Mmax estimates for the Australian stable continental region (SCR) derived from palaeoseismicity data

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Abstract

The inventory of over 200 fault scarps captured in GA's Australian neotectonics database, comprising both probable and proven palaeo-earthquake sources, has been used to produce preliminary estimates of the maximum credible magnitude earthquake (Mmax) across the Stable Continental Regions (SCRs) of Australia. This was done by first grouping the scarps according to the spatial divisions described in the recently published neotectonics domain model and calculating the 75th percentile scarp length for each domain. The mean Mmax was then found by averaging the maximum magnitudes predicted from a range of different published relations. Results range between Mw 7.0–7.5±0.2. This suggests that potentially catastrophic earthquakes are possible Australia-wide. These data can form the basis for future seismic hazard assessments, including those for building design codes, both in Australia and analogous SCRs worldwide.

Keywords: maximum magnitude earthquake, palaeoseismology, neotectonic

INTRODUCTION

Probabilistic seismic-hazard analyses (PSHAs) require an estimate of Mmax, the magnitude (M) of the largest earthquake that is thought possible within a specified area, and results are highly sensitive to the choice of Mmax (e.g. Mueller 2010). In seismically active areas such as some plate boundaries, large earthquakes occur frequently enough that Mmax might have been observed directly during historic times. In less active regions like Australia, and most of the Central and Eastern United States and adjacent Canada (CEUSAC), large earthquakes are much less frequent and generally Mmax must be estimated indirectly. Indirect-estimation methods are many, their results vary widely, and opinions differ as to which methods are valid (Wheeler 2009b, a). Consensus emerged from an expert workshop on Mmax (Wheeler 2009b) that estimates should be based upon analysis of the global catalogue of Stable Continental Region (SCR) earthquakes (e.g. Johnston *et al.* 1994). The two most favoured analysis methods, in order of preference, were the Bayesian analysis, which is extensively used in US industry PSHAs (e.g. Coppersmith 1994; Cornell 1994), and global tectonic analogues, which the USGS uses for its national hazard maps (Frankel 1995; Frankel *et al.* 1996; Wheeler & Frankel 2000). Palaeoseismology was seen as the most feasible way to acquire additional direct observations of large SCR earthquakes within a reasonable time frame. Furthermore, palaeoseismology was seen as pre-eminent amongst several methods that could be used to develop a Bayesian prior distribution as a tool for estimating maximum observed earthquake (Mobs) for a Bayesian likelihood function, and to obtain specific local geologic information.

The emphasis on applying global analogues and global catalogues to the CEUSAC stems from a small sample size of large SCR earthquakes within the CEUSAC, requiring a trade off between space and time (e.g. Coppersmith *et al.* 1987). In the 1980s and 1990s the US Electric Power Research Institute funded the most comprehensive analysis of SCR earthquakes worldwide to date, with the remit of understanding and estimating spatially varying Mmax (Johnston *et al.* 1994). This study resulted in the global definition of SCR crust, its division into domains suitable for analogue study (Kanter 1994b, a), and also in the parameterisation of SCR crust in terms of seismic source properties (Coppersmith 1994; Cornell 1994; Johnston 1994b). Unfortunately, very few paleoseismic studies had been conducted in SCR crust at the time of this research, so the global SCR catalogue relies heavily on the short instrumental record of seismicity (Johnston 1994a, b, c).

By virtue of a fortuitous combination of climatic conditions, geology and geomorphology, Australia boasts arguably the richest Quaternary faulting record of all the world's SCR crust (Crone *et al.* 1997; Clark & McCue 2003; Crone *et al.* 2003; Sandiford 2003a; Quigley *et al.* 2006; e.g. Hillis *et al.* 2008; Clark 2010; Clark *et al.* 2010a; Quigley *et al.* 2010). Herein we explore the hypothesis that Australia contains enough different geologic settings and enough samples within each setting to indicate which settings tend to have larger earthquakes. We propose a revised domain division of the Australian SCR crust (cf. Kanter 1994b) based upon geological, geophysical and neotectonics data, a simple analysis of Australian neotectonic data from which preliminary Mmax estimates are derived (cf. Cornell 1994), and a schema for pooling domains into "superdomains" that might be helpful in guiding the application of ground motion models.

THE NEOTECTONIC ERA AND AUSTRALIAN NEOTECTONIC FAULT DATA

The Neotectonic Era

For the purpose of estimating Mmax, all seismogenic fault movements that have occurred under conditions imposed by the current stress regime are of interest. The time over which the current stress field has pertained is here defined as the Neotectonic Era, and a "neotectonic fault" is defined as a fault which has hosted seismogenic displacement under conditions imposed by the current Australian crustal stress regime (cf. Clark *et al.* 2010a). Structural and sedimentary evidence from southeast Australian basins suggests that the current crustal stress regime in Australia was established in the interval 10-5 Ma (Dickinson *et al.* 2001; Dickinson *et al.* 2002; Sandiford *et al.* 2004; Hillis *et al.* 2008). The catalogue is therefore comprised of deformation structures of late Miocene and younger age.

Longevity of the Neotectonic record

Quantitative estimates of land-surface erosion, based upon a combination of apatite fission track and cosmogenic radionuclide methods, indicate low, but non-zero erosion rates across Australia (Belton *et al.* 2004). Low relief regions of the western two thirds of Australia are characterised by erosion rates of 0.2-5 m/Ma (Bierman & Caffee 2002; Belton *et al.* 2004; Fujioka *et al.* 2005; Chappell 2006; Quigley *et al.* 2010), higher relief areas of eastern Australia by rates of up to 30-50 m/Ma (Weissel & Seidl 1998; Heimsath *et al.* 2000, 2001; Wilkinson *et al.* 2005; Tomkins *et al.* 2007), and those in the Flinders Ranges by rates locally up to 122 m/Ma, but averaging around 40 m/Ma (Bierman & Caffee 2002; Chappell 2006; Quigley *et al.* 2007a; Quigley *et al.* 2007b). In general, erosion rates appear to correlate primarily with regional relief, and at second order to local relief. These data imply that the direct footprint of individual seismic events (e.g. a fault scarp) might be recognisable in the landscape for hundreds of thousands of years or more in central and western Australia, but only several tens of thousands of years to a hundred thousands years in the Flinders Ranges and eastern Australia. In extreme cases, such as on the Nullarbor Plain, it has been claimed that a seismic record spanning the last 15 Ma has been preserved essentially intact (Hillis *et al.* 2008). In terms of a prior distribution of seismicity, the neotectonic catalogue therefore spans at least several tens of thousands of years.

The catalogue of Neotectonic Faults – composition and completeness

Figure 1 (and **Appendix Table 1**) presents the more than 200 instances of potential neotectonic deformation (predominantly faults) compiled in the Australian Neotectonics Database at Geoscience Australia. The data have been collected as a result of analysis of DEMs, aerial photos, satellite imagery, geological maps and consultation with state survey geologists and a range of other earth scientists (Clark *et al.* 2010a). Verifying the features as relating to neotectonic faults is an ongoing process that remains at an early stage (e.g. Crone *et al.* 1997; Crone *et al.* 2003; Sandiford 2003b, a; Celerier *et al.* 2005; Quigley *et al.* 2006; Clark *et al.* 2007; Clark *et al.* 2008; Estrada 2009; Clark *et al.* 2010a; Clark *et al.* 2010b; Quigley *et al.* 2010). Perhaps a dozen faults, mainly from southern Australia, have been quantitatively examined to determine source parameters (e.g. timing of events, recurrence, maximum magnitude). Average slip rates may be estimated for several dozen more faults (e.g. Sandiford 2003a).

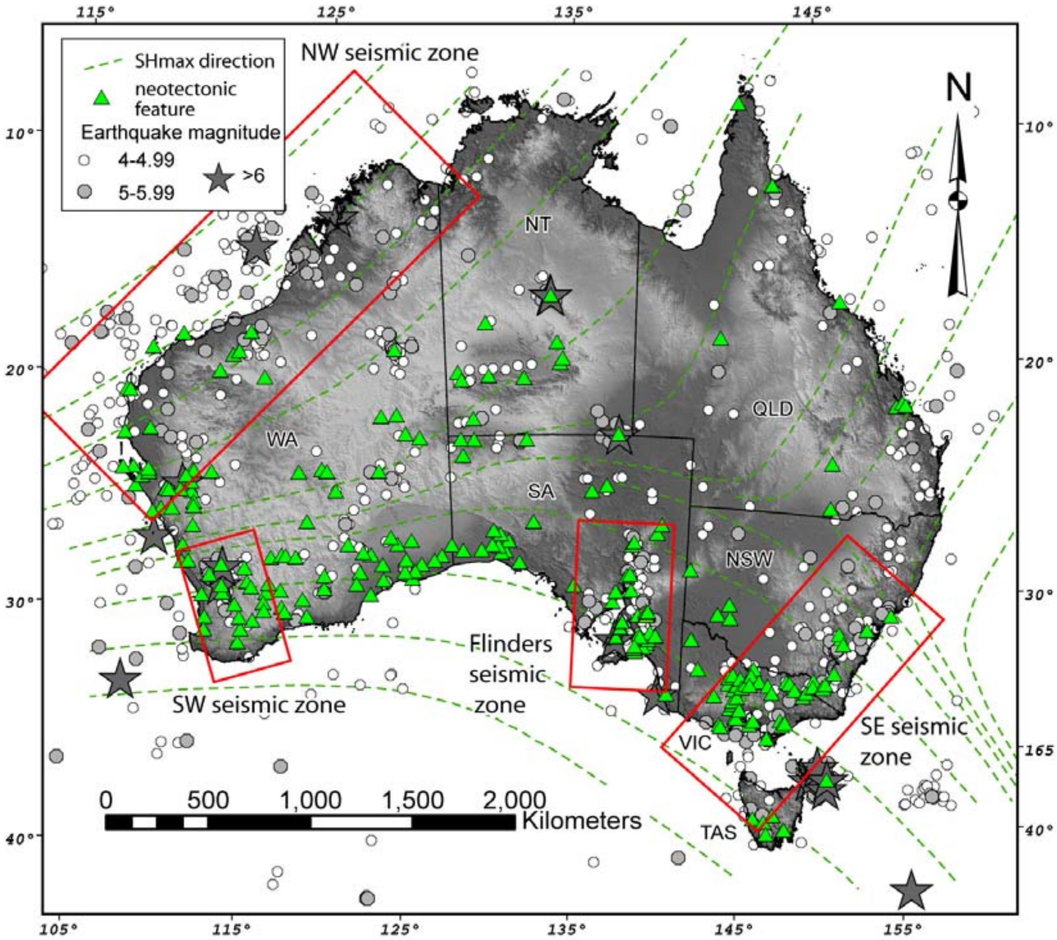

Figure 1. Earthquake epicentres (GA earthquake catalogue), probable and confirmed seismogenic neotectonic features (Clark *et al.* 2010a), maximum horizontal stress vectors (Hillis & Reynolds 2003) and zones of elevated seismicity (Hillis *et al.* 2008).

The catalogue is heterogeneous in terms of completeness and accuracy as sampling is biased by the extent and quality of the available datasets (e.g. DEMs, mine records, state survey records), by the extent of mobile unconsolidated sedimentary cover on the surface, the rate of landscape processes relative to the rate of tectonic processes etc. For example, the signal to noise ratio of the most aerially extensive DEM employed as a reconnaissance tool, the 3 arc second SRTM DEM (http://www2.jpl.nasa.gov/srtm/), is such that linear features only become discoverable above ~2-3m in relief. A significant portion of the tails of a rupture might consequently not be visible, leading to an underestimate of scarp length, with implications for the Mmax estimate derived from it. Large swathes of northern Australia have not yet been examined. The catalogue is most complete in the southwest of Western Australia (Clark 2010), where it might be expected that most surface ruptures relating to greater than M_w 6.5 earthquakes having occurred in the last 100 ka are represented. The Mount Lofty Ranges in South Australia might be considered to approach this level of completeness (although surprises continue to be unearthed), and perhaps also the Nullarbor Plain. As a whole, despite being far from complete, the neotectonic record provides a longer, richer and more robust measure of the largest earthquakes in the Australian SCR crust than that presented by the historic record of seismicity.

A REVISED AUSTRALIAN SCR DOMAIN MODEL USING NEOTECTONIC DATA

Earthquake hazard assessments for Australia, including those for the national seismic hazard maps, have typically taken the approach of assuming an Mmax value based upon adding a constant to the maximum earthquake magnitude observed continent-wide or in a zone of instrumental seismicity (Gaull *et al.* 1990; Gibson 1995; McCue 1999; Brown & Gibson 2004; Hall *et al.* 2007; Somerville *et al.* 2008). Only one attempt has been made to subdivide the Australian SCR crust on the basis of the expected influence of variation in geology (and by proxy, geophysical signature) on Mmax (Johnston *et al.* 1994). Kanter (1994b) initially divided the continent on the basis of geology and geophysics and the resulting domains were then assigned values of additional variables that "might be related to seismicity" (Kanter 1994b, p. 2-8 - 2-16). These were then combined into "superdomains" on the basis of variables that might control Mmax (Cornell, 1994). Principle amongst the variables that were thought to influence Mmax was whether the crust comprising the domain had been tectonically "extended" or not, and to a lesser degree the age of the major extension event (Coppersmith 1994; Johnston 1994b). No palaeoseismic studies had been conducted in Australia at the time of this research, so the Mmax estimates relied exclusively on the global SCR catalogue (Johnston 1994a, b, c).

The recognition that faults in different parts of the Australian continent respond in different ways to the imposed crustal stress (e.g. Clark 2006) has the potential to inform assessments of Mmax. Clark *et al.* (2010a) revisited the domains concept in light of the wealth of new neotectonic and palaeoseismic data that has accumulated in the last decade. Six source zones (domains) spanning continental Australia have been proposed based upon geological, geophysical *and* neotectonic data (**Figure 2a**). A seventh offshore source zone is defined based upon analogy with the eastern United States (Johnston *et al.* 1994; Wheeler 1996; Wheeler & Frankel 2000). In principle, each source zone contains neotectonic faults that share common recurrence and behavioural characteristics, in a similar way that source zones are defined using the historic record of seismicity. A simple visual appraisal of the variation in scarp length (which may be related to earthquake magnitude) between domains indicates the potential of this data for quantifying Mmax (**Figure 2b**).

In terms of the Johnston *et al*. (1994) schema, Domains 1, 3 & 4 are non-extended, and domains 5, 6 &7 are extended. Domain 2 is difficult to categorise as the domain is founded on a Late Proterozoic rift, which subsequently extensively inverted in the Delamerian Orogeny in the early Cambrian (Preiss 1987; Drexel *et al*. 1993). Seismic sections across the southern part of the domain indicate that the reverse faults associated with the topographic axis at the surface link into to a partly inverted east-dipping asymmetric normal faulting architecture at depth (Flottmann & Cockshell 1996). The seismic interpretation further shows that the extensional architecture only extends to a depth of ~10 km beneath the topographic axis of D2, beneath which exists a Cambrian Platform sequence overlying crust belonging to the Gawler Craton. A significant proportion of the recorded seismicity in the domain occurs below the 10 km depth of structured crust (Leonard 2008), similar to the circumstance in the Appalachian region of the eastern U.S (Wheeler 1995, 1996). This history is perhaps more like Domain 4 (non-cratonic) than the cratonic Domains 1 and 2. However, the intensity of neotectonic deformation in Domain 2 is arguably in part governed by the extensional architecture, suggesting similarities with extensional domains such as D5.

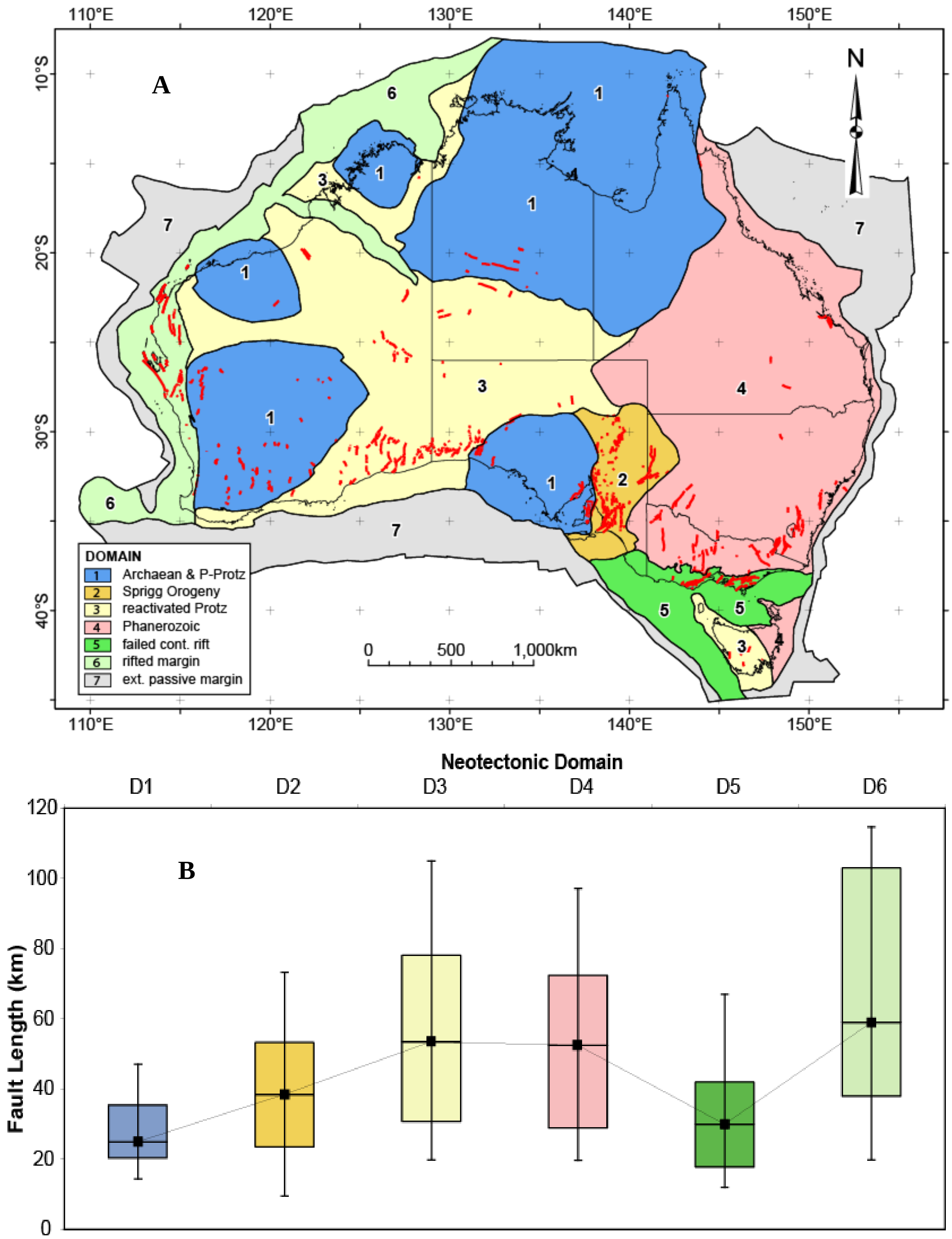

Figure 2. (a) Neotectonic domains (Clark 2010) with fault scarps from the Australian neotectonics database overlain, **(b)** Box and whisker plot for fault length, which is a proxy for Mmax. Boxes denote 75th and 25th percentiles, central point indicates median value, and whiskers define 90th and 10th percentiles. D1 - Archaean Craton and non-reactivated Palaeo-Proterozoic; D2 – Sprigg Orogeny; D3 - Reactivated Proterozoic; D4 - Eastern Australian Phanerozoic; D5 - SE Australian Rifted Crust; D6 - Extended Continental Crust; D7 – extended passive margin crust.

A SIMPLE DERIVATION OF MMAX FOR AUSTRALIAN SCR CRUST

Analysis of fault data from the neotectonics database allows for a preliminary Mmax to be assigned to each neotectonic domain. Where an active fault has been studied paleoseismically, its scarp length and single-earthquake displacements can provide two independent estimates of Mmax for the fault. However, because single event displacements are not known for the majority of features in the neotectonics database, Mmax was necessarily derived from scarp length assuming entire scarp-length rupture, and by averaging the maximum magnitudes predicted from a range of different published earthquake scaling relations (e.g. Somerville *et al.* 1999; Somerville 2001; Somerville *et al.* 2009; Leonard 2010) (**Table 1**, see also **Appendix Table 1 (Tab 2) for list of relations**). As a conservative measure, we have chosen to base calculations of Mmax on the 75th percentile fault length aggregated from all faults within a domain. We contend that this will to some degree account for missed scarp segmentation, and scarp growth as the result of multiple events, by excluding extremely long outliers.

The results, ranging from Mw 7.0–7.5±0.2, appear to be reasonable where palaeoseismological data is available to provide validation. For example, it has been estimated that the Cadell Fault in D4 has hosted events of magnitude Mw 7.3 (Clark et al. 2007), while the Lort River and Dumbleyung faults in D1 have hosted events of magnitude Mw 6.9 and Mw 7.0 respectively (Estrada 2009). Somerville et al. (2008) derive Mmax estimates of between Mw 7.3 – 7.5 from palaeoseismic data reported by Quigley et al. (2006) from several D2 faults. The upper boundary of this range is larger than our estimate for D2, again highlighting the conservative nature of calculations based upon remotely determined scarp length. Based upon analogy with the eastern United States, an Mmax of Mw 7.5 may be assigned to D7 (Wheeler & Frankel 2000).

The relatively large area of high-resolution DEM data available in the southwest corner of the Yilgarn Craton segment of D1 (Clark 2010) allows for a more rigorous estimate of Mmax to be calculated than that discussed above (cf. Cornell 1994; Leonard & Clark 2010). It was estimated that most earthquakes above M6.5 that have occurred in the last ~100 ka in the region were captured in the DEM data analysis, and from these a synthetic seismicity catalogue was constructed (Leonard & Clark 2006; Leonard & Clark 2010) comprising 65 events. The data has typical truncated Guttenberg-Richter recurrence characteristics with a slope (b) of 0.9-1.0 between magnitude 6.5 and 6.9, and a rapid roll off in recurrence above M6.9 towards an asymptote of M7.2±0.1, which is considered to be the Mmax. This compares with the value of M7.0±0.2 derived from the 75th quartile of all data in D1. There is great scope to conduct similar analyses in other parts of Australia as aerially extensive high resolution DEM datasets become available.

Table 1: Average Mmax estimates for the six onshore neotectonic domains based on *n* fault scarps in each domain.

Domain	Desc.	n	Fault Length (km) *[75th percentile value]* 50 degree dip; 15 km depth	*Mean Mmax* **(SCR only)**	*SD*
1	Archaean & P-Proterozoic	64	35.4	**7.0**	**0.2**
2	Sprigg Orogeny	40	53.25	**7.2**	**0.1**
3	Proterozoic Mobile Belt	50	78.15	**7.4**	**0.1**
4	Phanerozoic terrances	38	72.38	**7.3**	**0.1**
5	Failed continental rift	21	42	**7.1**	**0.2**
6	Inverting passive margin	17	103	**7.5**	**0.1**

IMPLICATIONS FOR SEISMIC HAZARD AND STABLE CONTINENTAL REGION (SCR) ANALOGUE STUDIES

While remaining incomplete over much of Australia, the neotectonic catalogue spans a timeframe that is likely to include a near-to maximum magnitude earthquake in most regions (cf. Crone *et al.* 2003). Consequently, our results represent a significant advance over Mmax estimates based upon adding an arbitrary constant to the maximum observed earthquake (Mobs + c) for a region of interest (e.g. Gaull *et al.* 1990; Brown & Gibson 2004), or using a perceived global analogue (cf. Wheeler 2009b, a). The major tenet of the Johnston *et al.* (1994) model, that extended crust is more seismically active than non-extended crust, appears to hold true for the Australian neotectonic record (compare D2, D5 & D6 with D1, D3 and D4) (c.f. Shulte & Mooney 2005). However, the Johnston *et al*. (1994) schema does not appear to predict variation in Mmax.

Application to hazard studies

The domains model described herein might be used to guide where ground motion models of various derivations might be applied. Ground motion models used in seismic hazard assessment for Australia (e.g. Somerville *et al*. (2009)) recognise a distinction between cratonic and non-cratonic crust. This divide roughly follows the Tasman Line (Glen 2005) (**Figure 2**), creating western (cratonic) and eastern (non-cratonic) domains. The former domain is thought to exhibit ground motion and seismic attenuation roughly similar to eastern North America (e.g. Somerville 2001) and the latter similar to western North America (e.g. Somerville *et al.* 1999). The neotectonic domain model might be geographically simplified to guide application of this class of ground motion models, as defined in **Table 2**. Note that the extra category of "Extended" has been added to recognise the variation in crustal properties that might be expected in this class of SCR crust. A ground motion model such as that presented in Toro *et al.* (1997) might be appropriate for this crustal grouping. If one tentatively assigns D2 to the "extended" category, one issue remains to complicate this grouping; the western side of Tasmania is assigned to Domain 3 (cratonic).

Western Tasmania has been tentatively placed within this domain based upon the widespread exposure of Neoproterozoic rocks, metamorphism and deformation fabrics (e.g. Berry *et al.* 2008), and its pre-Delamerian Orogeny correlation with crust west of the Tasman Line (Glen 2005). Despite a long Palaeozoic deformation history, and the proposal that analogous Proterozoic basement floors the Selwyn Block in the Lachlan Fold belt to the north (Cayley *et al.* 2002), we maintain that the character of the scarps is more akin to those in Domain 3, cf. Domain 4. Furthermore, there is little record of the rifting history that might align it with Domain 2, nor the strong organisation of scarps.

Table 2: Grouping of Domains as a guide to the application of ground motion models.

	Archean and Palaeo-Proteroz	Reactivated Proterozoic	Phanerozoic	Mesozoic Extended
Western	1	3		
Eastern			4	
Extended		2?		5,6,7

Global analogues

A fundamental implication of the results presented herein is that SCR fault characters are not universal in their applicability in analogue studies. Careful choice of subject faults within analogous crust of similar stress field character is required to extrapolate meaningfully to incompletely characterised areas (Clark *et al.* 2010a). Below, we briefly discuss some analogous crust from the North American SCR as a detailed example of the power of the domains approach.

The Archaean and Palaeoproterozoic core of the North American continent (including the Superior, Wyoming, Hearne, Rae, Nain and Slave Provinces and interstitial Proterozoic orogenic belts) (Hoffman 1989) can be considered analogous in terms of crustal properties to D1. This core is fringed on the southern and eastern sides by reactivated Proterozoic mobile belts and orogenic crust analogous to D3 (e.g. the Yavapai-Mazatzal Province and Grenville Belt) (Davis & Bump 2009). Further to the southeast Palaeozoic foldbelts similar to those in D4 extend to the coastal plain east of the Appalachian Orogenic Belt (Wheeler & Frankel 2000). The Appalachians themselves share some characters with D2, but fall far short in terms of activity level. Mesozoic aulacogens extending through the Palaeozoic and into the Precambrian shield (e.g. the Reelfoot Rift, the Southern Oklahoma aulacogen, the Ottawa Rift, the Saguenay Graben) can be considered similar to D5. The main orientation of the aulacogen with respect to the prevailing stress field might be used to further refine the expectation of analogous crustal response. For instance, the small angle between the major structures of the Reelfoot Rift and the maximum horizontal compressive stress (SHMax) is similar to the relationship expressed in the Gippsland Basin. The Reelfoot Fault (Van Arsdale *et al*. 1998) and faults such as the Haunted Hill Fault or Morwell Faults are well suited for analogue studies.

The Mesozoic rifted passive margin of the eastern United States, containing the Charleston source zone (Johnston 1996; Wheeler & Frankel 2000; Talwani & Schaeffer 2001), might be considered analogous with parts of D6 (and perhaps the Sorell Basin in D5), or perhaps D7. However, in contrast to our observations, Wheeler (1995) noted that Palaeozoic (Iapetan) passive margin crust to the west of and beneath Appalachian orogenic crust appears to be more active than Mesozoic rifted margin to the east, at least in terms of the historic seismic record.

CONCLUSIONS

We present the first maximum credible earthquake magnitude (Mmax) estimates for all Australian SCR crust based upon a neotectonic catalogue of palaeo-earthquakes. Mmax is reported for each of six onshore neotectonic domains based upon the 75^{th} percentile scarp length within that domain. Results range between Mw 7.0–7.5±0.2. While this approach is justified in that it removes extreme values relating to multiple event scarps, which cannot yet be discriminated within the data, it is inherently conservative. Consequently, in many cases our data represent an underestimate of 0.1-0.2 magnitude units relative to calculations based upon rare palaeoseismic data. Nonetheless, our findings have the potential to significantly reduce uncertainty in probabilistic seismic hazard assessments that rely upon assigning an Mmax. These data can form the basis for future seismic hazard assessments, including those for building design codes, both in Australia and analogous SCRs worldwide. As the completeness of the neotectonic catalogue improves with time, analysis of the type conducted by Leonard & Clark (2006; 2010) will lead to an improvement upon the results presented in this paper.

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APPENDIX – TABLE 1

Appendix Table 1 (see attached Microsoft Excel file) is an extract from the Australian Neotectonics Database (Geoscience Australia, internal database), accessed 15th of April 2009. Details of the methods used to compile the data and calculations are to be found in Clark et al. (2010a). Mmax estimates and single event displacements for single faults have been calculated using the relations presented in the second sheet of the table. No consideration has been given to fault segmentation so the results should be regarded as indicative only. Mmax values are typically associated with an uncertainty of ±0.6 magnitude units or less, which reflects only uncertainty in the relations, not the data. Fault dip has been arbitrarily fixed at 45 degrees. Seismogenic depth used in fault width calculations is 10 km for Domains 1 and 3, 15 km for Domains 4, 5 and 6 (after Leonard 2008),and 15 km for Domain 2 (recognising the crustal architecture reported by Flottmann & Cockshell (1996)).

The key to data reliability (Column L) is as follows:

Class A - definite neotectonic feature
Class B - probable neotectonic feature
Class C - possible neotectonic feature