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Do Australian intraplate faults generate characteristic earthquakes?

D.J. Clark & M. Leonard

Community Safety Group, Geoscience Australia, GPO Box 378 Canberra, ACT, 2601, Australia.

ABSTRACT: In probabilistic seismic hazard modelling the choice of whether faults are attributed with Characteristic or Gutenberg-Richter recurrence statistics has a major impact on the calculated hazard level proximal to the faults. Compared to a model that does not include fault sources, the addition of a high slip rate (by intra-plate standards) Characteristic fault results in a significant increase (+58%) in hazard for a 500 year return period event, and similar increases for events at longer return periods (i.e. ≥2500 years). In contrast, the addition of a Gutenberg-Richter fault with the same slip rate will result in an increase in predicted peak ground acceleration (PGA) almost twice that of a Characteristic fault at 500 years, decaying to a similar increase in PGA at very long return periods (i.e. ≥10,000 years).

Results from inter-plate and active intra-plate paleoseismological investigations have been used to suggest that earthquakes recurrent on a given fault often have the same characteristic rupture length and slip (i.e. a Characteristic Rupture Model). The scarcity of data precludes definitive validation of the model in Australian Stable Continental Region crust. However, preliminary indications are that a Characteristic Rupture model has some merit in cratonic regions of the country while faulting in non-cratonic regions may be more complex. In view of evidence for episodic rupture, the practise of using an average earthquake recurrence interval based upon a long-term slip rate should be critically examined.

1 INTRODUCTION

In the last two decades a number of intra-plate faults within Australia have been identified as being capable (cf. Clark, 2009; Machette, 2000) of generating recurrent large magnitude earthquakes (Clark *et al.*, 2011a; Clark *et al.*, 2012). The future contribution that these faults make to probabilistic seismic hazard assessments, both at an infrastructure and national scale, will depend in part on the choice of recurrence model assigned to describe seismicity on these faults. Two classes of recurrence model are considered herein; Gutenberg-Richter (Gutenberg & Richter, 1944) and Characteristic (Schwartz & Coppersmith, 1984; Wesnousky *et al.*, 1983). A third, as yet poorly parameterised model, accounting for pronounced episodic rupture behaviour (Clark *et al.*, 2015; Clark *et al.*, 2012), is discussed as a modifier to the above models with implications for how long-term slip rates should be understood in the intra-plate environment.

After introducing the models and their associated assumptions, we discuss Australian paleoseismic indicators that might be used to decide between the models. Examples of the significance of the choice of model for a simple study of the Adelaide region are provided. A detailed comparison of instrumental seismicity and 'active' fault data is not presently feasible for much of Australia owing to a paucity of data.

2 MODELS DESCRIBING RECURRENCE ON SEISMOGENIC FAULTS FOR PSHA

It is widely accepted, across a range of tectonic settings, that the magnitude–frequency distribution of earthquakes in a broad region generally satisfies the Gutenberg-Richter (G-R) relation: $\log N = a - b \times M$, where N is the number of earthquakes with magnitude greater than or equal to M and a and b are empirical constants (Gutenberg & Richter, 1944). It is also common to apply the G-R relation to seismicity on a single fault or fault segment. The inherent assumption is that during the period between maximum magnitude earthquakes on a fault (M_{max}), slip is also accommodated by the occurrence of smaller earthquakes that obey the G-R relation, up to the limiting value of M_{max} (Figure

1a). A full distribution of earthquake sizes (i.e. slip magnitudes) might be expected to occur randomly along the length of a fault (Variable slip model, Figure 2a), and because of a lack of permanent barriers or segments the fault will tend through time to distribute slip evenly along its length (Schwartz & Coppersmith, 1984).

A number of studies report that seismicity around a fault or fault system does not satisfy the G-R relationship across the entire magnitude range for one complete earthquake cycle (Schwartz & Coppersmith, 1984; Schwartz & Page, 2010; Stirling *et al.*, 1996; Wesnousky, 1994; Wesnousky *et al.*, 1983; Youngs & Coppersmith, 1985). These studies are interpreted to indicate that there is a gap between the largest event (called the characteristic event) and other events in magnitude-frequency distributions. The characteristic earthquake (CE) model postulates that individual faults and fault segments tend to generate essentially the same size (characteristic) earthquakes having a relatively narrow range of magnitudes near the maximum (Schwartz & Coppersmith, 1984). Stable asperities and barriers, which survive many earthquakes, are proposed to explain these results (Aki, 1984). The model implies that the characteristic earthquakes are occurring at the expense of the moderate-magnitude events. This does not mean that moderate-magnitude events smaller than the characteristic earthquake never occur on individual faults or fault segments; rather their frequency of occurrence is less than would be expected by a recurrence curve passing through the characteristic magnitude and having *b* value of ~1.0 (Schwartz & Coppersmith, 1984) (Figure 1b).

A subclass of the CE model, denoted the Maximum Magnitude Model, states that faults or fault segments generate earthquakes of a characteristic size that is a function of fault length and tectonic setting, and that these characteristic events, together with their foreshocks and aftershocks, account for all the seismic slip on the fault (Allen, 1968; Wesnousky, 1994; Wesnousky *et al.*, 1983). The period between maximum magnitude earthquakes along particular fault zones or fault segments is quiescent, except for the occurrence of foreshocks, aftershocks, and generally low-level background activity. This implies that in regional scale studies of seismicity the primary factors driving the occurrence of a G-R magnitude frequency distribution are the relative distribution of the slip rates and lengths of pre-existing faults (Wesnousky *et al.*, 1983). This phenomenon has been demonstrated in the Australian context for a catalogue of large events (N = 150) derived from paleo-earthquake data covering much of the Southwest Seismic Zone of Western Australia (Leonard & Clark, 2011). These authors show that their paleo-earthquake catalogue follows a typical truncated G-R recurrence distribution (Johnston, 1994; Kagan, 2002; Mazzotti & Adams, 2005), with a slope *b* of 0.95 between M6.5 and M6.9. Above M6.9 the distribution rolls off towards an asymptote of M7.25±0.1, which was considered to be M_{max} (Figure 1a).

In terms of fault-slip characteristics, the general CE recurrence model (Schwartz & Coppersmith, 1984) is best accounted for by the Uniform Slip Model of Sieh (1981), which introduces an element of non-random behaviour such that a large earthquake, which is assumed to have an essentially constant slip distribution, occurs periodically along the same fault segment (Figure 2b). Those parts of the rupture that experience relatively small amounts of slip in the large earthquake experience more frequent moderate displacement events that allow them to catch up (Schwartz & Coppersmith, 1984). Because moderate earthquakes occur more frequently than large events according to this model, a log-linear frequency-magnitude relationship may characterise earthquake recurrence along the segment (Figure 1b). The characteristic earthquake slip model (Schwartz & Coppersmith, 1984) (Figure 2c) is based on the assumption that the distribution of slip associated with the characteristic event along a fault segment is repeated in successive events, and closely matches what would be expected of the Maximum Magnitude recurrence model (e.g. Wesnousky *et al.*, 1983).

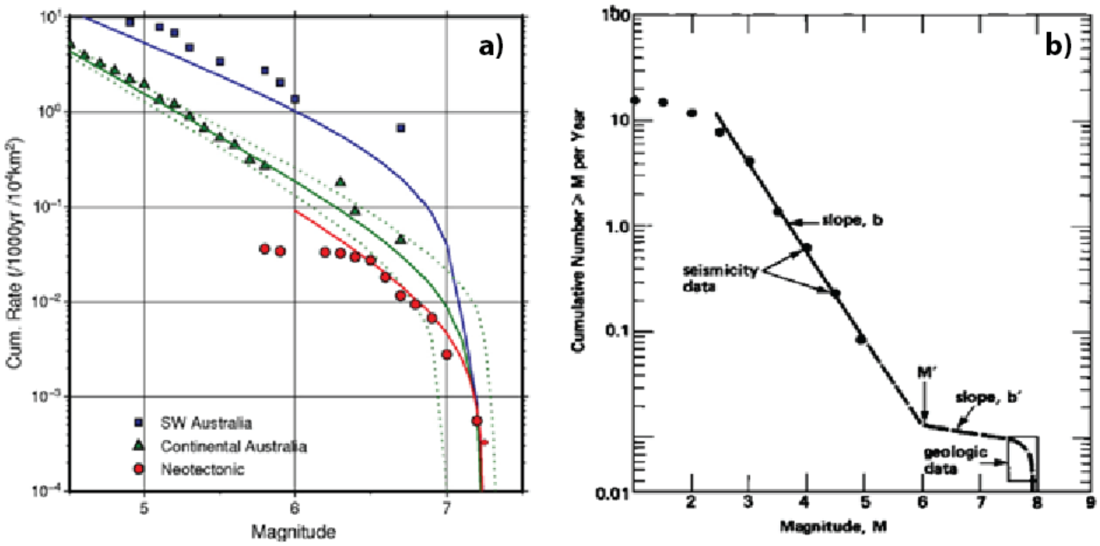

Figure 1. (a) Standard truncated Gutenberg-Richter recurrence relationship (after Leonard & Clark, 2011), (b) Hypothetical characteristic recurrence relationship for a fault showing constraints provided by seismicity data and geologic data (after Youngs & Coppersmith, 1985)

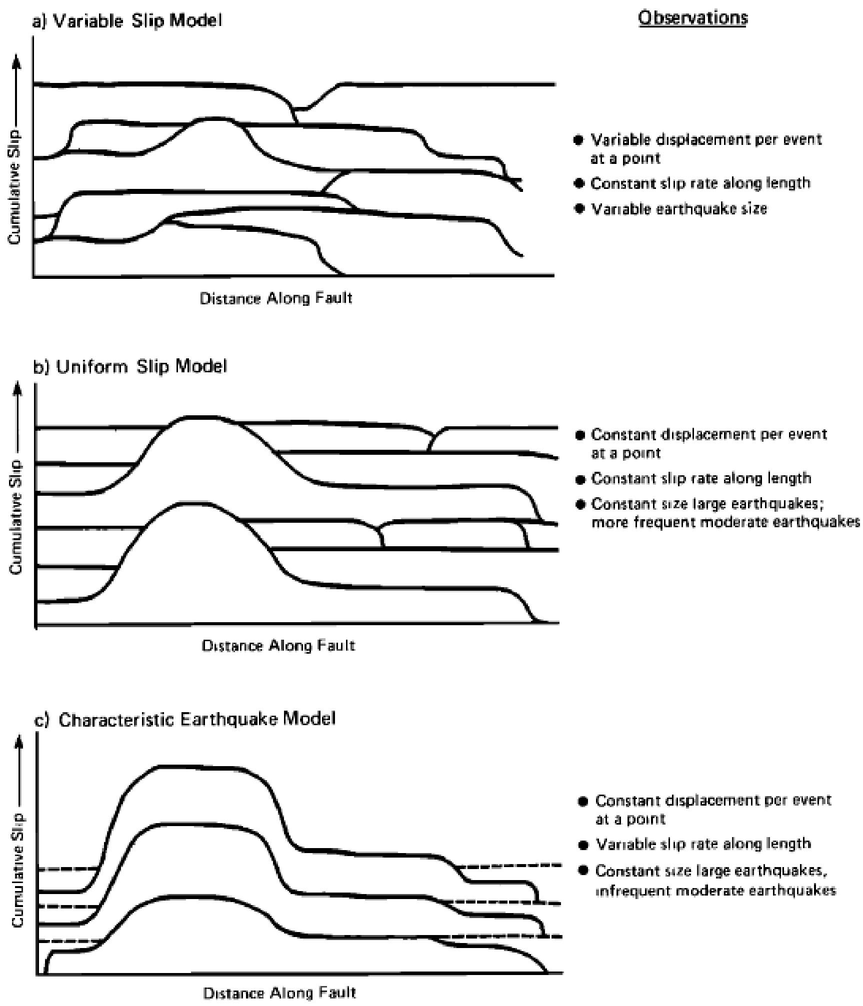

Figure 2. Fault displacement/slip models associated with large magnitude earthquakes and the implications of each model for paleoseismological observations on faults (Schwartz & Coppersmith, 1984).

3 IMPACT OF FAULT RECURRENCE MODEL CHOICE: AN EXAMPLE FROM ADELAIDE, AUSTRALIA

The choice of whether faults are attributed with Characteristic or G-R recurrence statistics has a significant impact on the calculated hazard level. Compared to a model that does not include fault sources (i.e. instrumental seismicity only) (Table 1, Figure 3a), the addition of a high slip rate (by intra-plate standards) Characteristic fault results in a 58% increase in hazard for a 500 year return period event (Figure 3c), with similar increases at longer return periods (i.e. ≥2500 years) (Table 1). A G-R fault with the same slip rate will result in a significantly higher hazard at 500 years (Figure 3b) with the relative difference decreasing at longer return periods. An alternative is to assume that earthquakes smaller than M_w5.5 (M_{min}) are accounted for in a background source zone and that the CE fault accommodates M_w5.5 and greater earthquakes (Figure 3d). This gives smaller increases at 500 years but similar increases at very long return periods (i.e. ≥10,000 years). For slip rates calculated on faults in the Adelaide region, the effect of faults reduces rapidly beyond 10 km from the fault zone and their influence is minimal beyond 25 km.

Table 1a. Comparison of hazard for 138.7 -34.8 at different recurrence periods (500, 2500 and 10,000 years) showing calculated PGA values for scenarios including no faults, CE faults, and G-R faults.

	Calculated PGA (% g)			**% difference compared to no faults**		
Return Period (years)	500	2500	10,000	500	2500	10,000
Recurrence Model						
Background with no faults	0.0615	0.165	0.323	-	-	-
Background + CE	0.0926	0.251	0.511	50%	51%	58%
Background + G-R	0.196	0.442	0.731	220%	167%	126%
Background + CE (M_{min} 5.5)	0.0779	0.222	0.495	27%	34%	53%

Table 2b. Comparison of hazard for 139.2 -34.4 at different recurrence periods (500, 2500 and 10,000 years) showing calculated PGA values for scenarios including no faults, CE faults, and G-R faults.

	Calculated PGA (% g)			**% difference compared to no faults**		
Return Period (years)	500	2500	10,000	500	2500	10,000
Recurrence Model						
Background with no faults	0.058	0.159	0.317	-	-	-
Background + CE	0.0697	0.197	0.425	20%	24%	34%
Background + G-R	0.124	0.328	0.599	115%	106%	89%
Background + CE (M_{min} 5.5)	0.064	0.180	0.391	11%	13%	23%

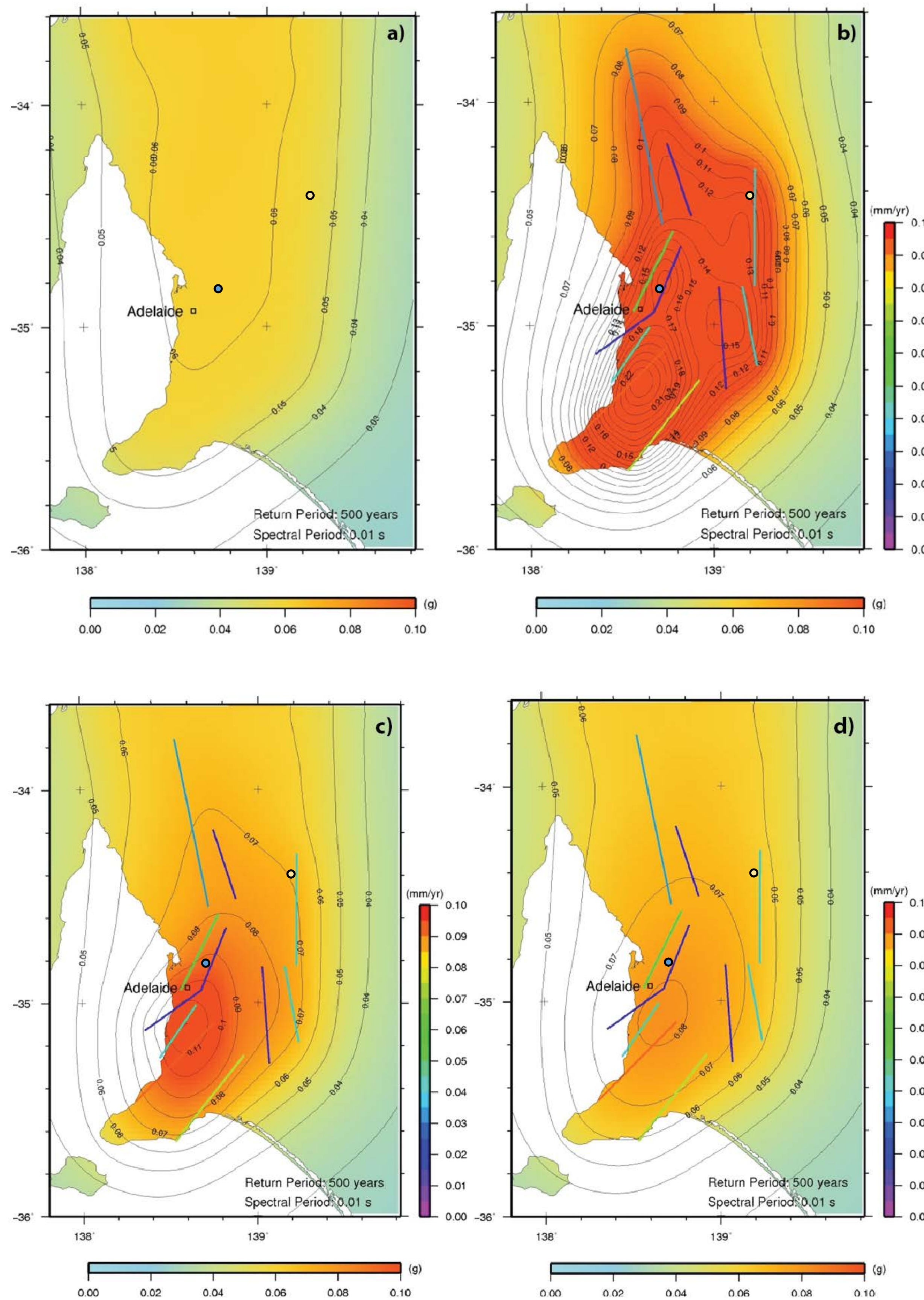

Figure 3. Comparison of 500 year return period hazard values for the Adelaide region calculated using (a) no faults, (b) G-R faults, (c) CE faults, and (d) CE faults with M_{min} of Mw 5.5. Faults are coloured by slip rate. The blue and yellow dots mark the locations considered in Tables 1a and 1b, respectively. Note that hazard values increase significantly (20-58%) by including CE faults and up to 220% where G-R faults are used.

4 EVIDENCE FROM AUSTRALIAN PALEO-SEISMOLOGICAL DATA

Reverse faulting, almost ubiquitous in Australia (e.g. Clark *et al.*, 2012), characteristically distributes slip on multiple imbricate faults and as off-fault folding (McCalpin, 2009). Consequently, the assessment of single-event displacement requires measurements across the entire zone of surface deformation. Significant uncertainty can be associated with the separation of the contributions of single events to multiple event scarps. One strategy useful in identifying single event displacements on active reverse faults is to examine terraces (fluvial and marine) and other planar geomorphic surfaces for evidence of offset or warping (McCalpin, 2009).

In eastern Australia the ancient course of the Murray River was defeated by uplift on the Cadell Fault, leaving an incised channel referred to as Green Gully (Bowler, 1978). Three inset paired fluvial terraces are preserved within Green Gully, attesting to attempts by the river to maintain its course during three distinct seismic events prior to defeat (Clark *et al.*, 2015). The terraces, and the pre-faulting land surface, are separated by tectonic risers of approximately equal vertical relief (Clark *et al.*, 2015, Figure 6b), consistent with similar size, similar slip or characteristic causative events. Similarly, tectonic terrace risers of 2.4 m, 3.1 m and 2.6 m separating fluvial terraces inset into the Lake Edgar Fault scarp in southwest Tasmania led Clark *et al.* (2011b) to propose that the scarp formed as the result of three surface-rupturing earthquakes with a narrow range of magnitudes (M_w6.8-7.0).

Crone *et al.* (2003) report two 0.8 m slip events from the Hyden Fault in Western Australia. The older of the two Crone *et al.* events was identified as a 0.2 m slip event in a trench on the same fault, but 4 km distant from the Crone *et al.* trench (Clark *et al.*, 2008). An additional two older slip events, of 1.5 m and 1.5 – 1.7 m, were recorded in this second trench (Clark *et al.*, 2008). It is tempting to describe this fault with a characteristic slip model given the similar magnitude of slip for the two larger events described in each trench. Further, the slip rates over (albeit different) seismic cycles in the two trenches are similar (Clark *et al.*, 2008, Figure 8), consistent with the uniform slip model. A characteristic model seems reasonable in that the scarp terminates at its southern end in a prominent horsetail splay, and at its northern end at an intersecting fault which is well imaged in aeromagnetic data. However, it is possible that degraded scarps associated with this intersecting fault (Clark *et al.*, 2008, Figure 3a) might be the result of strain sharing between the intersecting fault and the Hyden Fault, or periodic breaching of segment boundaries, leading to infrequent, apparently non-characteristic ruptures.

One drawback to relying heavily on reverse fault scarps for segmentation is the tendency of reverse fault surface ruptures to be discontinuous, with many breaks between short scarps; gaps caused by transitions between faulting and folding (McCalpin, 2009). This point was emphasised by Rubin (1996), who documented that almost all historic $M > 7$ reverse fault surface ruptures produced multiple geometric segments. Thus paleoseismological data collected from just a single scarp segment may result in an underestimation of the magnitude of a paleo-earthquake.

The interpretation of paleoseismological data from the Wilkatana Fault in the Flinders Ranges of South Australia by Quigley et al. (2006) provides evidence for strongly non-characteristic slip behaviour. Their preferred interpretation of the data from several natural fault exposures is that a single 8.3 m – 11.3 m slip event was followed by a 3.8 m slip event. The older event appears to have ruptured the Depot Creek Fault to the south, whereas the younger (smaller) rupture did not. Multiple fault-controlled knick-points in the hanging wall block of the Wilkatana Fault also appear to have been active in the late Quaternary, and likely link into the main range-front fault at depth. The evidence for vertical and along-strike fault linkage is repeated along the Flinders and Mt Lofty range fronts (e.g. Clark & Leonard, 2014; Flöttmann & Cockshell, 1996), allowing that slip sharing or mechanical interaction between faults may lead to similar and widespread non-characteristic rupture behaviour. An anomalously large (for the 54 km fault length) single event displacement of ~7 m on the Milendella Fault (Clark *et al.*, 2011a) might also relate to a multiple-segment or multiple-fault (e.g. Milendella + Palmer faults) rupture.

It should be noted that the average earthquake “recurrence interval” for characteristic slip models assumes that the amount of slip that occurred in a past earthquake will be repeated and, when divided by the fault slip rate, will give the average recurrence interval between these same size events (Schwartz & Coppersmith, 1984; Wallace, 1970). Several paleoseismological studies in intra-plate regions have found evidence for profoundly episodic rupture behaviour, with episodes of activity comprising a handful of events being separated by long periods of quiescence (Clark *et al.*, 2011a; Clark *et al.*, 2015; Clark *et al.*, 2012; Crone *et al.*, 2003; Crone & Machette, 1997). In this context the practise of using an average earthquake recurrence interval based upon a long-term slip rate should be critically examined.

5 DISCUSSION

Both Gutenberg-Richter and Characteristic fault recurrence models are commonly applied in probabilistic seismic hazard assessments (PSHAs) in Australia. As demonstrated in this paper, the choice of model has a significant impact on the calculated hazard levels. Two pertinent questions (courtesy of Don MacFarlane, AECOM) are:

1. Does a G-R approach over-estimate the total hazard because it infers faults to be active based on historical seismicity which is mostly very low-level and difficult to clearly relate to specific faults?

and

2. Does a characteristic approach of using only known neotectonic faults under-estimate the hazard because of the difficulty in identifying neotectonic fault activity (affected by weathering, long timeframes, episodic movement, etc.)?

Question 1 is fundamentally related to whether Australian instrumental seismicity of small magnitude can be spatially related to earthquakes sufficiently large to be confidently associated with known faults (e.g. Clark, 2009). Using a modified Kafka (2002) routine, Williams and Leonard (2001) showed that the power of small earthquakes to predict where large earthquakes might occur varied across Australia. The statistics indicated that in the southwest of Western Australia most large events occur <10 km from small events, in South Australia and Tasmania large events occur 10-25 km from small events, and in south-eastern Australia most large events occur 25-50 km from small events. The implication of this work is that a G-R model becomes less applicable from west to east (bearing in mind that Tasmanian crust has a mixed affinity between eastern and central Australian crustal types - cf. Clark et al. (2012)). Three examples serve to show that this analysis should be treated with caution.

Firstly, the southwest of Western Australia was the only area considered where surface rupturing earthquakes form part of the instrumental catalogue. Except in the case of the historical surface ruptures (e.g. Clark *et al.*, 2013), the spatial correlation between contemporary seismicity and known neotectonic faults over much of the continent appears to be poor (Clark *et al.*, 2012). Further, Leonard and Clark (2011) show that, despite the apparent predictive power of small earthquakes, the rate of contemporary seismicity is much greater than that required to build the 100,000 year catalogue of surface ruptures in the southwest of Western Australia. Non-stationarity of seismicity is implied on timescales greater than 500 years. Hence, the location of current seismicity might be a poor predictor of the location of future seismicity for longer return periods.

In a study of the Central and Eastern United States (CEUS), a region characterised by crust similar to that of south-eastern Australia, Kafka (2002) concluded that two thirds to three quarters of future large earthquakes will occur in zones delineated by historical seismicity. The disparity between results for south-eastern Australia and the CEUS may reflect the presence in the CEUS population of the 1811-1812 New Madrid surface rupturing events. A probability plot analysis of the cumulative distribution function of events in the New Madrid region suggested a different result; that the seismicity could be better characterised as three distinct populations normally distributed with respect to magnitude (Speidel, 1998); the larger of the populations (mean of M7.2) was related to a characteristic earthquake pattern. These findings challenge the validity of modelling seismicity using a G-R distribution in this region.

Another cautionary example is presented by the seismicity of the Mt Lofty/Flinders Ranges. An apparently good correlation between earthquake epicentres and range-bounding and intra-range faults in plan-view belies complexity in the third dimension. The faults bounding the ranges are listric and sole into an east-dipping master structure at 12-15 km depth (Flöttmann & Cockshell, 1996). Using data from a spatially dense temporary seismometer deployment, Balfour et al. (2015) show that approximately half the events in their catalogue occur below ~12 km depth. That is, a significant proportion of events are occurring below the extent of the upper crustal geology, in the underlying extended cratonic crust, and so bear a highly cryptic to no relationship to faults observed at the surface.

In relation to Question 2 above, it is very likely that the incompleteness of the neotectonic catalogue would result in an under-estimate of the hazard in regions where landscape modification rates (erosion/deposition) are comparable to or exceed the rates of tectonic relief building (Clark & Leonard, 2014, Figure 2). The pronounced episodic rupture behaviour of the few faults that have been subject to paleoseismological investigation (Clark *et al.*, 2015; Clark *et al.*, 2012; Crone *et al.*, 2003; Crone *et al.*, 1997), which may be reasonably assumed to be common to the entire catalogue of neotectonic faults, presents a mitigating factor. Given the comparatively rapid relief-building on intra-plate faults during active periods it may be inferred that a large percentage of those which are associated with relief in central and western Australia are likely to be within, or have recently finished, an active period. A corollary is that we might expect large earthquakes in unanticipated places on faults entering a new active period. In eastern Australia relief may not always be associated with recent activity. Whereas the Cadell Fault built ~20 m of relief in the last 70 kyr (Clark et al. 2015), the Lapstone Monocline, west of Sydney, was found to be predominantly an exhumed ancient structure (McPherson *et al.*, 2014).

Little is known of the distribution of slip through time within an active period on intra-plate faults. For example, do ruptures recur periodically within an active period? Investigations of the Lake Edgar Fault (Clark et al. 2011b), and the Hyden Fault (Clark et al. 2008), suggest perhaps not. However, paleoseismological investigations in intra-plate regions typically only obtain information regarding the most recent few events (e.g. Clark *et al.*, 2012 and references therein), precluding robust statistical analysis. While the data support faults in many intra-plate regions being modelled using a characteristic rupture, slip distribution is non-periodic, calling into question the meaning of the long-term slip rates used to calculate recurrence times for PSHA. Perhaps the best we can hope to achieve with the existing data and knowledge is to capture the uncertainty using the branches of logic trees (e.g. Petersen *et al.*, 2014).

In summary, in the intra-plate environment, assumptions must be made that are poorly supported by evidence when applying both the G-R and CE recurrence models to neotectonic faults. The relationship between small magnitude seismicity and faults (and by proxy, large magnitude seismicity) has not been demonstrated, and counter examples abound. Similarly, the long-term slip rates used to parameterise CE models of seismicity are questionable.

6 CONCLUSIONS

Despite the availability of large paleoseismological datasets and instrumental seismicity catalogues in inter-plate regions such as California and Japan, the suitability of the G-R versus the CE model for individual faults remains in question (e.g. Kagan, 1993; Kagan, 1996; Kluegel, 2010; Parsons & Geist, 2009; Speidel, 1998; Youngs & Coppersmith, 1985). If a characteristic recurrence model better fits the true state of nature, then the recurrence rate of the largest earthquakes along a fault zone may be significantly under-estimated if a G-R recurrence model is assumed. A simple comparison of PSHA for the Adelaide region of Australia, containing faults with typical intra-plate slip rates, confirms that large differences in hazard (up to 220%) might be expected depending upon the model adopted and the return period being considered. The sparse paleoseismological data in Australia favours a characteristic slip model in some regions, and more complex models in others (e.g. the Flinders Ranges). However, in light of the potential for pronounced episodic rupture behaviour on Australian faults it is questionable whether long-term slip rates (and the recurrence estimates based upon them in Characteristic earthquake models) are appropriate for probabilistic seismic hazard assessment (Clark, 2009). Alternatives are yet to be satisfactorily explored.

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