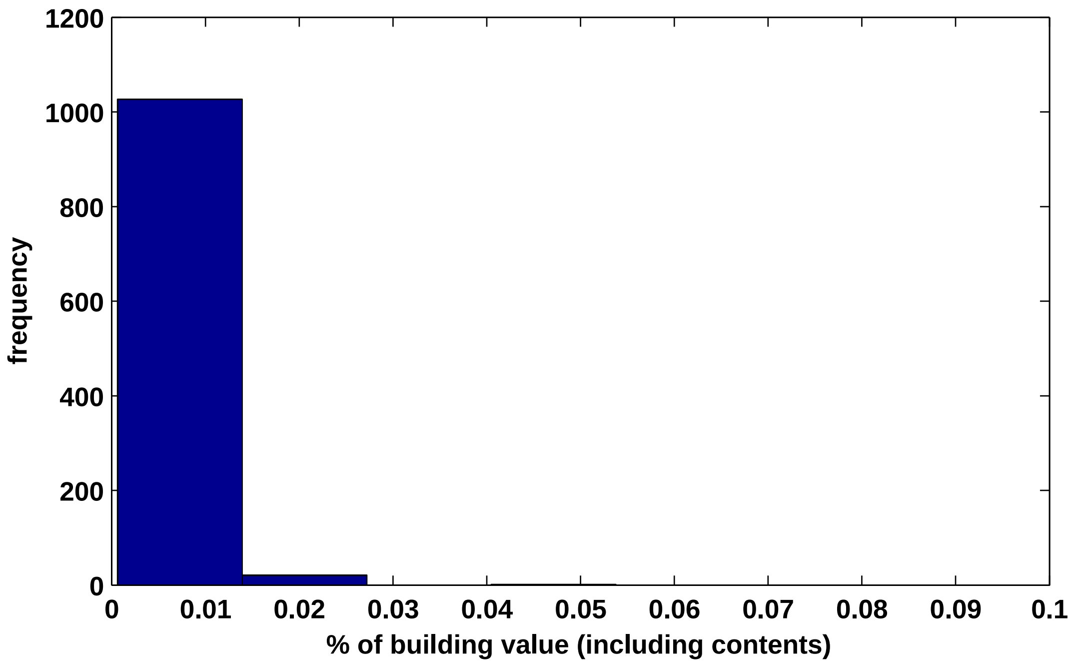


Figure 5.28: Estimated loss from the Cadoux 1979 earthquake

Discussion

Despite the uncertainties associated with this process, the EQRM simulated losses for the two historical events are of similar magnitude to the best estimate of the loss associated with the Meckering event and the negligible reported loss levels for the Cadoux earthquake. It is noted that the damage levels for both events are at the very threshold of damage making a precise prediction of a very small damage level challenging. Despite this the comparisons have provided some, albeit limited, verification of the composite risk model used by GA to assess the earthquake risk in Perth.

5.9 Financial Vulnerability

The financial vulnerability of households and businesses needs to be considered in order to assess the ability of a household or business to rebuild and replace damaged property post-event. The level of household insurance, together with tenure type and income level, are generally fair indicators of this ability after a major hazard event. An uninsured household would usually be considered financially vulnerable if exposed to a natural hazard event as they would have to use up existing savings, borrow needed funds (with additional interest payments) or require longer to save the required amount. If the affected households are also in a lower income bracket, they will tend to have limited disposable income to spend on replacing damaged property and hence are more likely to have to borrow funds or have to wait longer to replace damaged property. Uninsured households in the lower income brackets are also more likely to require government relief, both in terms of payments for replacing damaged items and temporary accommodation and services.

According to the Insurance Council of Australia (ICA, 2002), lower income households who are renting are more likely to be uninsured whilst high-income earning homeowners with a mortgage are most likely to be insured. Dwyer *et al.* (2004) also highlight the significance of tenure type and house insurance in determining the time required for an individual to recover from a natural hazard event.

In metropolitan Perth, about 65% of the households are purchasing or own a property and approximately 30% of households live in rented places (ABS, 2001b). According to the ICA (2002), almost three-quarters of uninsured households rent property (Table 5.14).

In terms of contents insurance, approximately 70% of rental tenants in WA do not insure their household contents. In contrast, over 90% of homeowners with or without a mortgage have either or both building and contents insurance policies (see Table 5.15).

Table 5.14: Tenure type of Perth metropolitan area, 2001

Tenure type	Households by tenure type (%)	Uninsured households by tenure type (%)
Rent	26	74
Rent free	3	6
Ownership without mortgage	37	11
Ownership with mortgage	28	8
Not stated	7	

Source: ABS, 2001b and ICA, 2002

Table 5.15: Insured and uninsured households by tenure type, WA

Tenure type	Percentage insured contents	Percentage uninsured contents	Number of uninsured households
Rent	32	68	14 7840
Rent free	40	60	12 840
Ownership without mortgage	92	8	21 555
Ownership with mortgage	92	8	16 855

Source: ICA, 2002

Table 5.16: Percentage uninsured Australian households by tenure type and income

Tenure type	Quintile 1 (%)	Quintile 2 (%)	Quintile 3 (%)	Quintile 4 (%)	Quintile 5 (%)
Rent	82	74	72	52	50
Ownership with mortgage	6.5	6.6	7	4.3	1.2
Ownership- no mortgage	13	8	6.7	5.8	4

Source: ICA, 2002

In dividing all households across Australia into quintiles1 it is evident that the number of uninsured households decreases with increasing levels of income across all tenure types (Table 5.16).

Using tenure type and household income as indicators of financial vulnerability to a natural hazard event, Census data were used to identify Perth LGAs with high numbers of government tenants (equal to or greater than 5% of households), other rental (equal to or greater than 20% of households in the LGA) and low income households (average household income less than $900/week) (see Table 5.17).

1 Each quintile contains approximately 20% of the population, ranked according to average household income, where 1 is the lowest income group and 5 is the highest income group.

Table 5.17: LGAs and financial vulnerability indicators

LGA	No. of house-holds	High % govt. tenants (>= 5% of households)	High rental other (>= 20% of households)	High no. of household renting (>1900 households)	Low household average weekly income (<$900/week)
Armadale	18,064				
Bassendean	5,493				
Bayswater	23,127				
Belmont	12,446				
Cambridge	8,936				
Canning	27,441				
Claremont	3,638				
Cockburn	24,058				
Cottesloe	3,006				
East Fremantle	2,626				
Fremantle	10,901				
Gosnells	28,644				
Joondalup	50,889				
Kalamunda	16,481				
Melville	34,915				
Mosman Park	3,391				
Mundaring	11,869				
Nedlands	7,314				
Peppermint Grove	514				
Perth	4,105				
South Perth	16,221				
Stirling	72,839				
Subiaco	7,101				
Swan	28,449				
Victoria Park	12,392				
Vincent	11,600				
Wanneroo	27,366				

Source: ABS, 2001b

From Table 5.17 it can be observed that Bayswater, Belmont and Victoria Park have a high percentage and number of households renting and a high percentage of households on low average weekly incomes. It can also be seen that Armadale has a large number of households on low income and renting. Due to the confidentiality limitations on household census data, it was not possible to calculate the number of households who are both on low incomes and renting.

Given that low income households and those who live in rented places are more likely to be uninsured, households with either or both of these characteristics are also more likely to require relief payments to assist in their recovery such as personal hardship and distress (PHD) payments under the Natural Disaster Relief Arrangements. Under the PHD arrangements, individuals are eligible for immediate assistance, temporary living expenses, essential household contents and building repairs and structural damage payments. The arrangements in Western Australia are currently under review in order to establish eligibility criteria and approved formal limits. Historically, no means or assets test has been applied to PHD payments.

5.10 Results and Discussion

In this section the results of both the earthquake hazard and risk calculations are discussed. These are reviewed in the context of the currently applied hazard definitions found in the building design standards and the earthquake risk determined elsewhere in Australia. The hazard and risk is also examined at both suburb and LGA level with reference made to the financial vulnerability of population sub-groups that may struggle to recover following a major earthquake impact on Perth.

Bedrock and regolith hazard

The assessment of bedrock hazard has been undertaken with all efforts made to produce the most reliable results possible. Notwithstanding this there have been several uncertainties in the model components. Achieving consistency in the earthquake catalogue is difficult and the definition of source zone boundaries has required considerable judgement. The Perth hazard was found to be influenced to a significant extent by the local earthquakes in the background source zone. Very few historical earthquakes beneath Perth exist in the catalogue making the definition of recurrence parameters for this zone difficult. Finally, the hazard and downstream risk assessment is very dependent on the choice of attenuation relationships. The need for models developed for Australian crustal zones that can accommodate the significant effects of sedimentary basins is clear.

The bedrock hazard assessment reported in this study has a wider scope than the immediate metropolitan study region. The results have provided an opportunity to compare the re-assessed seismic hazard to that defined in the current earthquake loadings standard (Standards Australia, 1993) that furnishes the design loadings for structures. It has also been possible to review the hazard definition in the draft standard (Standards Australia, 2004) that will soon replace AS 1170.4 1993. The peak ground accelerations for both the 500-year and 2,500-year return periods significantly exceed those published in both standards. This result has little structural significance as the spectral values of 0.3 s and 1.0 s better reflect the earthquake demands placed on buildings. It was found that the 0.3 s spectral values compared favourably with the current standards with a 20% reduction in hazard suggested for the Perth metropolitan area. The 1.0 s spectral values from the study also compared favourably with the draft standard values. Limited strong motion data has shown that the basin does de-amplify ground motion suggesting that the bedrock hazard assessed is conservative. Future research may substantiate a further reduction of the Perth Basin bedrock hazard by incorporating the basin attenuation effects that could not be captured in this study.

The effects of regolith and the Perth sedimentary basin were combined into a localised ground motion model. This approach required a generalisation of the four Perth study region site classes into a single class, thereby losing a definition of the localised effects of regolith that can influence damage to certain structure types and, hence, local risk. The model was also based on very limited strong motion data from a relatively low magnitude event. Despite this, the model did contribute centrally to the achievement of a measure of correspondency between the overall risk model predictions and historical earthquake damage. The predicted regolith accelerations for a spectral period of 0.3 s compared favourably with the hazard defined in the new draft standard, though moderately lower. The spectral accelerations at a period of 1.0 s were considerably lower. The effect of the combined basin and regolith model is to increase the bedrock hazard for low-rise structures and de-amplify the earthquake demands on taller structures that have a longer natural period of response.

The significance of the findings of this study is that design earthquake loads presently being applied to structures outside the Perth Basin are largely compatible with the local hazard. One opportunity for refinement is in the extent of the elevated hazard for low rise structures (S_A at 0.3 s) in the Wheatbelt region where the region of elevated hazard was found to be more extensive both in a northerly and westerly direction. The portion of the Wheatbelt with the greatest hazard has also shifted from the proximity of Meckering to north of Wongan Hills. The new draft standard (Standards Australia, 2004) gives a more extensive coverage of the region of elevated hazard by moderately increasing the spectral accelerations. However, a north-westerly shift of the hazard contours will achieve an improved coverage of the revised hazards determined by the study (refer Figure 5.18).

Study region risk

Each of the 9,400 earthquakes simulated in the risk calculations was assigned a magnitude, location and probability. The epicentral locations were randomly distributed within each source zone and the magnitude and probability taken from the corresponding GR distribution. For each earthquake scenario, the economic damage loss values were determined for a suite of 6,000 reference structures which were then expanded to represent every building in the building database. Each scenario was simulated twice to obtain a loss result from each of the two earthquake attenuation relationships used. The process involved over 110 million individual predictions of building earthquake response and attendant damage.

By considering the impact of all earthquake events on any one or group of buildings an annual probability of exceedance loss curve can be generated. The probability of a loss level being exceeded and the associated annualised loss are of particular interest for risk management decision-making. They can provide guidance on how much should be spent annually on mitigation efforts such as building improvement, emergency response facilities, insurance premiums, etc. Annualised economic loss can also be determined for building sub-populations, depending on the interests of the stakeholder. For example, federal and state governments may be interested in the whole study area, local governments in their own local area, emergency management agencies in their own districts, and insurance companies may be interested in their portfolio exposure to loss. The approach is applicable to populations of structures distributed over a region of interest rather than to discrete structures. Consequently, property owners interested in the risk posed to their buildings would best seek risk advice from experienced professionals. Annualised economic loss values are also useful for making comparisons to other hazards, particularly if rankings of impact intensity are dependent on the return period selected. The earthquake risk results have been evaluated for both the study region as a whole and for the individual suburbs that comprise the study region, each of which are presented separately below.

Aggregated study region risk

The economic loss curve estimated for the entire study region is presented in Figure 5.29. This curve describes the probability of the study region incurring various minimum levels of building plus contents damage loss within a single year. Economic loss is expressed as a percentage of the total value of all buildings and their contents in the study region. The integration of the area under the annual probability of exceedance-economic damage loss curve gives the annual expected economic damage loss (or annualised economic loss). The annualised economic loss for the whole study region, varying according to the rarity (return period) of events considered, is shown in Figure 5.30.

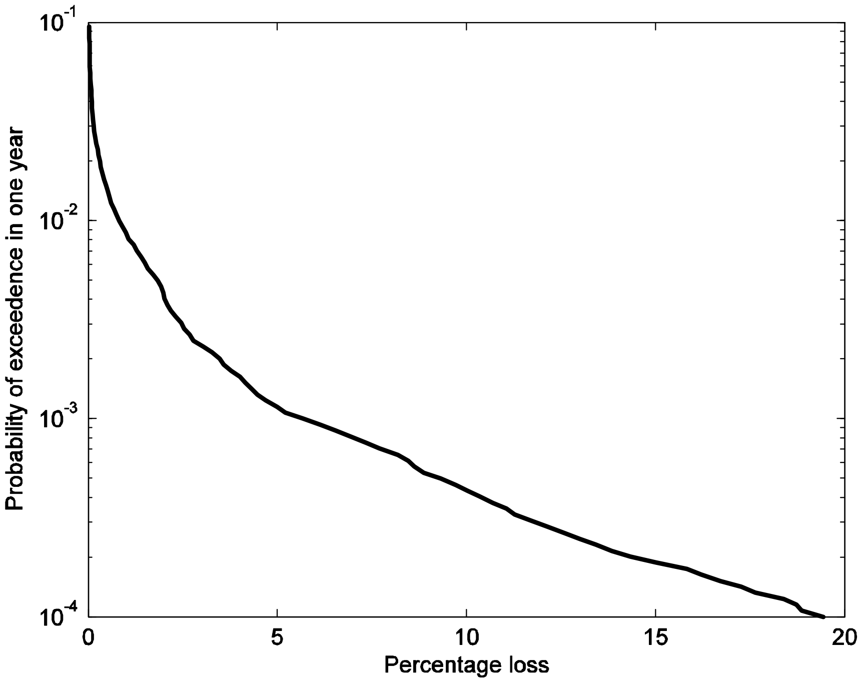


Figure 5.29: Probable maximum loss curve for Perth study region

The results of this study suggest that, on average, the Perth metropolitan region will suffer an estimated economic loss of around 0.040% per year. This corresponds to an annualised loss of the order of $69 million per year. This value has been calculated on the basis of the total value of buildings in the study region, which is estimated by our models to be approximately $171 billion. This compares with a value of 0.022% for the Newcastle/Lake Macquarie region (Robinson *et al.*, 2004), showing that Perth has a significantly greater risk.

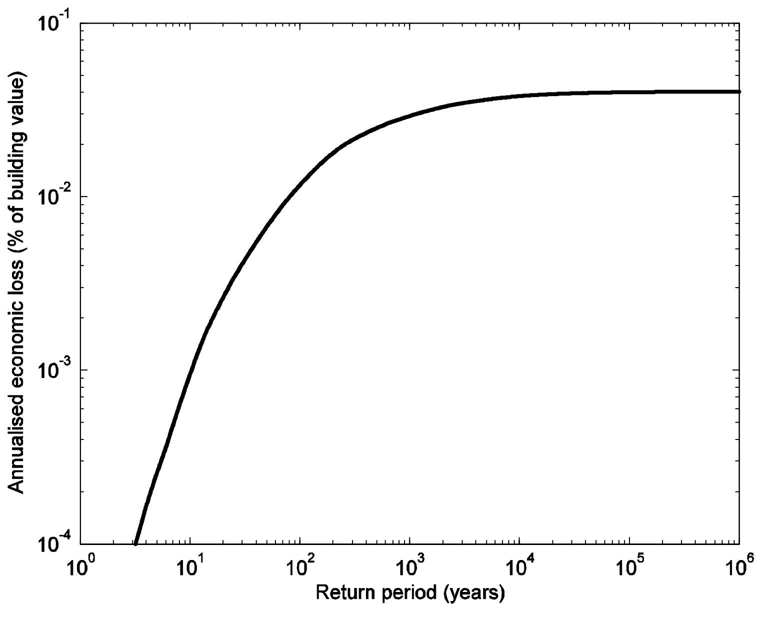


Figure 5.30: Annualised economic loss versus maximum return period considered, for the Perth study region

A prima facie comparison of the average annualised loss to those from historical Perth earthquake losses suggests a poor correspondency. For the period 1967–1999, the actual average annual losses were $3 million, which differs greatly from those assessed. However, the majority of the earthquake risk in the study region is from events that have annual probabilities of occurrence of 0.004 or less (return periods of 250 years or more). This indicates that the risk to the region is primarily from relatively infrequent events having moderate to high impacts. In contrast, very frequent events will have low impacts, and, in the case of Perth, represent a smaller part of the overall risk. Very high impact events could also occur in the region. These extremely rare events contribute little to the annualised risk but present a serious challenge to emergency management due to their sometimes catastrophic consequences.

It is possible to determine the relative contributions to annualised risk of earthquakes from the suite simulated that comprise a range of magnitudes and distances from each building location. The distance used is the Joyner–Boore distance, which is the closest horizontal distance from the building of interest to the rupture plane of the earthquake. In Figure 5.31, a histogram is given for the contribution of overall annual risk for a number of moment magnitude and distance combinations.

The plot shows some interesting features. Most of the earthquake risk in the study region is due to earthquakes with moment magnitudes around 5 at distances of less than 30 km. This result further suggests that the majority of the risk in the region is from moderate-impact, relatively infrequent events rather than high-impact but extremely rare events. The contribution of the SWSZ can also be discerned with large events at the Perth edge of this region (80 km distance) of higher activity making a significant contribution. The Newcastle/Lake Macquarie region lacked this feature as the primary region of seismic activity was directly located under the study region.

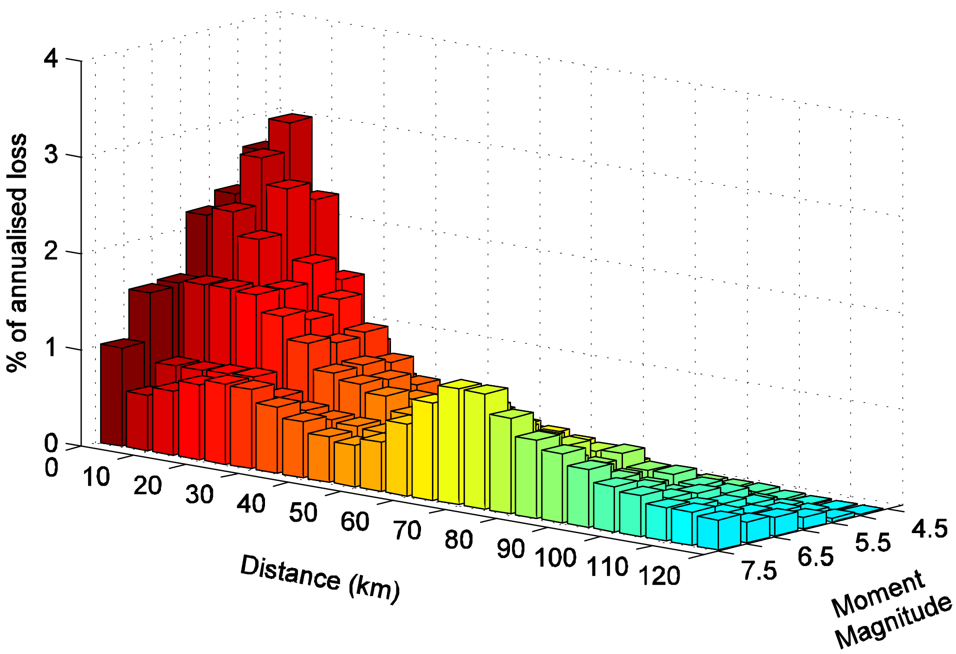


Figure 5.31: Contributions to the earthquake risk in Perth from earthquakes of different magnitudes at varying distances to the building stock

The unique capital city profile of Perth has greatly influenced the risk results. In total 89% of the total building stock and 91% of the residential building subset are of unreinforced masonry construction. The performance of residential construction of this construction type in historical Australian earthquakes has shown it to be a significantly more vulnerable than timber framed construction (Edwards *et al.*, 2004b). Consequently, buildings constructed from unreinforced masonry (cavity brick construction) were found to have a higher annualised loss than any other building type in the study region. The variation of annualised loss across all the building construction types is shown in Figure 5.32 with masonry construction significantly higher. The more engineered steel and concrete structures were found to have much lower annualised losses within their building populations.

The construction type contribution to regional annualised loss is also a function of the relative predominance of the building types. In Table 5.18 annualised risk results are given for the sub-divided building construction types for the four common classes of Perth buildings. Unreinforced masonry (URMLTILE and URMLMETAL) contributes 93% of the total annualised loss. If the population of residential structures were predominantly timber framed the regional risk would be approximately halved. The Perth building profile has 8% timber framed buildings which represent a further 2.7% of the risk. Steel structures were the next largest contributor after masonry to risk (3.2%) by virtue of the greater value of these typically larger structures (13% of the total building stock value) offset by their reduced vulnerability.

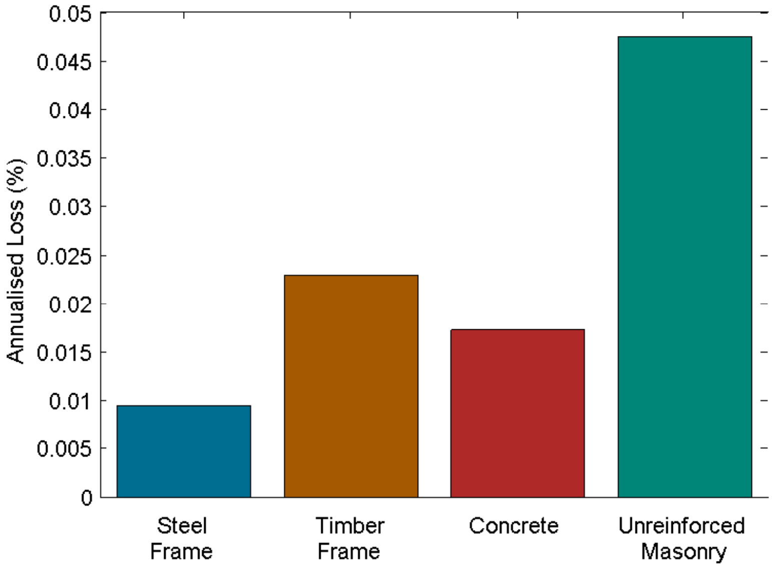


Figure 5.32: Annualised risk for a selection of building types in the study region. The annualised loss for a specific building type is described as a percentage of the total value of that building type in the study region.

Localised impact and risk

Of key interest to this study is the spatial variation of risk and a determination of which suburbs are most at risk. The risk value is a function of the local hazard and the composition of its building stock. By calculating the annualised risk for each suburb in the study region as a percentage of the total annualised risk for the entire study region it appears that some locations are more at risk (on average) than others. A map of the annualised economic loss due to building and contents damage has been determined and aggregated up to the suburb level in Figure 5.33 to help assess the proportion of risk carried by each local authority. Indicated also on the figure are the four LGAs identified in Section 5.9 to be more financially vulnerable. The respective risks of the twenty highest Perth suburbs are also presented in Table 5.19 along with the corresponding LGAs. Finally, the earthquake risk faced by the LGAs (the aggregation of the risk of all suburbs in each LGA) with more vulnerable sub-populations is summarised in Table 5.20. It can be seen that all four LGAs face close to the mean study region annualised loss of 0.04% or greater. The highest annualised loss of 0.048% was for Armadale.

Table 5.18: Annualised risk for building construction types

Building construction type	Structural model	Estimated number of buildings (% of total)	Estimated total value of buildings of that type (% of total)	Annualised risk (% of total annualised risk)	Annualised risk (% of building value)
Steel framed buildings	S1L	0.052	0.30	0.048	0.006
	S2L	0.59	4.47	0.98	0.009
	S3	0.044	0.55	0.16	0.012
	S5L	1.85	8.04	1.97	0.010
Timber framed buildings	W1BVTILE	2.54	1.28	0.67	0.021
	W1BVMETAL	0.44	0.21	0.12	0.023
	W1TIMBERTILE	3.19	1.54	0.83	0.022
	W1TIMBERMETAL	2.22	1.73	1.09	0.025
Reinforced and pre-cast concrete buildings	C1LMEAN	0.045	1.40	0.61	0.018
	C1LNOSOFT	0.006	0.066	0.021	0.013
	C1MMEAN	0.007	0.32	0.020	0.003
	PC1	0.19	1.29	0.66	0.021
Unreinforced masonry	URMLTILE	87.8	75.6	89.8	0.048
	URMLMETAL	1.00	3.23	3.04	0.038

Figure 5.33 clearly demonstrates that risk varies spatially across the study region. The variation in annualised risk can be partially attributed to differences in building stock across the study region. Some suburbs may have a greater proportion of less vulnerable building types that another. Significantly the impact of building age on vulnerability has not been captured in Figure 5.33 as the vulnerability models available for this study were independent of age. The older residential areas of the city were identified in Figure 5.23 in which the building stock is expected to be, on average, of poorer construction that has been more affected by corrosion, decay and poor building maintenance. The underlying regolith also affects the annualised losses, and areas that are built on substantial thicknesses of regolith typically have an accentuated risk. In this instance the regolith effects have not been captured due to the generalised regolith treatment in which the Perth Basin attenuation and the average regolith amplification have been combined into a single generally applied relationship. What can be seen from the figure is the gradual reduction in risk across the region in a south westerly direction as distance from the SWSZ increases. Changes to the building parameters used could change this spatial distribution. For example, changes to unreinforced masonry parameters to account for degradation and age may well increase the annualised risk in suburbs containing older buildings.

The implications of these results and recommendations for future work that could improve the models that are the basis of these results are discussed in Section 5.11 'Recommendations and Future Research'.

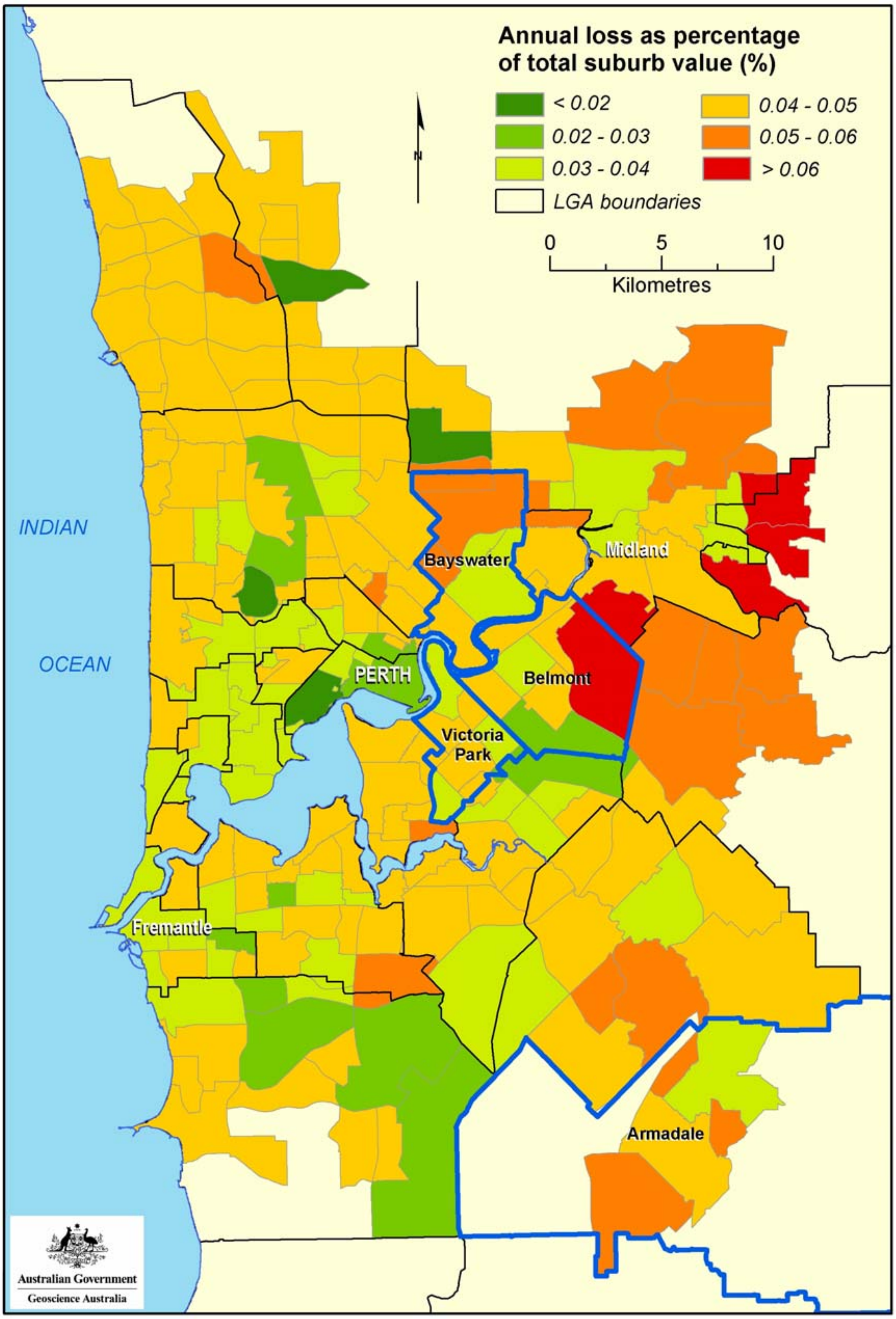


Figure 5.33: Annualised risk by suburb. Note that some suburbs have not been classified due to the relatively low number of buildings surveyed. Suburbs identified as financially vulnerable are indicated

Table 5.19: Annualised risk for the 20 worst impacted Perth suburbs

Suburb	LGA	Building stock value ($)	Annualised loss ($)	Annualised loss (%)
Perth airport	Belmont	1.07m	691	0.064
Swan view	Mundaring	261.7m	165,231	0.063
Helena valley	Mundaring	170.6m	105,992	0.062
Greenmount	Mundaring	73.3m	44,604	0.061
Gooseberry hill	Kalamunda	82.9m	49,932	0.060
Stratton	Swan	89.2m	53,172	0.060
Westfield	Armadale	429.0m	249,052	0.058
Forrestfield	Kalamunda	1,568m	878,323	0.056
Viveash	Swan	105.4m	59,327	0.056
West swan	Swan	58.9m	32,274	0.055
Brookdale	Armadale	112.9m	60,552	0.054
Morley	Bayswater	2,244m	1,203,646	0.054
Herne hill	Swan	2.19m	1,186	0.054
Mount Nasura	Armadale	14.7m	7,837	0.053
Noranda	Bayswater	778.7m	415,193	0.053
Gosnells	Gosnells	2,027m	1,081,116	0.053
High Wycombe	Kalamunda	999.4m	533,054	0.053
Kalamunda	Kalamunda	50.6m	27,054	0.053
Leeming	Melville	1,438m	756,409	0.053
Bedford	Bayswater	390.9m	203,969	0.052

Table 5.20: Annualised risk for LGAs with vulnerable sub-populations

LGA	Building stock value ($)	Annualised loss ($)	Annualised loss (%)
Bayswater	7.25b	3.23m	0.045
Belmont	7.04b	2.52m	0.036
Victoria Park	4.34b	1.77m	0.041
Armadale	2.71b	1.29m	0.048

5.11 Recommendations and Future Research

From the earthquake assessment of this study the following recommendations are made:-

- that the updated earthquake hazard maps for Perth and the Perth region are used to review, improve and complement the design and construction guidelines for earthquakes set by state and local governments. The inclusion of the wider region of hazard identified in the Wheatbelt area into building regulations is one specific application of the research that should be considered;
- that state and local authorities enforce the compliance of all new structures with current earthquake loadings standards;

- that post-disaster essential facilities such as police, SES, fire and ambulance stations and hospitals, be structurally retrofitted to ensure operability immediately following a major earthquake. These facilities should be examined by suitably qualified engineers on a site-by-site basis to assess their expected performance under earthquake loadings. This recommendation is pertinent for SWSZ communities;
- that the importance of adequate insurance against earthquakes be promoted with householders, small business operators and corporations, and;
- that the fields captured in the VGO database be slightly enlarged to include other features besides roof and wall type to enable the more accurate assignment of structural response, vulnerability and replacement cost models. The database could be further improved by the inclusion of additional non-rateable buildings, thereby developing a more comprehensive assessment of the building stock exposed to hazard.

The following areas for future research in the Perth region have also been identified:-

- Research to develop a better understanding of the sedimentary basin attenuation. The seismic hazard and risk assessment of the Perth region has been heavily influenced by the selection of attenuation functions to capture the energy dissipation of the full wave path through the bedrock. Geoscience Australia has recognized the importance of developing a robust spectral attenuation model for Australian conditions in order to reduce the uncertainties in its risk assessments.
- The development of improved regolith modelling to capture the localised amplification of regolith.
- The development of building vulnerability models that can differentiate between building age and proximity to a marine environment.
- The inclusion of critical infrastructure (e.g. utilities, energy production assets and transportation facilities) in the range of vulnerable infrastructure considered in regional earthquake risk assessments. Historical Australian earthquakes have shown that the direct damage to assets of this type can be expensive and the service disruption can have wide reaching economic and community impacts.
- Research into a wider range of economic losses including indirect tangible losses and intangible losses that all contribute to a holistic assessment of risk.

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