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Regional variations in neotectonic fault behaviour in Australia, as they pertain to the seismic hazard in capital cities

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ABSTRACT:

Four of Australia's largest five population centres are topographically constrained by prominent escarpments (i.e. Sydney, Melbourne, Perth, Adelaide). These escarpments are underlain by faults or fault complexes capable of hosting damaging earthquakes. Paleoseismological investigations over the last decade indicate that the seismogenic character (e.g. recurrence and magnitude) of these structures varies markedly. Uplift rates on range-bounding faults in the Mt. Lofty Ranges suggest that average recurrence for M_{max} earthquakes on individual faults is in the order of several tens of thousands of years. A high density of faults with demonstrated Late Quaternary surface rupture occurring proximal to Adelaide suggests that recurrence of damaging ground-shaking from earthquakes on these faults is in the hundreds to few thousand years. Uplift rates on faults proximal to Melbourne (and the Latrobe Valley, where much of Victoria's power is generated) in some cases exceed those of the Mt. Lofty Ranges. However, a lower relative density of seismogenic faults proximal to the conurbation of Melbourne implies a lower level of hazard than in Adelaide. In contrast to Melbourne and Adelaide, paleoseismological investigations on the Darling Fault near Perth, and the Lapstone Structural Complex near Sydney, indicate average recurrence for M_{max} events in the hundreds of thousands to millions of years. These faults contribute little to probabilistic assessments of hazard, while larger, distant events and proximal sub-M_{max} events have been demonstrated to be damaging in all of these areas (e.g. 1968 Ms6.8 Meckering, 1989 M_L5.6 Newcastle, 1954 M_L5.4 Adelaide, 2012 M_L 5.4 Moe). Further research is required to demonstrate that earthquakes of sub-morphogenic and morphogenic magnitude might be modelled on the same Gutenberg-Richter distribution curve.

Keywords: paleoseismology, neotectonic domains, seismic hazard

INTRODUCTION:

Rare paleoseismic data indicate pronounced temporal clustering of large earthquake events across all geological environments within Australia (Figures 1A and 1B), with a finite number of relatively closely-spaced events being separated by much longer periods of quiescence (Crone *et al.* 1997, Crone *et al.* 2003, Clark *et al.* 2011a, Clark *et al.* 2012, Clark *et al.* 2014a, Clark *et al.* 2014b) (Figure 1C). An active period might constitute half a dozen events or less (e.g. the Cadell Fault in eastern Australia, McPherson *et al.* 2012a, Clark *et al.* 2014b), and perhaps as few as two or three in Western Australia (e.g. the Hyden Fault, Crone *et al.* 2003, Clark *et al.* 2008). The inter-seismic intervals between large events in an active period in the cratonic west of Australia might be in the order of 10–40 kyr (Clark et al., 2008; Crone et al., 1997, 2003; Estrada, 2009). In eastern non-cratonic Australia data from the Cadell Fault indicate the potential for more frequent rupture, with perhaps as many as 6 events occurring in a 50 kyr period (McPherson *et al.* 2012a, Clark *et al.* 2014b). Relationships between deformed fluvial surfaces suggest that these events are likely to have been spaced thousands of years apart, similar to the Meers and Cheraw faults in the intra-plate eastern United States (Crone & Luza 1990, Crone & Machette 1995). Quiescent intervals can be sufficiently prolonged, in the cratonic western and central parts of Australia in particular, that most or all relief relating to an active period might be removed by erosion prior to the next active period. These data imply that the slip rate in an active period (spanning a few tens of thousands of years) might be several orders of magnitude greater than that over the long-term (spanning millions of years) (Figure 1C). Accounting for non-periodic large earthquake behavior in probabilistic seismic hazard assessments will ultimately require knowledge of the mechanisms controlling this behavior in each geological environment (e.g. Braun *et al.* 2009, Clark 2010, Clark *et al.* 2014b), and accurate parameterisation of large earthquake recurrence models.

A critical question is whether a long-term slip rate on a fault is a meaningful quantity for seismic hazard applications if the fault is either 'on' (i.e. slipping at much greater than this rate) or 'off' (slipping at a fraction of this rate) (Figure 1C). This paper discusses the character of Australian intra-plate faults, the slip rate data available for them, and explores the contribution that the Australian neotectonic features catalogue, which is heavily skewed towards long-term rather than active period slip rate data, might make to future iterations of the Australian National Seismic Hazard Map (NSHM). Test-case example hazard maps are presented for four of Australia's major population centres, albeit using simplified assumptions at this stage.

AUSTRALIAN NEOTECTONIC FAULT CATALOGUE COMPLETENESS AND RELIABILITY:

The Neotectonic Features Database comprises over 300 instances of known and suspected sources of potentially damaging ground-shaking (http://www.ga.gov.au/earthquakes/staticPageController.do?page=neotectonics). In most cases features are characterised by their trace and physical expression at the Earth's surface only, and details of slip rate, characteristic magnitude, and recurrence are unknown. Maximum rates of activity may often be inferred from landscape erosion rates (i.e. a mountain range is not forming as the result of fault uplift, so regional erosion rates must exceed uplift rates). While it is nowhere complete, the catalogue tends to be most reliable in southern Australia, coincident with areas of major population density (Figure 2).

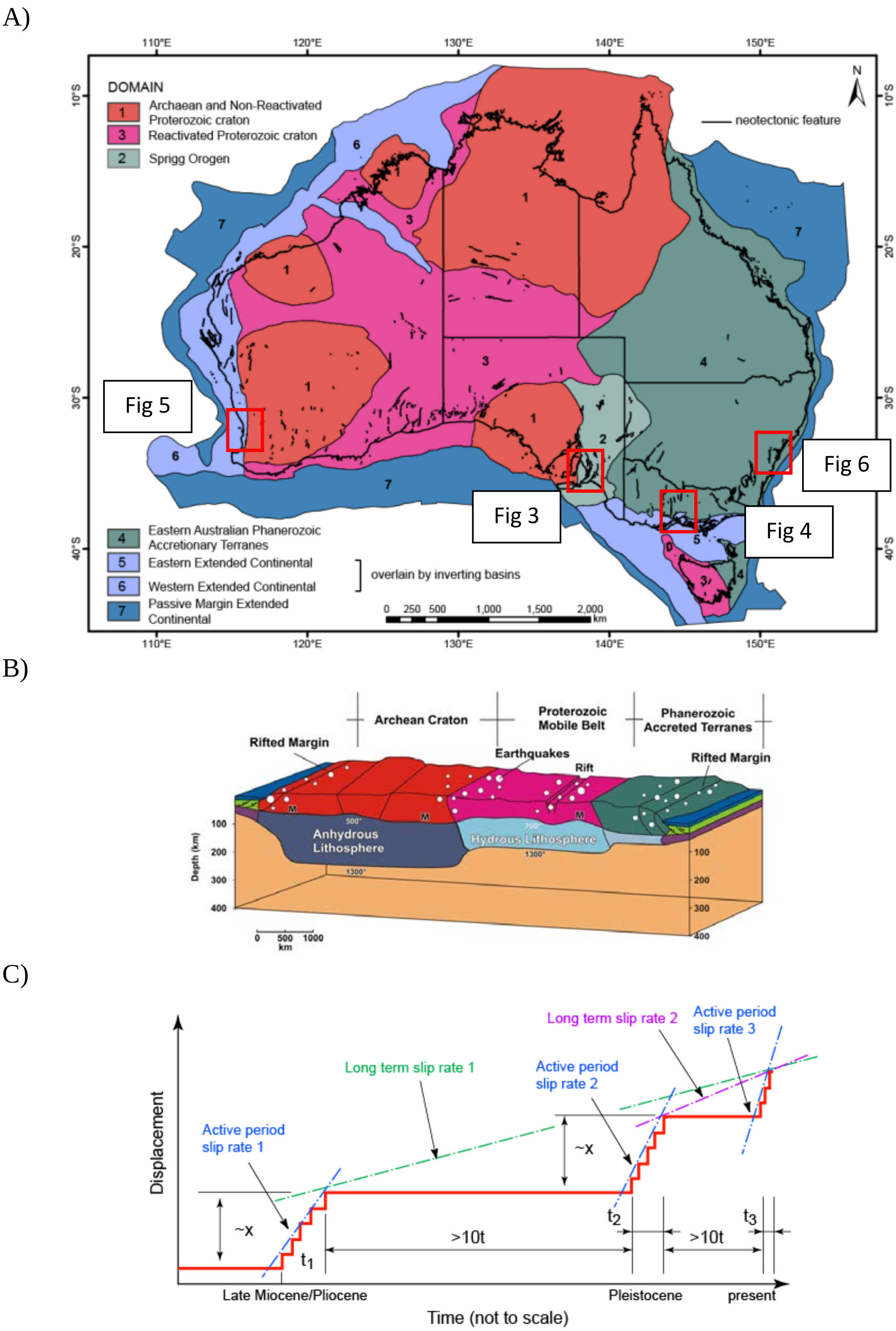

Figure 1. Spatial and temporal models describing variation in neotectonic fault behavior in Australia. (A) simplified neotectonics domains model, after Clark *et al.* (2012). (B) Crustal basis for definition of domains (after Mooney *et al.* 2012). Red and cyan = cratonic crust (non-extended), greens = non-cratonic crust (Phanerozoic), and dark blue= extended crust, (C) Temporal clustering model, modified after Clark *et al.* (2014b), showing differences between active period and long-term slip rates. Note that long-term slip rate varies depending upon the age of the strata used to calculate the rate (green vs cyan line). The parameterisation of the model in part C varies with location, as predicted by model in part A.

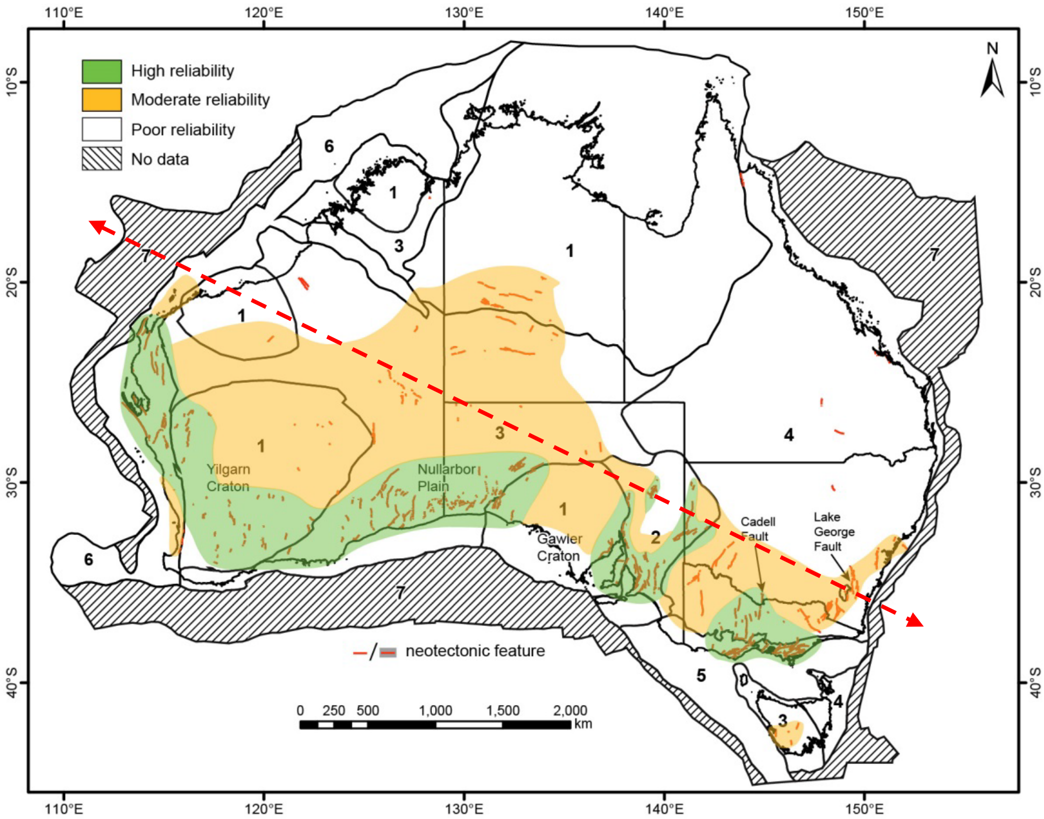

Figure 2. Schematic map depicting the completeness/reliability of the neotectonic catalogue for Australia. High reliability implies that 75% or more of features relating to Mw>6.5 earthquakes that have occurred in the last *ca.* 100 kyr are known. Moderate and poor reliability relate to 50-75% and <50% thresholds respectively. The approximate location of the large-scale continental tilt axis (after Sandiford 2007).is shown as a red dashed line.

Factors that influence catalogue completeness, and consequently the reliability of inferences made from the data, include:

Environmental: Bedrock erosion rates within Australia are generally very low (Clark *et al.* 2012, and references therein), and vary according to precipitation (influencing rates of weathering) and relief (influencing rates of removal of weathering products). In the arid, low relief parts of Australia, erosion rates are in the order of 0.2-5 m/Myr, whereas rates may be up to 30-50 m/Myr in the higher relief, more humid areas of eastern Australia. In order for tectonic relief to be maintained, relief-building rates must exceed bedrock erosion rates. A threshold is thereby set for the discoverability of tectonic relief that favours relief preservation in drier climates, with the caveat that relief may be buried by wind-blown sediment in very arid regions. Temporal clustering of morphogenic earthquake events allows for greater discoverability potential during and immediately following an active period on a fault as active period slip rates may far exceed long term erosion rates (Figure 1C). Indeed, the catalogue of neotectonic features in cratonic Australia likely comprises faults that are in, or have recently concluded, an active period. In contrast the Flinders/Mt. Lofty Ranges appear to be anomalous, having long-term slip rates commensurate with, or slightly exceeding, erosion rates (Quigley *et al.* 2007, Quigley *et al.* 2010).

***Geological and Seismological**:* Plate tectonic motion combined with large-scale mantle dynamics are such that southern Australia is uplifting and northern Australia is lowering with respect to mean sea-level (Sandiford 2007). The vast majority of known neotectonic features occur to the south of the tilt axis shown in Figure 2. Why this is so has not been investigated in detail, but it might be hypothesised that preservation of neotectonic features in northern Australia is generally limited by deposition obscuring features. South of the tilt axis 'uplifted' features may be etched by erosion, enhancing discoverability. By the same token erosion may limit discoverability by more readily removing features in southern Australia.

Earthquakes generate surface expression (fault scarps) more readily in cratonic western and central Australia versus non-cratonic eastern Australia by virtue of typically shallower hypocentres in the former (Leonard 2008, Clark *et al.* 2014a), and relatively low relief. So while long-term fault activity rates tend to be lower in cratonic regions, and higher in non-cratonic regions of Australia (cf. Mooney *et al.* 2012), faulting-related relief may be more discoverable in cratonic Australia.

Reconnaissance Dataset Availability: Over a large proportion of Australia, where the Shuttle Radar Topography Mission (SRTM) DEM is the only exploration tool, it might be expected that discoverability of neotectonic landforms relies upon temporal clustering of large events, as uplift relating to a single rupture would likely be beneath the threshold of discoverability for that spatial dataset. Fortunately, temporal clustering of morphogenic events appears to be common in the intra-plate environment (Crone *et al.* 1997, Crone *et al.* 2003, Clark *et al.* 2014a). Various higher resolution but spatially-localised elevation datasets exist across southern Australia, coincident with population centres, and within the Murray-Darling Basin (e.g. Lawrie *et al.* 2012). The most extensive is in the southwest of Western Australia, where a 10 m digital elevation dataset allowed for the mapping of a comprehensive catalogue of sixty features relating to M>6.5 events spanning at least the last 100 kyr (Clark 2010, Leonard & Clark 2011). With the exception of LiDAR, digital elevation datasets have a range of limitations in seeing through vegetation. Reliability is therefore generally less where vegetation covers a greater proportion of the ground surface (e.g. eastern Australia, SW Western Australia).

REGIONAL VARIATIONS IN NEOTECTONIC FAULT BEHAVIOR PROXIMAL TO CAPITAL CITIES:

Youthful topography/bathymetry can in many cases be used as a proxy for fault activity (Quigley *et al.* 2010, Clark *et al.* 2014a), although exceptions are common (e.g. Jakica *et al.* 2010, McPherson *et al.* 2014). Four of Australia's largest five population centres are topographically constrained by prominent escarpments/ranges underlain by faults or fault complexes capable of hosting damaging earthquakes (i.e. Adelaide, Melbourne, Sydney, Perth). Below, each of these regions is examined in terms of its regional neotectonic fault behaviors, and the associated considerations necessary when assessing seismic hazard.

Adelaide

Of all Australia's capital cities, Adelaide has the greatest exposure to neotectonic faults, with more than a dozen known faults occurring within 50 km of the urbanized area (Figure 3). The fault inventory is likely to be reasonably complete for range-bounding faults, and less complete for intra-range faults. Mio-Pliocene near-shore marine sediments preserved in the intra-range Meadows Basin (Stoian 2004) (Figure 3C) indicate that at least ~280 m of uplift of the Mt. Lofty Ranges has occurred in the past 5-10 Myr, at a rate of ~30-60 m/Myr. In addition to faults overlapping in plan view (Figure 3A), seismic reflection data indicate that the faults associated with the greatest activity rates merge at depth (Flöttmann & Cockshell 1996) (Figure 3B), allowing for strainsharing and temporal clustering of events. It is therefore difficult to assign uplift rates to individual faults based upon surface expression and the regional uplift rate. Measured slip rate estimates vary along the length of individual faults. Examples include the Para Fault (27 m of slip across the *ca*. 125 ka Pooraka Formation proximal to Adelaide CBD (Sheard & Bowman 1996), yet only ~0.5 m of slip across the same unit north of Elizabeth (Geoscience Australia, unpublished data), and the Willunga Fault (2-3 m uplift since 125 ka at Sellicks Beach (Reid 2007), and >10 m of uplift across last interglacial strata ~12 km further south at Normanville (Bourman *et al*. 1999)). Geologic units of a range of ages are displaced by faulting, allowing for the calculation of a time span-heterogeneous and point-specific set of uplift rate estimates for individual faults, ranging from ~5-80 m/Myr (see Appendix). Assuming a homogeneous slip distribution, and that the displacement has accumulated in the last 5–6 million years (Sandiford et al., 2004), Sandiford & Quigley (2009) obtain time-averaged displacement rates on bounding faults of ~40–50 m/Myr, in line with that inferred from historical seismicity rates. This is a surprising result as 75% of well-located earthquake hypocentres occur in the depth range 8-14 km (Leonard 2008, Cummins *et al.* 2009), likely centred within Gawler Craton crust below the structural architecture seen at the surface (blue box on Figure 4B). A definitive link between instrumentally recorded seismicity and surface faulting is hence yet to be determined.

Despite abundant evidence for recent deformation, paleoseismic data on large earthquake recurrence rates from the Mt. Lofty Ranges are almost entirely lacking. An exception is the northern Williamstown-Meadows Fault (Tarlee Scarp) with two events in the past *ca*. 60 kyr (Geoscience Australia, unpublished data). Single event slips of ~1.6-1.8 m on the Milendella (Clark *et al.* 2011b), Williamstown-Meadows and the Alma faults (Clark & McPherson 2011) indicate the potential for earthquake magnitudes of Mw≥6.8.

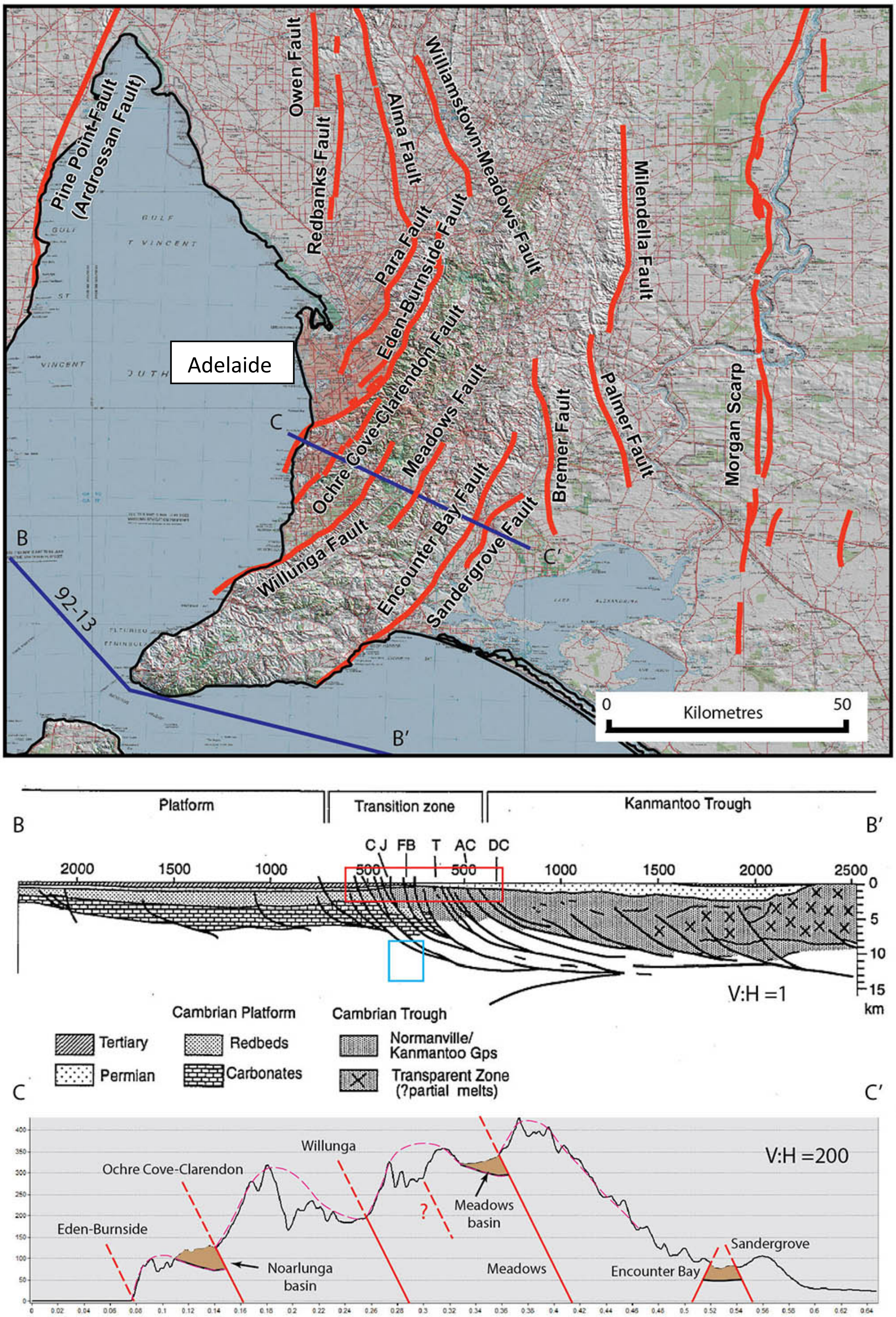

Figure 3. Known neotectonic faults proximal to Adelaide (see Fig 1 for location). (A) map of fault traces, (B) interpreted seismic section acquired through Investigator Straight (B-B') showing partially inverted extensional architecture (modified after Flöttmann & Cockshell 1996) and the setting of the Mt Lofty Ranges on the boundary between cratonic and non-cratonic Australia, (C) topographic section C-C' showing schematic faults and fault-angle basins. Location of section is marked on parts A and B. Blue box on Part B contains 75% of well-located earthquake hypocentres (Leonard 2008).

Melbourne

The Greater Melbourne conurbation straddles the northern edge of the Tertiary to Quaternary Port Phillip Basin, which overlies the eastern parts of the Cretaceous Otway Basin (Holdgate *et al.* 2002) (Figure 4). The bounding and intra-basin faults of these basins were reactivated in compression to varying degrees in the Late Miocene to Pliocene (4-8 Ma, Dickinson *et al.* 2002, Holford *et al.* 2011). However, neotectonic fault density proximal to Melbourne is significantly less than in the Mt. Lofty Ranges, with only five faults recognised within 50 km of the Melbourne CBD. The Selwyn and Rowsley/Lovely Banks faults bound the Port Phillip Basin, and are associated with long-term average uplift rates of 35-55 m/Myr. Intra-basin faults, such as the Beaumaris, Avalon and perhaps Bellarine faults, are associated with significantly lower uplift rates (≤10 m/Myr).

Further afield (but still <100 km from the CBD), Melbourne is bracketed by two of the most actively deforming parts of the Australian continent; the Otway and Strzelecki Ranges (Figure 4). The faulting catalogue is relatively complete in these areas. Similar to the Mt. Lofty Ranges, the Otway Ranges have been uplifted by between 175 m and 240 m since the Early Pliocene, at rates of 35-50 m/Myr. Slip rates along the length of individual faults are again difficult to estimate as they merge at depth, allowing for strain sharing (see Appendix; cf. Figure 4B). Furthermore, Sandiford (2003) suggests that a significant portion of the relief generation occurred as a pulse in the interval 2-1 Ma.

To the east, the Strzelecki Ranges mark the inverted deeps of the Gippsland Basin. The range bounding faults of the Strzelecki Ranges (Narracan and Balook geologic blocks) support some truly remarkable uplift rates averaged over the last 1-2 Ma, in the order of 80 – 100 m/Myr (see Appendix). Despite prominent relief, these uplift rates are inconsistent with the landscape on a timescale of 5-10 Myr. Evidence from the near offshore Gippsland Basin suggests that uplift rates are not constant through time. The parallelism and conformable nature of most Pliocene strandlines across Victoria has been taken as evidence for very little tectonism in the interval 6-3 Ma (Wallace *et al.* 2005). In the eastern onshore Gippsland Basin an angular unconformity between the Jemmy's Point Formation (Pliocene) and the overlying Haunted Hill Formation (late Pliocene to Quaternary) suggests significant post 3 Ma deformation. Seismic reflection evidence combined with palynological age constraint suggests that a major episode of deformation involving folding ceased at 1 Ma in the offshore Gippsland Basin but continued onshore until approximately 0.20-0.25 Ma (Holdgate *et al.* 2003). The time over which long-term slip rates are averaged is hence very important in assessing the validity of the results of seismic hazard studies in this region.

While representing the potential sources of relatively frequent large earthquakes (perhaps in the thousands of years, cf. Stirling *et al.* 2011), the Otway Ranges and Gippland Basin faults are too distal to significantly influence the probabilistic hazard in Melbourne (see Results section). However, critical infrastructure such as the Latrobe Valley power stations, Gippsland Basin oil and gas infrastructure, and the Otway CO_2 capture and storage facilities, have much greater exposure. A predominance of folding at the surface rather than discrete surface faulting (see Figure 4C) results in an absence of single event slip or large earthquake recurrence data for any faults proximal to Melbourne. However, examples from analogous crust elsewhere in the world suggest that large earthquake recurrence rates might be in the few thousands (Charleston Seismic zone, Talwani & Schaeffer 2001), even hundreds (New Madrid Seimic Zone, Tuttle *et al.* 2005) of years.

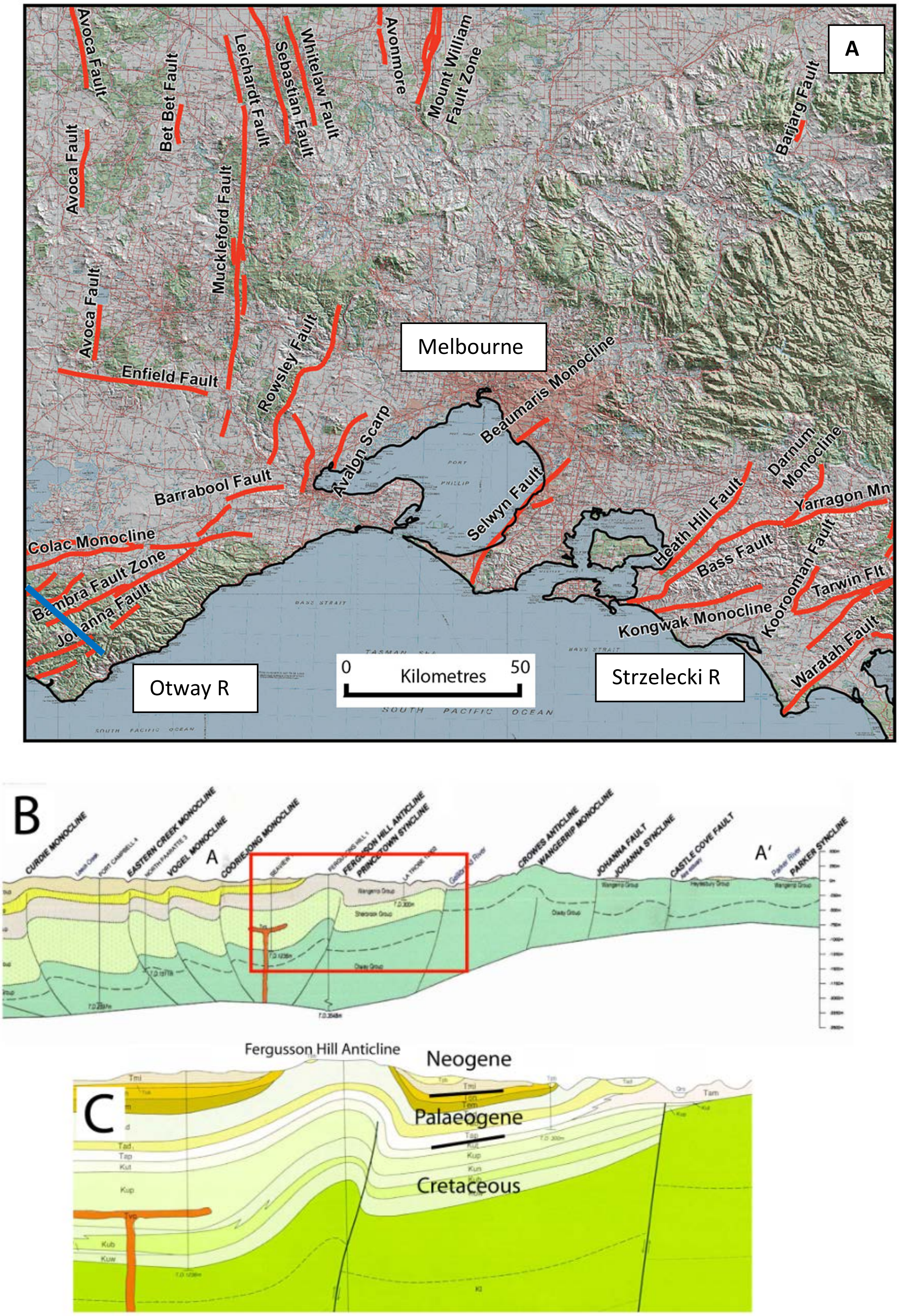

Figure 4. Neotectonic faults proximal to Melbourne (see Fig 1 for location). (A) map of neotectonic fault traces, (B) NW-SE cross section through the Otway Ranges showing inverted rift basin structure (after Edwards *et al.* 1996) - location shown by blue line in (A), (C) detail of stratigraphy folded over the Fergusson Hill Anticline (after Tickell *et al.* 1992).

Perth

The ~900 km long Darling Scarp in Western Australia is one of the most prominent linear topographic features on Earth. Despite the presence of over-steepened reaches in all west-flowing streams that cross the scarp, there is no historical seismicity and no reported evidence for Quaternary tectonic displacements on the underlying Darling Fault (except perhaps for the unproven Serpentine Scarp – see Fig 5 and Appendix). Measurements of the cosmic-ray produced nuclide beryllium-10 from outcropping bedrock surfaces along the scarp summit and face, in valley floors, and at stream knick-points indicate that ongoing maintenance of disequilibrium longitudinal stream profiles is consistent with slow, regional scale base-level lowering associated with recently proposed continental-scale tilting (Sandiford 2007), as opposed to differential uplift along discrete faults (Jakica *et al.* 2010, Quigley *et al.* 2010) (Figure 2). Fault slip rates in the order of 5-10 m/Myr on this fault system would likely be beneath the detection limit of the cosmogenic radionuclide method, and could be removed by erosion such that tectonic relief is not generated.

Significant seismicity has been documented to the east of Perth in the Yilgarn Craton (i.e. the SW seismic zone, Doyle 1971), within 100 km of the CBD, including the 1968 Ms6.8 Meckering earthquake (Gordon & Lewis 1980). As relief is not being generated in this area, and bedrock erosion rates are in the order of 5 m/Myr (Belton *et al.* 2004), it is unlikely that seismogenic faults with long-term slip rates exceeding the erosion rates exist in this environment. However, rare paleoseismological studies indicate that morphogenic earthquake recurrence during an active period on an individual fault could be as low as ~10 kyr (Estrada 2009). The active fault catalogue from the SW Yilgarn Craton (Clark 2010, Leonard & Clark 2011) is likely to comprise only faults that have been active in the last ~100 kyr.

Normal faults reactivated in compression are known from both the onshore and offshore Perth Basin (Figure 5). The neotectonic record for the onshore environment is highly incomplete, as dune fields obscure the Perth coastal plain. Kink faulted dune deposits ~500 kyr old are known from one instance in a quarry wall near Jurien (Mory 1994), ~ 185 km north of Perth. As this feature does not have a traceable surface expression, there is no reason to believe that similar features do not occur closer to Perth. In the near offshore Perth Basin, some faults of the Badaminna Fault Zone are seen to host up to ~ 20 m of post-Mid Miocene displacement (Borissova *et al.* 2014). While being potential sources of strong ground motion, these faults are unlikely to support long-term uplift rates of greater than 2-5 m/Myr. However, by analogy with the Charleston Seismic zone in the eastern United States (Talwani & Schaeffer 2001), it is possible that damaging ground-shaking from large earthquakes in this region may recur with a frequency of hundreds to a few thousand years.

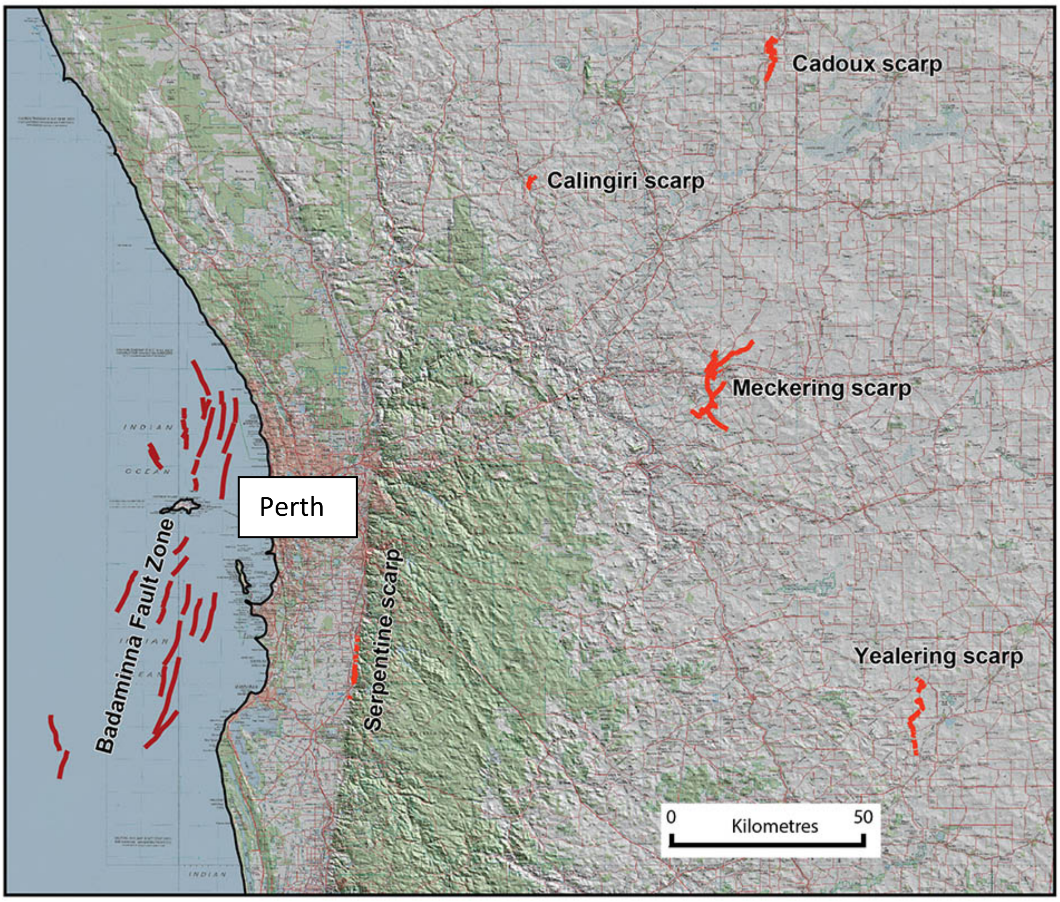

Figure 5. Neotectonic faults proximal to Perth in both the Yilgarn Craton (east of Perth) and near offshore Perth Basin (see Fig 1 for location). Offshore faults from Borissova *et al.* (2014).

Sydney

Faults of the Lapstone Structural Complex (LSC) have been identified as being the most likely source of future large earthquakes in proximity to Sydney (Clark 2009) (Figure 6A). Slip rates on individual faults comprising the complex have largely remained elusive. Work on the Kurrajong Fault at Mountain Lagoon suggests that only 15 m of the 130 m total throw of the fault has accrued in the last 18.8 Ma (Clark *et al.* 2009, McPherson *et al.* 2012b, 2014). It is proposed that approximately 6-7 m of this relief generation occurred in the Mid Pleistocene (≥170 - 200 ka). It is possible, but not proven, that the remainder accrued in the interval 10-5 Ma, coincident with a widespread period of fault activity in SE Australia (Dickinson *et al.* 2002, Sandiford *et al.* 2004).

A link between the west-facing scarps (including the Kurrajong Fault scarp), and the east-facing Lapstone Monocline has not been demonstrated. However, it is plausible to assume a linkage as shown in Figure 6B. The 130 m of throw across the Kurrajong Fault relates to ~400 m of structural relief across the Lapstone Monocline. If this ratio is assumed to be preserved, ~ 15 m of Neogene and younger throw on the Kurrajong Fault might relate to ~46 m of throw on the Lapstone Monocline, with ~21 m occurring in the mid Pleistocene. This number should be treated with caution. Paleomagnetic ages obtained from the Lapstone Monocline suggest that folding had ceased prior to 8±5 Ma (Pickett & Bishop 1992, Pillans 2003). The implication is that the ~21 m of mid Pleistocene throw must have been accommodated by slip along the fault plane (i.e. the Lapstone Monocline is breached). No field evidence has been found to support this possibility. The data, while not compelling, are consistent with slip rates on the Kurrajong Fault of 1.5–3 m/Myr in the last 10–5 Ma, and on the Lapstone Monocline of 5–9 m/Myr. Rates might be half these values within the uncertainty of the constraints. The evidence for a pulse of mid Pleistocene activity suggests that rates might be much greater than the long-term average for brief periods. More research is required to constrain the ages of events comprising the last active period on these faults.

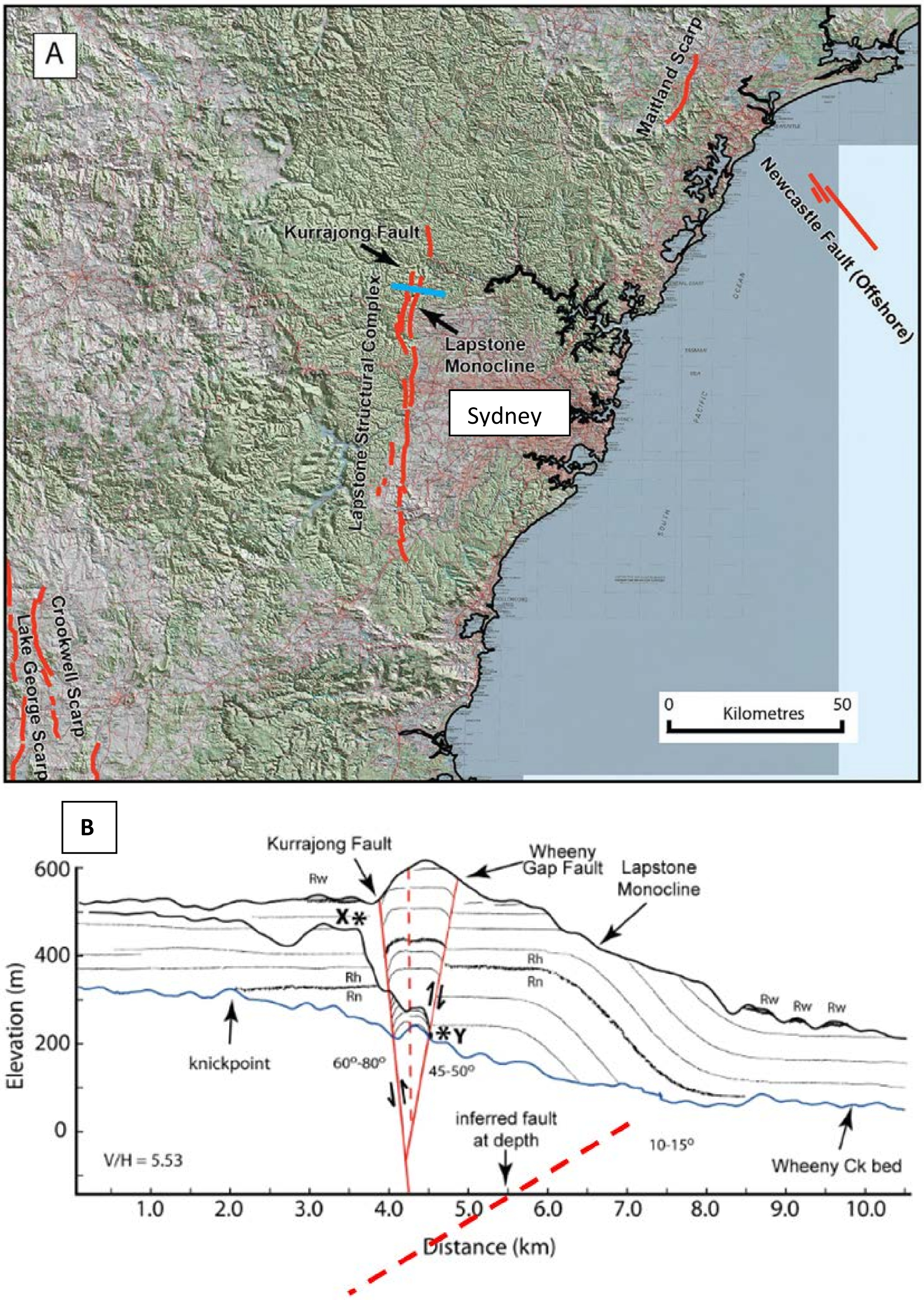

Figure 6. (A) Neotectonic faults proximal to Sydney (see Fig 1 for location). (B) section through the LSC at Bilpin (blue line in A) showing rock relationships and inferred fault structure (after Clark & Rawson 2009).

Using the seismic moment release rate and the estimated number of faults that exist in the Sydney geographic basin east of the LSC, Berryman *et al.* (2009) obtain a mean interval for recurrence of reverse faulting (M5-6 earthquakes) on any single structure as several million years. These events are unlikely to be morphogenic, and so, while potentially damaging, are beyond the scope of this paper and are not further considered.

At the northern margin of the Sydney Basin, where it is faulted against the New England Fold Belt, warping of Miocene strata during the Pleistocene has resulted in the formation of a monocline of 30 m amplitude (Huftile *et al.* 1999) (Newcastle Offshore Fault, Figure 6A). This ~33 km long northwest trending structure occurs along strike of the Hunter Thrust system, and close to the epicentre of the 1989 M5.6 Newcastle earthquake. An uplift rate of ~11 m/Myr can be estimated for this fault. A linear escarpment oriented at a high-angle to the Hunter Thrust system occurs at Maitland (Figure 6A). It is not known if this feature is fault-related.

COMBINING FAULTS AND ZONES FOR PSHA MODELLING:

Over the last several decades there have been extensive discussions on how faults should be incorporated into Probabilistic Seismic Hazard Assessments (PSHA). The idea that the statistics describing fault behavior are better described as Characteristic rather than Gutenberg-Richter has been around for 30 years (Aki 1984, Schwartz & Coppersmith 1984, Youngs & Coppersmith 1985). In the Characteristic model, faults tend to rupture in large earthquakes which occupy 50% to 100% of the fault length, with very few small earthquakes occurring on the fault. The approach is mostly used to combine historical seismicity in the region with geologically derived slip-rates and/or recurrence intervals on individual faults. In a review paper Ben-Zion & Sammis (2003) cite 20 studies covering many different regions which all fitted a Characteristic rather than a Gutenberg-Richter Magnitude Frequency Distribution (MFD). The evidence is not clear cut with various papers arguing that many particular faults/earthquakes do not fit the Characteristic model (e.g. Kagan *et al.* 2012). One of the many objections to the Characteristic model is that it has apparently led researchers to divide long faults into subsections thereby excluding the possibility of multiple segments rupturing in a single large earthquake (e.g. 2011 Tohoku, Kagan & Jackson 2013). Hecker et al. (2013) analyse a composite global data set of paleoseismic observations and find that the data is more consistent with a Characteristic than a Gutenberg-Richter model.

In several recent studies of the Flinders/Mt. Lofty Ranges (Pilia *et al.* 2013, Love 2013) no correlation between instrumental seismicity and known faults has been identified. Similarly no clear relation has been identified between seismicity and known faults in East Gippsland (Brown & Gibson 2004, Gibson & Dimas 2012), and there is little correlation between local seismicity and either the Darling Fault or the Lapstone Monocline (e.g. Leonard 2008). This is consistent with a Characteristic rather than a Gutenberg-Richter model of fault seismicity. In PSHA it is common practice to combine Characteristic faults with G-R zone sources (e.g. California: Field et al., 2009, 2014, Working Group on California Earthquake Probabilities, 1995, 2003; Italy: Romeo, 2005; Central and Eastern US: Petersen et al., 2008, 2014). For both the Meers fault in Oklahoma and the Cheraw Fault in eastern Colorado a Characteristic fault model is adopted for the US NSHM (Petersen *et al.* 2014).

As the evidence from Australia suggests that a Characteristic fault model is more appropriate than a Gutenberg-Richter model, and this is the approach adopted by the USGS for the US stable continental region faults (Petersen *et al.* 2014), we adopted the Characteristic fault model for this study. Accordingly, we keep the existing Leonard *et al.* (2013) regional zonation model and add the individual fault sources as Characteristic models. The EQRM software uses the formulation of Youngs and Coppersmith (1985) to generate the MFD, from the slip rate, Mmax and Mmin provided. The Mmax is calculated from the full fault length using the scaling relation of Leonard *et al.*(2014).

Currently temporal clustering in large earthquake occurrence has not been built into the modelling process. In the final section of this paper, we invite discussion regarding how best to model Australia's unique seismo-tectonic environment. The slip rates used are typically upper limit estimates from point sources along the faults, averaged across displaced geologic strata of various ages (see Appendix). This approach might underestimate hazard if the fault is in an active period, and will overestimate hazard at other times (refer to Figure 1C).

RESULTS; EFFECT OF SIMPLE FAULTS ON HAZARD CALCULATIONS:

For the Characteristic Model the zone source layer is unchanged and the fault source layer is added in as an additional source of earthquakes. As such, the inclusion of faults will always lead to an increase in seismic hazard. Due to the low slip rate of the faults in Australia, a single fault has minimal impact on the hazard. For example, the Selwyn Fault, on the eastern edge of Port Phillip Bay (Figure 7), increases the 2500 year Peak Ground Acceleration (PGA) by 10–20%. In contrast, where several faults converge the hazard increases by up to 100%. This also seen around Adelaide (Figure 8) where the single faults to the north and east have a small impact on the hazard but in the southern suburbs of Adelaide, where multiple faults converge, there is a significant increase in hazard.

For the purposes of this modeling exercise, both Perth and Sydney have only a single proximal fault, the Darling and Lapstone respectively. While both are long faults capable of hosting a M 7.5 earthquake, their low slip rate (< 10 m/Myr) results in a very small contribution to the overall hazard (see Appendix).

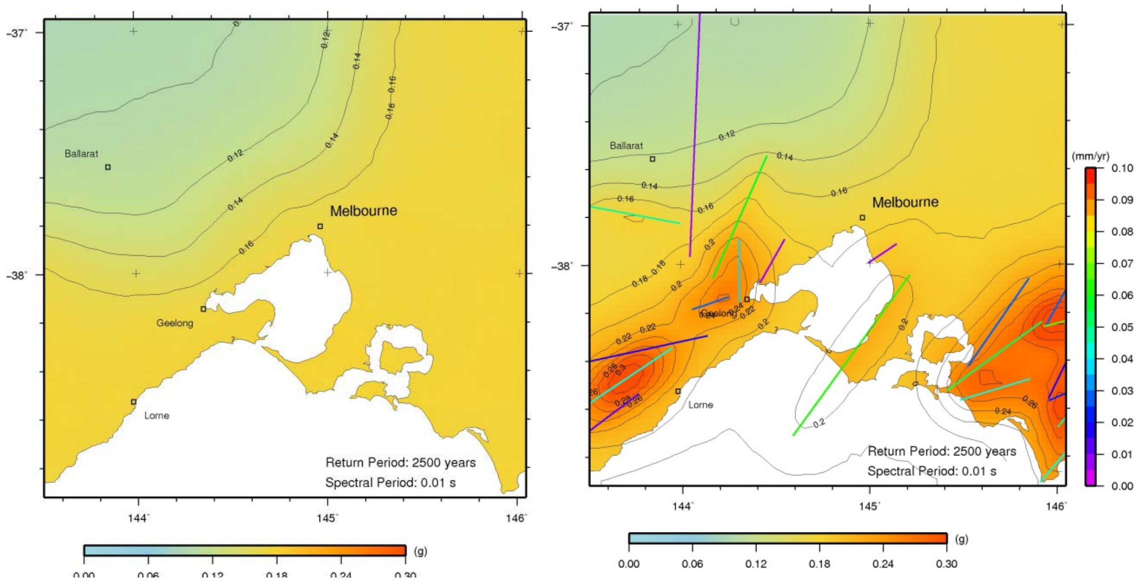

Figure 7 The impact on the 2500 year hazard of including fault sources for hazard estimation in the Melbourne region. The faults are considered Characteristic and have been added to the Leonard *et al.* (2014) source zone without any adjustment of the source zone recurrence parameters (a, b, Mmax).

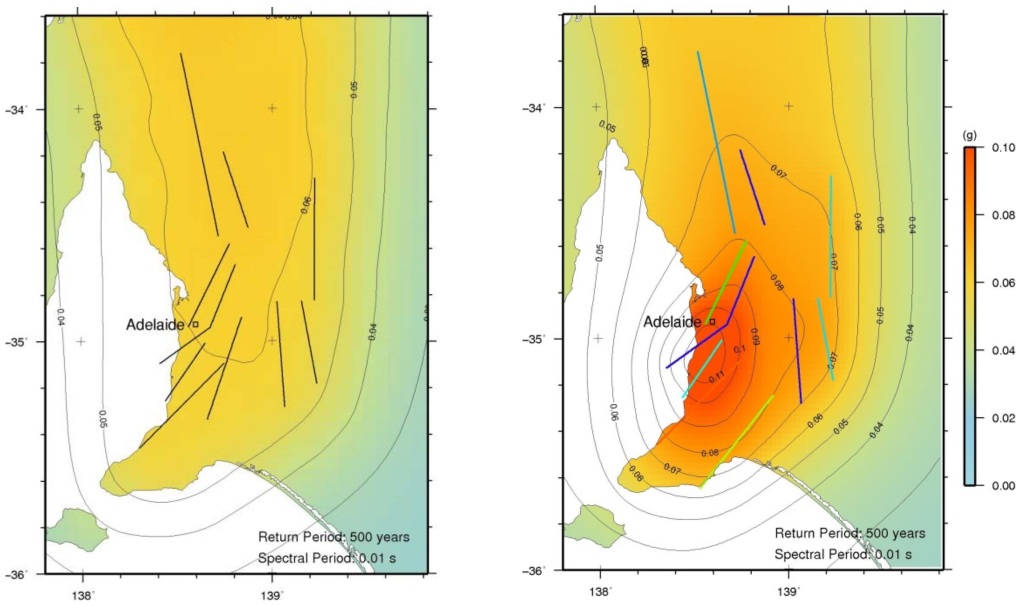

Figure 8 500 year PGA around Adelaide with and without faults. Faults added as in Figure 7

Table 1 Estimated hazard for five Australian cities with and without faults.

	500 year			2500 year		
Location	Zone only PHA(g)	Zone + Faults PHA (g)	Diff.	Zone only PHA(g)	Zone + Faults PHA (g)	Diff.
Adelaide	0.061	0.115	88%	0.163	0.310	91%
Melbourne	0.061	0.067	10%	0.166	0.172	4%
Perth	0.050	0.051	1%	0.146	0.150	3%
Sydney	0.062	0.063	2%	0.164	0.169	3%
Geelong	0.061	0.81	32%	0.167	0.25	50%

DISCUSSION; THE FUTURE OF ACTIVE FAULT SOURCES IN THE AUSTRALIAN NSHM:

Our modelling suggests that long-term average slip rates on individual Australian neotectonic faults are not typically large enough to significantly influence probabilistic seismic hazard assessments for short return periods (e.g. 10% chance of exceedance in 50 years level). However, a combination of multiple proximal fault sources with slip rates in the tens of metres per million years can contribute several tens of percent or more to hazard calculations (cf. Somerville *et al.* 2008) (Figures 7 & 8 and Table 1). Based on the current work, Adelaide is the only capital city in Australia where the inclusion of faults significantly increases the hazard. In this modelling we have added the Characteristic Faults to the source zone layer and applied a consistent Mmin (i.e. M 5.0) to the source zone layer. It could be argued that it would be more reasonable not to include smaller earthquakes (e.g. < M 5.0) on the fault and/or reduce the Mmax of the source zone (e.g. reduce Mmax from M 7.5 to 7.0 for the Adelaide source zone). The argument for this decision is that these small earthquakes are in the earthquake catalogue so they are already included in the source zone.

The hazard maps generated by applying these parameters are shown in Figure 9. For Adelaide this parameterisation gives a 500 year PGA of 0.075 g, which is approximately the mean of the source zone (0.061 g) and the source zone plus Characteristic faults (0.09) models. At 500 and 2500 year return periods the final hazard is most sensitive to changes in the Mmin of the fault rather than changes to Mmax of the source zone. In this exercise we have assumed a long-term average slip rate. The issue of how to model faults when applying an active-quiescent model of fault activity has not yet been discussed in the scientific literature. For example, if a fault is in an active phase perhaps Mmin should be set to a higher value (e.g. Mmax-[1.0 or 2.0]) but during quiescence perhaps Mmin should be set to a low value (e.g. M 4.5)). In this context perhaps using a low value of Mmin for the average rate is reasonable.

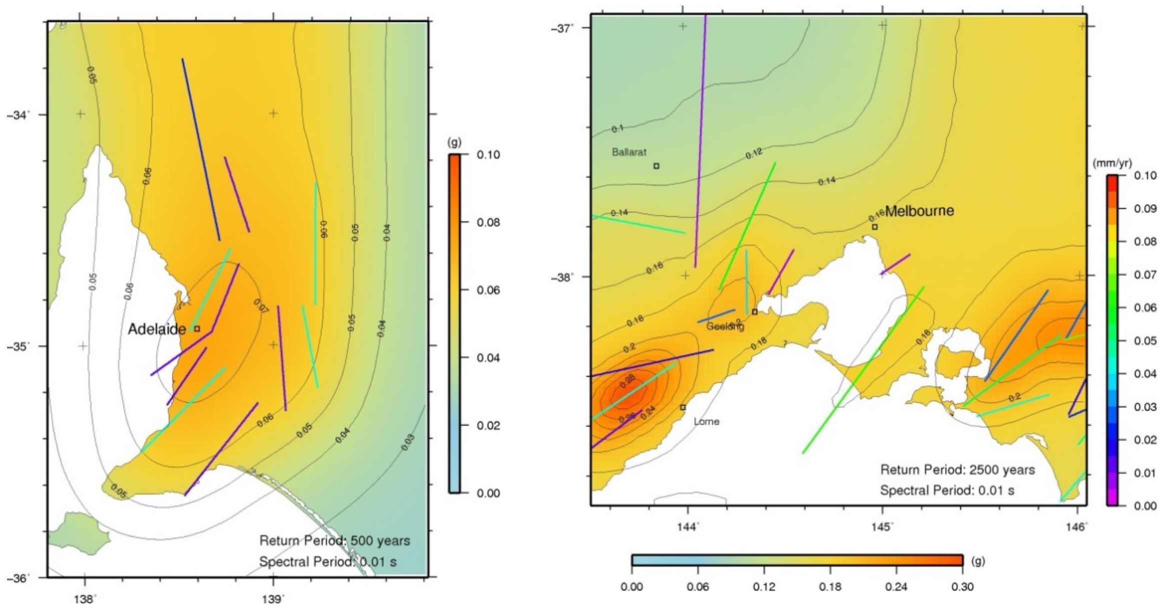

Figure 9 Hazard where the Mmax of the zone source has been lowered lowered by 0.5 and the Mmin of the faults set to 5.0.

The question remains as to whether a 'long-term' slip rate on a fault is a meaningful quantity for seismic hazard purposes if the fault is either 'on' (i.e. slipping at much greater than this rate) or 'off' (slipping at a fraction of this rate) (see Figure 1C). For example, the same long-term slip rate estimate would be obtained across a common geologic unit for a fault that slipped X metres between 100 ka and 50 ka (and is now quiescent), as for a fault that slipped X metres between 50 ka and the present (and remains active). Figure 1C also illustrates the variation in long-term slip rate that is possible depending upon the age of the geologic strata that is displaced (cyan line vs green line). A further complication arises if slip rate varies along the length of a fault as the result of strain sharing between proximal faults. What value should be used to represent the fault as a whole?

The 2014 United States National Seismic Hazard Map (USNSHM), covering the intraplate Central and Eastern US (CEUS), includes ten fault-based characteristic or repeating large magnitude earthquake (RLME) sources (Petersen *et al.* 2014). The geometric and seismicity characteristics of these sources were compiled as part of a four year study conducted for the US Nuclear Power industry (CEUS–SSCn 2012). Each of the sources contribute to the hazard at both the 2 percent probability of exceedance in 50 years, and the 10 percent probability of exceedance in 50 years level, for a Vs30 site condition of 760 m/s (Petersen *et al.* 2014, Figures 7-12). Weightings are given to both periodic characteristic and temporally clustered rupture models (Figure 10).

Long-term (e.g. over the entire Quaternary Period or longer) average slip rates on individual active faults are typically not known from the CEUS, with return period estimates and magnitudes for each source being based upon historic and/or paleoseismic data from the most recent few large magnitude events on/within the source over the last few tens of thousands of years at most (e.g. Crone & Luza 1990, CEUS–SSCn 2012). Perhaps a dozen faults in the Australian setting are documented to a comparable level of detail, with long-term (≤5-10 Myr) slip rates being known for many more Australian faults (Quigley *et al.* 2006, Estrada 2009, Quigley *et al.* 2010, Clark *et al.* 2011a, Clark *et al.* 2011c, Clark *et al.* 2012). Comparison of CEUS and Australian recurrence values for large earthquakes in analogous crustal settings (e.g. Johnston 1994, Clark *et al.* 2012) suggests that the values adopted in the 2014 USNSHM relate to 'active period' data from faults that show pronounced temporal clustering of large earthquake events. Even so, recurrence times for large events in the hundreds of years, as is arguably the case for the New Madrid Seismic Zone of the Eastern United States (cf. Tuttle *et al.* 2005, Hough 2014), are not yet known from Australia.

In the absence of sufficient data to definitively drive a model, the approach used in the 2014 USNSHM (Petersen *et al.* 2014), which effectively weights active period (short-term) slip rates and characteristic magnitude rupture (Figure 10), seems reasonable, and avoids the problems associated with long-term slip rates mentioned above. In the Australian context, faults that are associated with youthful relief are most plausibly in an active period. This is because quiescent intervals can be sufficiently prolonged, in the western and central parts of Australia in particular, such that most or all relief relating to an active period might be removed by erosion prior to the next active period (Crone *et al.* 2003, Clark *et al.* 2008, Clark *et al.* 2014b). In regions of higher neotectonic uplift rate, such as the inverting Mesozoic basins (Otways, Gippsland, Carnarvon), active period relief may not be completely removed in a quiescent period, but the youthfulness of the relief will be noticeably degraded. A hybrid model that recognises that long-term slip rates are often the only data available for a group of Australian faults, and weights active, quiescent *and* long-term slip rates, has been used for hazard assessment in the Otway Basin with some success (Stirling *et al.* 2011).

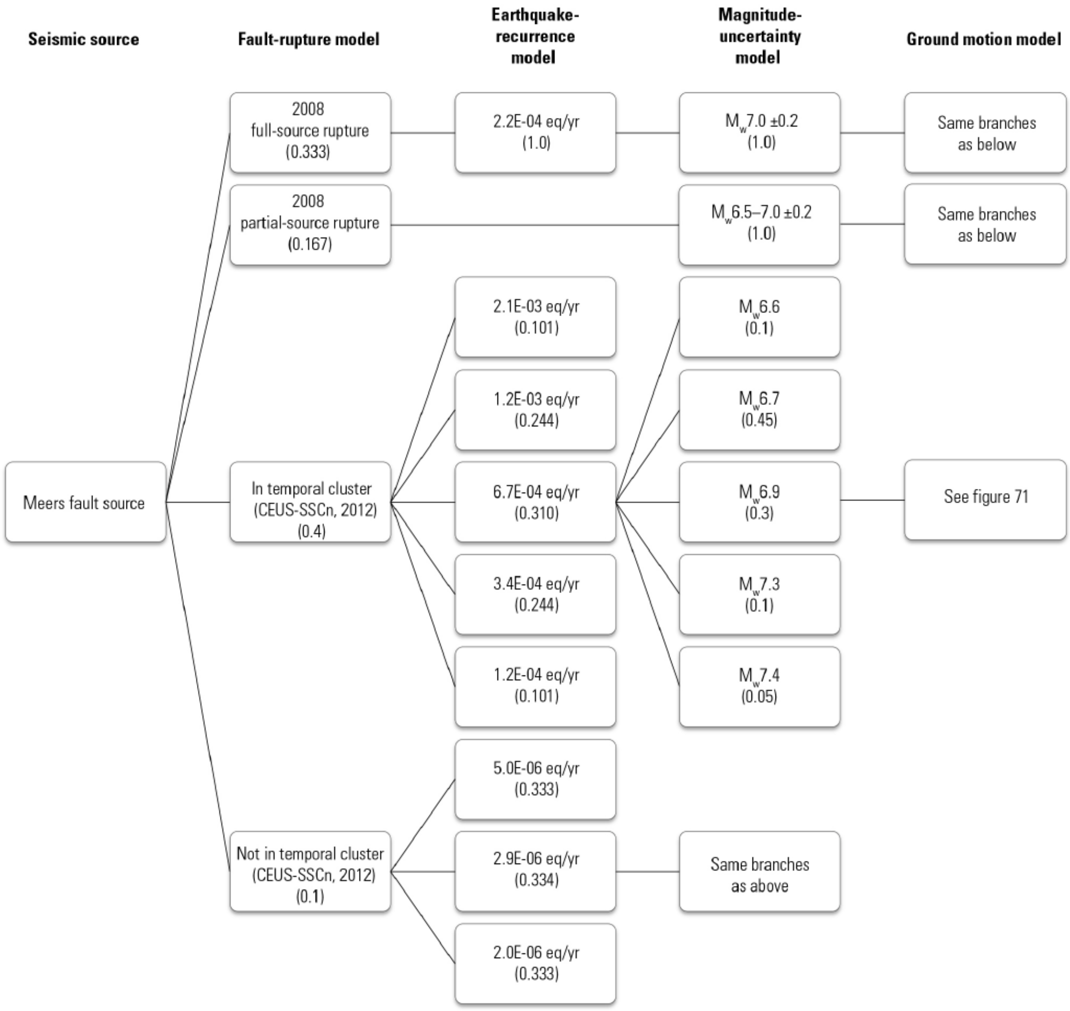

Figure 10. Logic tree for the Meers fault source (from Petersen *et al.* 2014, Figure 31). Value given in "Earthquake-recurrence model" branch is number of earthquakes per year (eq/yr). Assigned branch weight shown in parentheses.

CONCLUSIONS AND AN INVITATION:

Four of Australia's largest five population centres (i.e. Sydney, Melbourne, Perth, Adelaide) are topographically constrained by prominent escarpments underlain by faults or fault complexes capable of hosting damaging earthquakes. Regional variation in the location, arrangement and large earthquake recurrence characteristics of these faults leads to very different forecasts of seismic hazard levels at each of these conurbations. Our modelling suggests that long-term average slip rates on individual Australian neotectonic faults are typically not large enough to significantly influence probabilistic seismic hazard assessments for short return periods (e.g. 10% chance of exceedance in 50 years level). However, a combination of multiple proximal fault sources can contribute several tens of percent or more to hazard calculations (e.g. Somerville *et al.* 2008). In this context, Adelaide and Melbourne might be considered to be exposed to a greater hazard than Perth and Sydney.

Australia has a rich intra-plate neotectonic fault record with which to inform national probabilistic seismic hazard mapping – far richer than that employed in the 2014 USNSHM. Unfortunately, that record suggests significant complexity in large earthquake recurrence behavior that needs to be accounted for in order to defensibly include fault sources in future iterations of the Australian NSHM (e.g. see Figure 10). Preliminary modelling presented herein suggests that Australian faults can have a significant impact on estimates of seismic hazard, and we invite the earthquake research community to provide input into how to develop more robust models to capture this..

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APPENDIX TABLE – FAULT SLIP RATE DATA USED IN OUR MODELS:

Fault/Monocline	length km	dip	dip direction	uplift rate* m/Myr	slip rate m/Myr
Melbourne					
Avalon	23	50	W	6	8
Avoca				-	
Bambra	52	50	SE	4	5
Barabool	25	60	SE	30	35
Bellarine				-	
Bet Bet				-	
Castle Cove	22	60	NW	12	14
Colac	51	60	SE	25	29
Cooriejong	11	60	NE	4.9	6
Curdie	24	60	SE	20	23
Curlewis	17	60	S	3.6	4
Enfield	45	60	N	50	58
Fault 2	16	60	S	15	17
Fault 4				-	
Fault 5	27	50	W	10	13
Fault 7	20	60	NE	12.5	14
Fergusson Hill	39	60	NW	58	67
Johanna	44	60	NW	13	15
Love Creek				-	
Lovely Banks	31	50	W	35	46
Mt Ararat/Stawell				-	
Muckleford	116	50	W	5	7
Pirron Yallock	36	60	S	12.5	14
Rowsley	70	50	W	55	72
Selwyn	97	60	E	50	58
Simpson	27	60	N	12.5	14
Bass/Almurta	58	50	S	50	65
Beaumaris	13	50	NW	8	10
Budgeree	25	60	S	20	23
Carrajung	23	60	S	25	29
Darnum	25	50	NW	18	23
Darriman	34	60	N	38	44
Doomburrin	28	60	SE	42	48
Geoliondale	22	60	N	50	58
Haunted Hills	19	70	W	17.5	19
Heath Hill	50	50	SE	25	33
Kongwak	33	60	N	50	58
Koorooman	32	60	N	15	17
Morwell	30	60	W	43	50
Napier	12	60	NW	50	58

Rosedale	78	60	S	80	92
Selwyn	97	50	E	50	65
Snake Ridge	37	60	SSE	50	58
Tap Tap	14			-	
Tarwin	32	60	N	25	29
Toora	14	60	N	50	58
Waratah	37	60	NW	40	46
Wonwron	30	50	N	40	52
Yallourn	64	50	N	100	131
Yarragon	32	60	S	90	104
Yarram	53	60	NNW	112	129
Adelaide					
Alma	93	50	E	25	33
Ardrossan (Pine Point)	111	50	W	2.5	3
Bremer	46	50	E	12.5	16
Burra	57	36	W	10	17
Coobowie	13	50	W	3	4
Crystal Brook	64	60	E	50	58
Eden-Burnside	53	60	E	16	18
Encounter Bay	79	60	NW	64	74
Meadows-Williamstown (Kitchener)	38	60	E	15	17
Milendella	55	50	W	30	39
Morgan	172	50	W	5	7
Ochre Cove-Clarendon	33	60	E	36	42
Owen	24	60	E	64	74
Palmer	42	50	W	30	39
Para	43	60	E	53	61
Redbanks	47	60	E	32	37
Sandergrove	43	60	E	15	17
Willunga	55	60	SE	80	92
Worlds End	30	48	E	15	20
Yorketown	23	60	E	8	9
Perth					
Darling (Serpentine scarp)	19	60	W	5	6
Sydney					
Kurrajong	28	70	E	3	3
Lapstone	30	45	W	9	13
Newcastle offshore	33	50	SW	11	14

* slip rates are mostly high end estimates of the long term rates. Contact the authors for individual fault notes, and for low end estimates. Faults highlighted yellow are considered potentially active, but no slip rate data exists.

APPENDIX – SUPPLEMENTARY FIGURES:

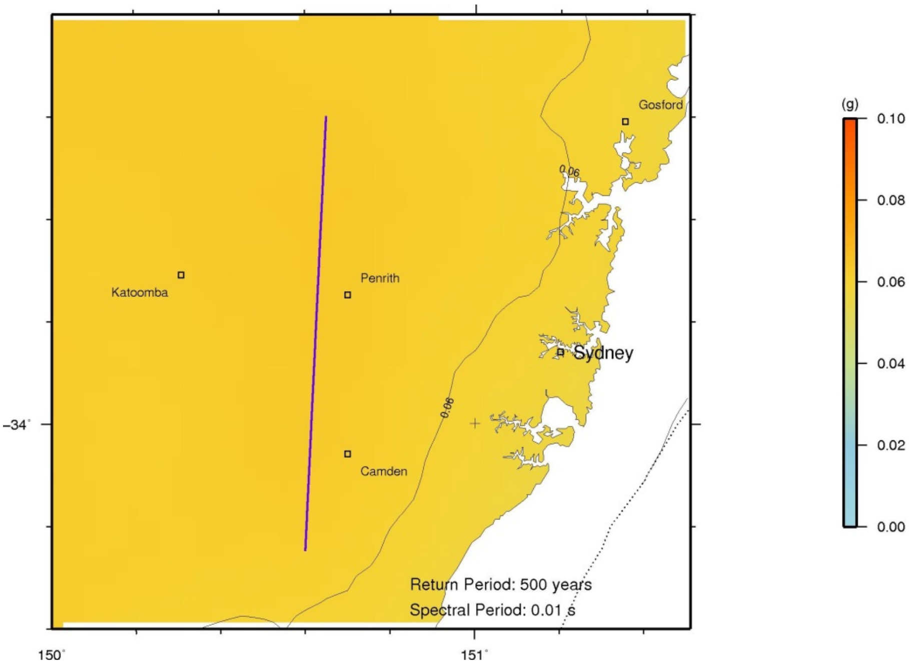

Figure A1 - The impact on the 500 year hazard of including faults in the regional around Sydney. The faults are considered Characteristic and have been added to the source zone without any adjustment of the source zone recurrence parameters (a, b, Mmax)

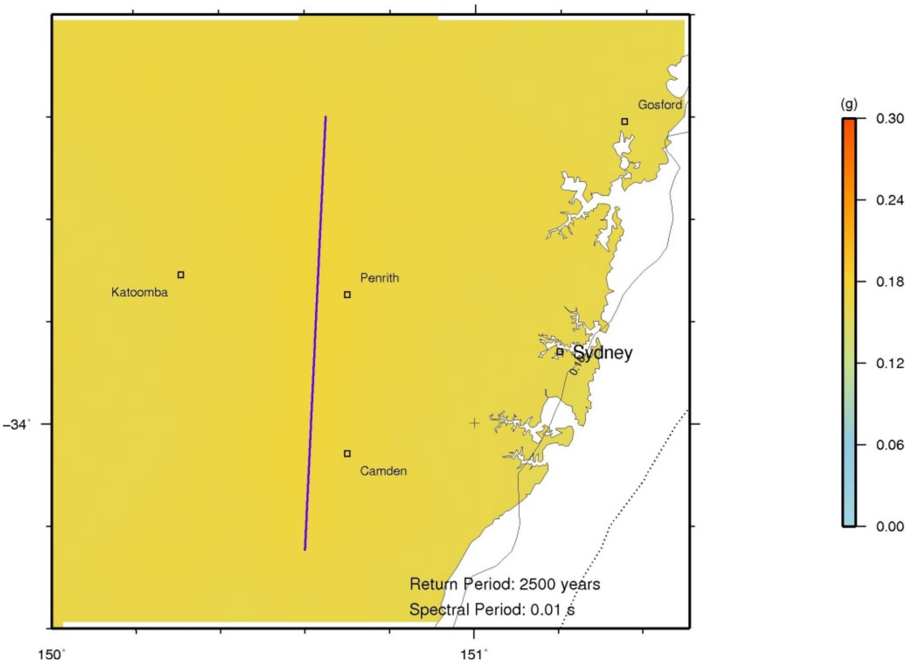

Figure A2 - The impact on the 2500 year hazard of including faults in the regional around Sydney. The faults are considered Characteristic and have been added to the source zone without any adjustment of the source zone recurrence parameters (a, b, Mmax)

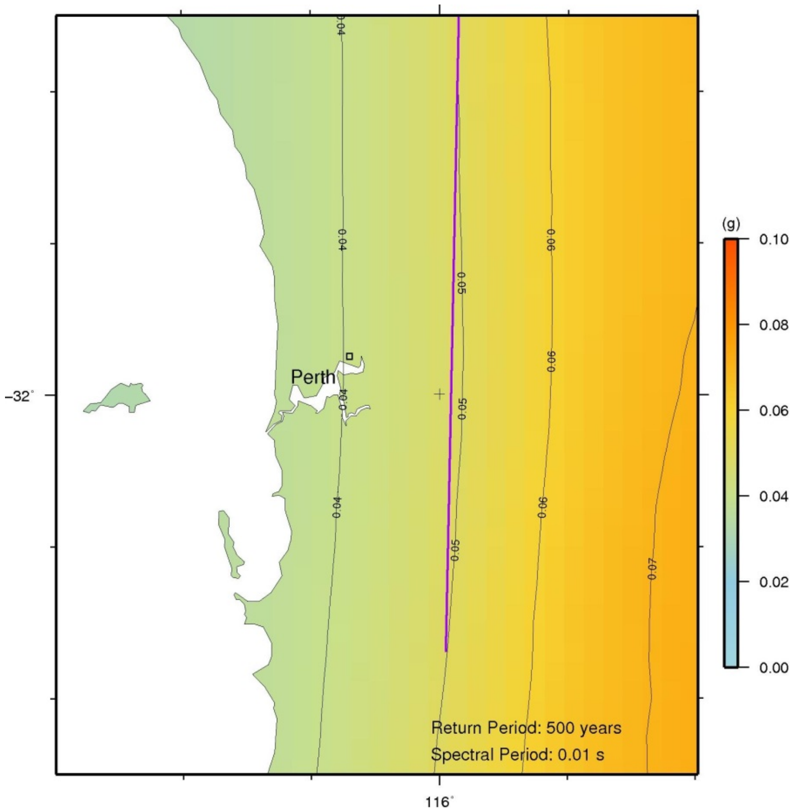

Figure A3 - The impact on the 500 year hazard of including onshore faults in the regional around Perth. The faults are considered Characteristic and have been added to the source zone without any adjustment of the source zone recurrence parameters (a, b, Mmax)

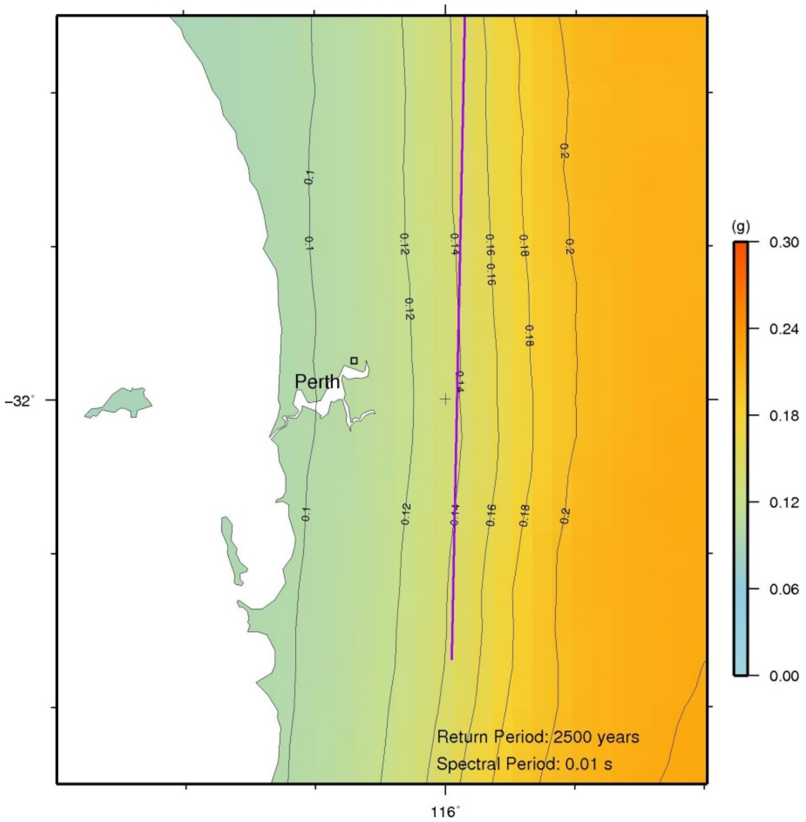

Figure A4 - The impact on the 2500 year hazard of including onshore faults in the regional around Perth. The faults are considered Characteristic and have been added to the source zone without any adjustment of the source zone recurrence parameters (a, b, Mmax)