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What have we learnt regarding cratonic earthquakes in the fifty years since Meckering?

Dan Clark & Trevor Allen

Geoscience Australia, GPO Box 378, Canberra, ACT 2601
Email: dan.clark@ga.gov.au

Abstract

The 14th of October 1968 Ms 6.8 (Mw 6.58) Meckering earthquake was the first of a remarkable series of nine historical surface rupturing earthquakes to occur in the Precambrian craton of western and central Australia. Geological investigations of the ruptures, including that relating to the 26th of May 2016 Mw 6.1 Petermann Ranges earthquake, found no evidence to suggest a prior event in the geologically recent past. The handful of paleo-earthquake scarps that have been investigated in the same cratonic crust setting show evidence for limited recurrence of large events (e.g. Dumbleyung, Hyden, Roopena). Further research is required to determine if the events forming the current topography are the only events that have occurred on a given fault scarp, or if they represent only the more recent of a protracted series of events. Irrespective, these data challenge the plate margin paradigm often adopted in intraplate environments that large earthquakes recur periodically on 'active' faults. This raises the question of whether the models used in seismic hazard analyses to describe earthquake recurrence in intraplate cratonic regions are appropriate.

Keywords: earthquake recurrence, Precambrian Craton, earthquake, paleoseismology

INTRODUCTION

On the 14th of October 1968 the small agricultural town of Meckering, about 115 km east of Perth, was largely destroyed by an Ms 6.8 (Mw 6.58) earthquake (Gordon & Lewis, 1980; Vogfjörd & Langston, 1987). The Meckering earthquake was the first known to have ruptured the ground surface in Australia, and prompted the production of Australia's first earthquake building code, AS 2121 in 1979 (cf. Woodside & McCue, 2017). The seismic hazard assessments underpinning this code, and its successors AS1170.4 (1993, 2007), have increased in sophistication with time as the science of earthquake analysis evolved and earthquake catalogues accrued new data. Knowledge of the recurrence characteristics of Australian intraplate seismogenic faults, such as those which ruptured during the Meckering earthquake, has progressed at a slower rate. Several fault scarps associated with physiography consistent with the 1968 rupture were identified in the course of routine geological mapping in the years after Meckering (e.g. Thom, 1972; Chin *et al.*, 1984; Chin, 1985; Chin & Brakel, 1986; McCue, 1990). However, it was only in the early to mid – 1990s that the first paleoseismic data were obtained (Crone *et al.*, 1997; Crone *et al.*, 2003; McCue *et al.*, 2003), and the process of characterising the recurrence behaviour of Australian intraplate faults was begun.

Knowledge of the characteristics of Australian seismogenic faults has advanced in the last two decades (Sandiford, 2003b; Quigley *et al.*, 2010a; Clark *et al.*, 2012; Clark *et al.*, 2014a; Clark *et al.*, 2015) to the stage where faults are now more commonly being explicitly included in probabilistic seismic hazard assessments, at scales from site–specific to national (e.g. Somerville *et al.*, 2008; Clark *et al.*, 2016; Griffin *et al.*, 2016). Despite the advances, most faults in Australia remain poorly characterised in terms of their paleoseismology, and in many cases, their geometry. Hence, hazard modellers face significant uncertainty in assigning magnitude, rupture geometry, segmentation behaviours, and recurrence behaviours. The 2018 revision of the Australian National Seismic Hazard Assessment (NSHA18), for the first time, includes intraplate fault sources (Clark *et al.*, 2016; Griffin *et al.*, 2016; Allen *et al.*, 2018a). Epistemic uncertainty in the fault source model is captured in the NSHA18 through a weighted logic tree framework (Clark *et al.*, 2016; Griffin *et al.*, 2018). In terms of recurrence behavior the model described a seismogenic fault as either; slipping at the long term average rate, in a period of heightened activity – slipping at a rate ten times the average rate, or in an inactive period – slipping at one tenth of the long term average rate (cf. Stirling *et al.*, 2011). By virtue of the scarcity of data with which to validate such a model, the underpinning assumption that a 'long-term slip rate' is a meaningful concept in an intraplate setting, as per the prevailing plate margin paradigm, remains to be fully tested. Indications are that the concept may be useful in the Phanerozoic stable continental region (SCR) crust of eastern Australia (Figure 1), where faults with up to a couple of hundreds of metres of slip occur (cf. Clark *et al.*, 2015; Clark *et al.*, 2017b). However, it is not so certain whether assigning a long-term slip rate is meaningful for Precambrian SCR crust (e.g. Calais *et al.*, 2016). This contribution re-examines some of the recurrence assumptions underpinning the NSHA18 fault-source logic tree as they pertain to the Precambrian SCR crust of central and western Australia.

LARGE EARTHQUAKE OCCURRENCE IN PRECAMBRIAN WESTERN AND CENTRAL AUSTRALIA

Including the 2016 Petermann Ranges event, nine earthquakes are documented to have produced surface rupture in historical times in Australia (Table 1, Figure 1). These ruptures are located exclusively in the Precambrian SCR rocks of central and western Australia (Clark *et al.*, 2014a), and are associated with magnitudes in the range from Mw 4.73 - 6.76 (Clark *et al.*, 2014b). None of the nine historical surface ruptures could have been identified and mapped using topographic signature prior to the historical event (Table 1). For example, Crone *et al.* (1997) excavated trenches across the 1986 Marryat Creek and 1988 Tennant Creek ruptures and found that while each rupture in part exploited pre-existing bedrock faults, there was no unequivocal geomorphic, stratigraphic or structural evidence to suggest a penultimate event in the preceding 50,000 to 100,000 years or more.

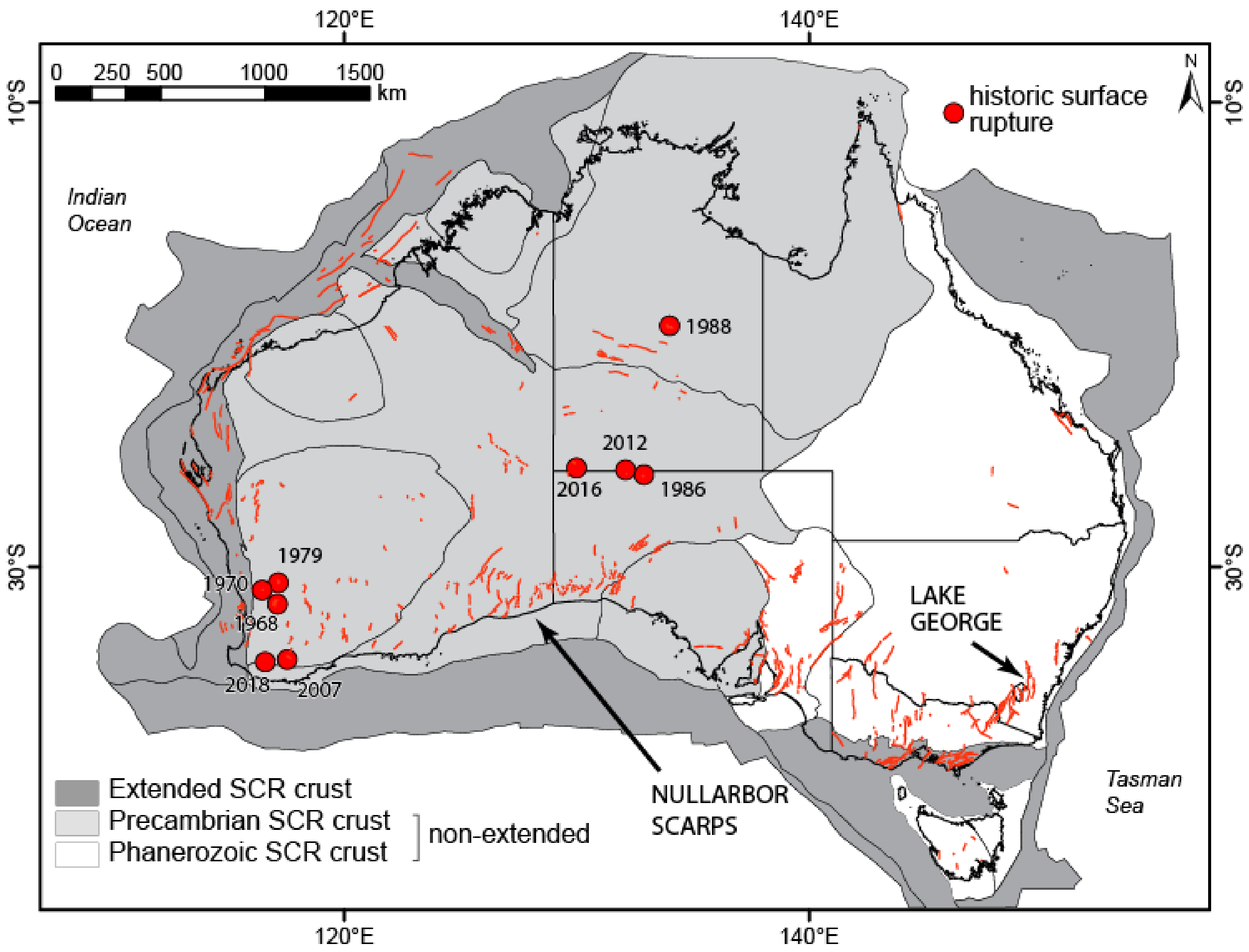

Figure 1: Neotectonic features (red lines) from the Australian Neotectonic Features database (updated from Clark *et al.*, 2012). Historical surface ruptures shown as red dots annotated with the year of the event. Base map are neotectonic superdomains (after Leonard *et al.*, 2014). Note all historical surface ruptures have occurred in Precambrian SCR crust.

Table 1: Historical events known to have produced surface rupture in Australia (expanded after Clark *et al.*, 2014b).

Earthquake	Year	Magnitude (Mw)	surface rupture length (km)	vertical displacement (max: m)	Pre-existing fault?	Pre-existing topography?
Meckering	1968	6.58	37	2.5	part	no
Calingiri	1970	5.46	3.3	0.4	no	no
Cadoux	1979	6.13	14	1.4	part?	no
Marryat Creek	1986	5.74	13	0.9	part	no
Tennant Creek*	1988	6.76	36	1.8	yes	part?
Katanning	2007	4.73	1.26 (0.2)#	0.1	no	no
Ernabella	2012	5.37	1.5	0.5	no	no
Petermann Ranges	2016	6.10	20	1.0	part?	no
Lake Muir	2018	5.30	8(?)	0.4	yes	no

** The Tennant Creek surface rupture was produced by three events in a 24 hr period (Bowman, 1992)*

 # The InSAR interferogram (Dawson et al., 2008) showed a 1.26 km rupture length. However, a rupture could only be traced on the ground for 0.2 km (Vic Dent, Pers. Comm. 2007).

High-resolution digital elevation data obtained over alluvial valleys affected by the 1968 earthquake show no evidence for pre-existing relief along the 1968 rupture trace (e.g. Figure 2). A trench excavated across the 1968 scarp in the valley shown in Figure 2 preserved evidence for only the 1968 event in sediments more than twenty thousand years old (Clark *et al.*, 2011, Fig. 5, north trench). However, a trench excavated across the rupture where it crossed a low hill to the south revealed evidence for a potential prior event deforming Tertiary duricrust (Clark *et al.*, 2011, Fig. 5, south trench). No relief was evident across shear bands in the deformed duricrust, leading the authors to suggest that any penultimate event must have occurred several hundred thousand years prior, or more. An aeromagnetic interpretation of basement geology and structure in the Meckering region suggested that the complex surface rupture utilized northeasterly-trending dykes and faults, and northwesterly trending stratigraphic contacts (Dentith *et al.*, 2009). This complex rupture geometry may not favour strain localisation, and hence recurrence, as would a simple through-going fault, as slip planes may lock at intersections (e.g. Talwani, 1988).

Paleoseismic investigations of several faults in the same Precambrian SCR tectonic setting provide evidence for limited recurrence of large earthquakes, with up to four events documented on an individual fault within the last *ca.* 100 kyr (Crone *et al.*, 2003; Clark *et al.*, 2008; Estrada, 2009). These scarps, the Roopena, Hyden, Lort River and Dumbleyung (see the Australian Neotectonic Features database for location), all overlie simple through-going faults imaged in aeromagnetic data (https://researchdata.ands.org.au/total-magnetic-intensity-vrtp-greyscale/1256158). The two to five Quaternary events documented on the Hyden (Clark *et al.*, 2008) and Lort River (Estrada, 2009) scarps are all that are evident across Tertiary duricrust. While shallow trenches across the 2 – 5 m high Roopena scarp exposed Precambrian bedrock on both sides of the fault (Crone *et al.*, 2003), nearby scarps are associated with an extended Tertiary to recent history of movement (Miles, 1952; McCormack, 2006; Weatherman, 2006). For example, the Randell and Poynton Faults on the northeastern Eyre Peninsula are associated with 30-70 m of Pliocene and younger vertical displacement (McCormack, 2006). Scarps developed in the *ca.* 15 Ma surface of the Nullarbor Plain, which overlies Neoproterozoic mobile belt basement, are associated with up to 15 – 30 m of vertical surface displacement (Hillis *et al.*, 2008; Clark *et al.*, 2012), implying the recurrence a dozen or so events at most. In general, scarps developed within Archaean and Paleoproterozoic crust tend to be more modest in height, less well connected (e.g. spatially isolated), and more complex in plan than scarps in Mesoproterozoic and Neoproterozoic crust (neotectonic Domain 1 cf. Domain 3 of Clark *et al.*, 2012) (Figure 3).

The remarkable sequence of three one-off surface breaking earthquakes in 1968, 1970 and 1979 (Meckering, Calingiri and Cadoux — Gordon & Lewis, 1980; Lewis *et al.*, 1981) raises interesting questions about the potential for multiple modes of upper crustal failure when stress thresholds are exceeded. The structurally ‘complex’ Meckering, Calingiri and Cadoux scarps (Figure 1) are 70–100 km apart; too distant for static stress changes to have promoted rupture (cf. Caskey & Wesnousky, 1997). Furthermore, the ruptures were sufficiently temporally separated that dynamic stress changes are unlikely to have promoted rupture. The observations are consistent with the postulate that blocks of upper crust on the scale of $\sim 10^4$ square kilometres can unload in the space of a decade (Clark *et al.*, 2012). In the case of the southwest of Western Australia, this process may be facilitated by a mid- to upper-crustal architecture characterised by fundamental sub-horizontal structural discontinuities (most notably at ~10 km and ~25 km depth) (Everingham, 1965; Drummond & Mohamed, 1986; Goleby *et al.*, 1993; Dentith *et al.*, 2000) that are compartmentalised by major moderately-dipping fault systems, forming “superterranes” as presented by Wilde et al. (1996). Perhaps the presence of through-going faults perpendicular to the crustal stress field may mean the difference between an unloading scenario involving strain localization in successive events on a single fault (e.g. Dumbleyung), or on several proximal structures (e.g. Meckering). Intersection of structural trends, and rheological changes at the boundaries of mafic dykes have been proposed as stress concentrators, potentially promoting ‘weakness’ (Everingham & Gregson, 1996; Dentith & Featherstone, 2003). With only the Meckering, Calingiri and Cadoux ruptures as examples, it is not possible to draw conclusions with any certainty.

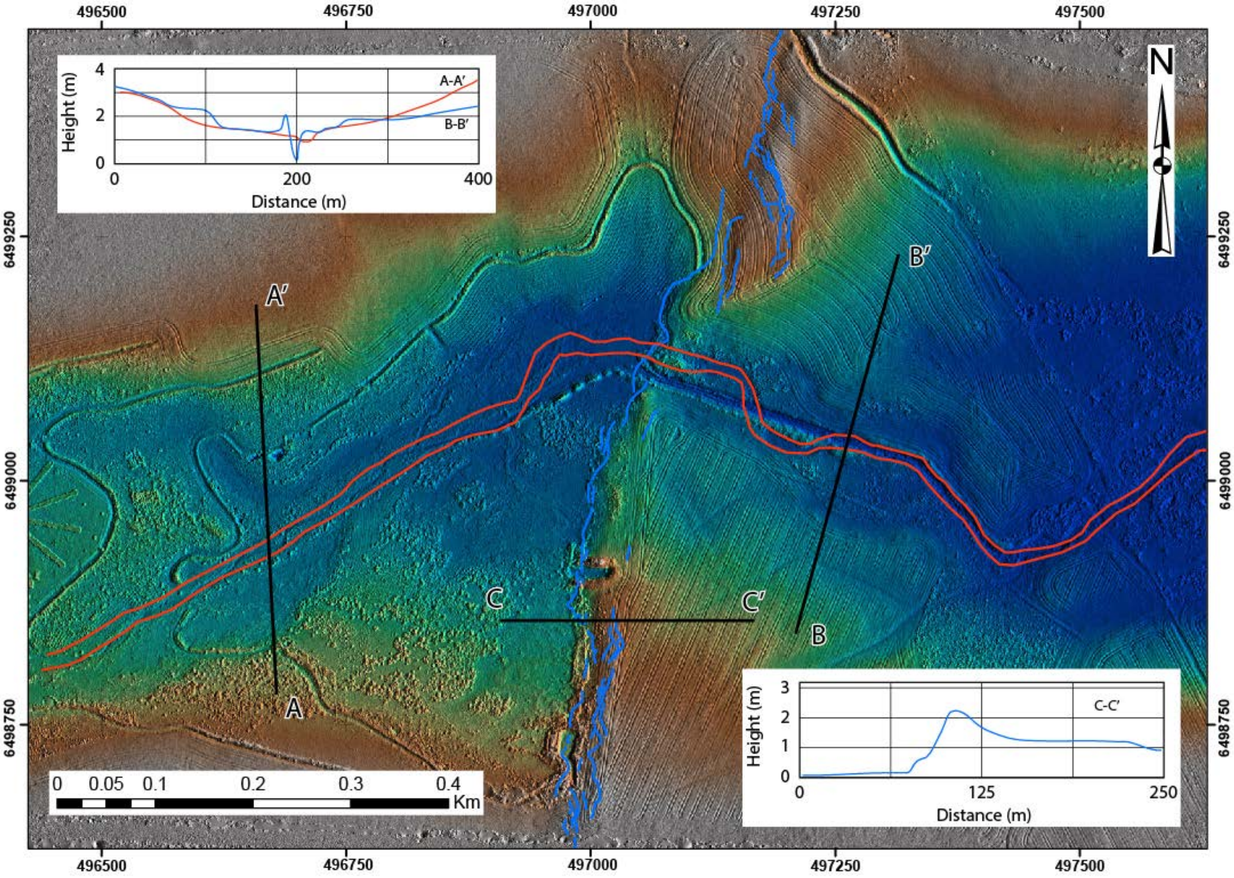

Figure 2: High resolution UAV digital surface model over the 1968 Meckering scarp between the Great Eastern Highway and the Perth-Kalgoorlie Railway (obtained August 2018). Scarp elements (blue lines) and the pre-1968 course of the stream (red lines) were traced from aerial photography captured two days after the event (Meckering Fault Line Run 6, photo 5147). Earthworks were conducted in the months after the earthquake to re-establish the course of the stream and alleviate flooding and salinisation. The northerly of the 2005 paleoseismic trenches is in the centre of the view. Note that valley profile (A-A’ and B-B’) does not change across the scarp, suggesting an absence of pre-existing relief.

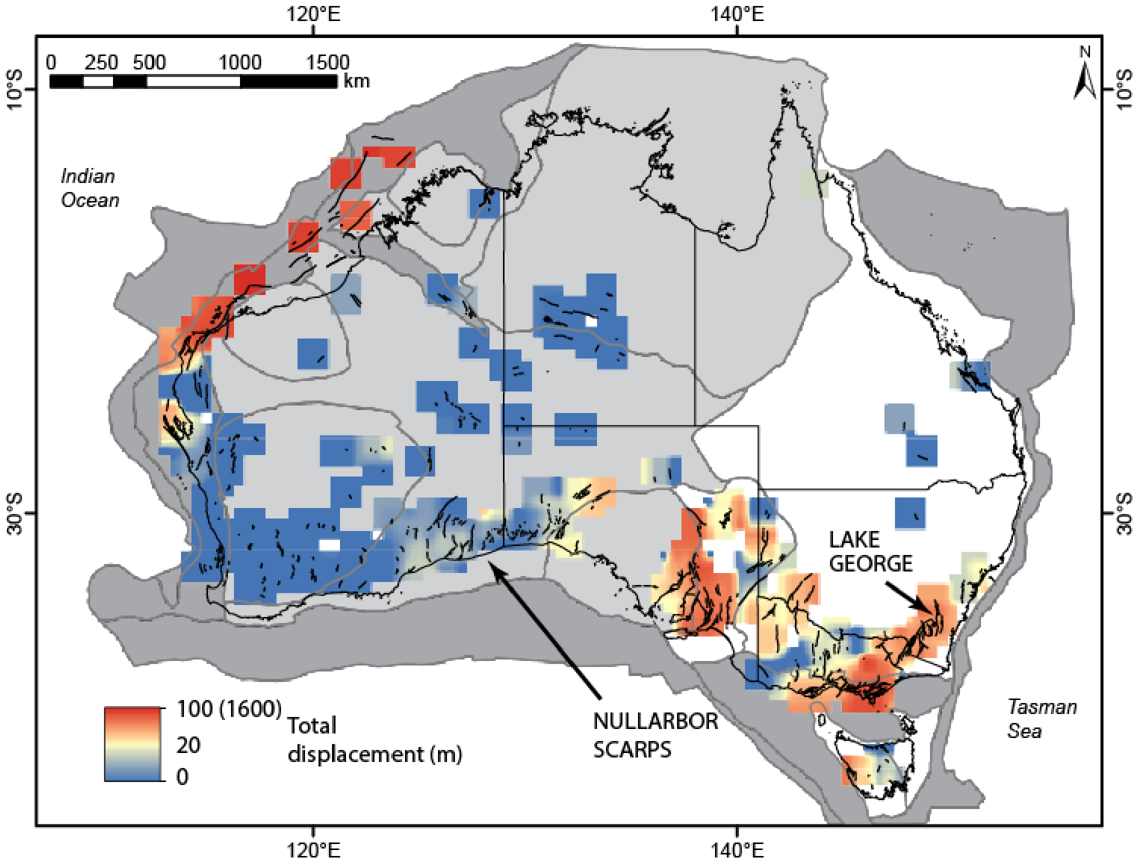

Figure 3: Mean total displacement for neotectonic features (black lines) from the Australian Neotectonic Features database (updated from Clark *et al.*, 2012; Clark *et al.*, 2014a). For instances where robust displacement information is not available in the database, estimates have been made using offset landscape features imaged in SRTM 90 m and ALOS 30 m resolution DEMs (https://github.com/GeoscienceAustralia/NSHA2018/tree/master/source_models/faults/FSM). Interpolation generated using ARCGIS Point Statistics routine with 0.5 degree output cell dimension and 1.5 degree search radius. Color ramp is stretched using histogram equalize (i.e. is not linear), and saturates at the upper end at 100 m displacement. Reverse ruptures are assumed to be exclusively dip slip (which may underestimate displacement in the Otway and Gippsland basins), and features on the northwest shelf are assumed to be exclusively strike-slip. See Figure 1 for explanation of base map shading.

DISCUSSION: EARTHQUAKE “RECURRENCE” ON AUSTRALIAN SEISMOGENIC FAULTS

Figure 3 clearly shows a variation in neotectonic fault displacement across the continent, and the utility of the neotectonic domains model in describing that variation. The warm colours in the eastern part of Australia (Figure 3) relate to the southeast highlands (Clark *et al.*, 2017b), the Otway and Gippsland basins (Holdgate *et al.*, 2003; Sandiford, 2003b; Sandiford, 2003a; Holdgate *et al.*, 2008; Holford *et al.*, 2011), and the Mount Lofty/Flinders ranges (Sandiford, 2003b; Quigley *et al.*, 2006). Warm colours in the northwest of Australia relate to the Western Australia Shear Zone (Whitney *et al.*, 2014; Hengesh & Whitney, 2016) on the Northwest Shelf. The most active faults have accumulated several hundred metres of slip under the current crustal stress regime at long term average rates of several tens of metres per million years. Temporal clustering of large events is reported from several faults that have been subject to paleoseismic investigation (Clark *et al.*, 2015; Clark *et al.*, 2017b; Clark *et al.*, 2018). Preliminary results from modelling of this clustered behavior as a non-homogeneous Poisson process are promising in that fault source parameters (rate within a cluster, temporal spacing of clusters and decay rate from a cluster) appear to varying degrees to be proportional to long term slip rate (Clark *et al.*, 2017a). The analysis also allows that there may be a continuum from relatively faster average long-term slip-rate intraplate faults in the Phanerozoic SCR crust and the slowest slip rate faults in the Australian Precambrian SCR.

However, as described in the previous sections, this has not been demonstrated for the low slip rate faults by paleoseismic investigation.

The cool colours in Figure 3 are predominantly restricted to the Precambrian SCR crust, and relate to scarps that are high enough to be visible on regionally extensive DEM datasets (i.e. > 1.5 – 3 m high, Clark, 2010). Pre-historical 'one-off' ruptures cannot generally be detected. Irrespective, displacements are typically less than 5 m across much of the Precambrian SCR. An upper limit on the long-term rates at which the displacement has accrued is provided by regional bedrock erosion rates of less than 5 m/Myr (Stone *et al.*, 1994; Belton *et al.*, 2004; Jakica *et al.*, 2010). Displacement accumulation rates over the last 100 kyr can be as high as 30 m/ Myr (Clark *et al.*, 2008). Such rates are clearly unsustainable over the long term, leading researchers to propose that displacement is highly episodic in this setting (e.g. Crone *et al.*, 1997; Crone *et al.*, 2003; Clark *et al.*, 2008). This finding is consistent with an analysis of the expected relief generation rates by Leonard & Clark (2011) which imply that the historical catalogue of seismicity in the south west seismic zone is ten times that required to build the scarps. However, revised earthquake rate estimates based on the remediation of catalogue magnitudes for the NSHA18 (Allen *et al.*, 2018b) suggest that long-term forecasts of large-earthquake rates in Precambrian crust may have been overestimated, providing an improved correspondence between the historical and pre-historical earthquake records. Nevertheless, the question remains as to whether the seismic activity within a given area containing neotectonic fault scarps is episodic? Or does the locus of seismicity migrate over time, never to return to previously active regions/faults, as suggested by the nine historical surface ruptures?

Over the last few decades, permanent and campaign GPS studies across Australia have failed to detect a tectonic deformation signal from which a strain budget could be calculated (e.g. Tregonning, 2003). Similar studies have used these observations, amongst others (e.g. Calais et al., 2005), to propose that one-off events of clusters of large events either deplete long-lived pools of 'fossil' lithospheric stress (Calais et al., 2016; Liu & Stein, 2016) and/or that there is an orders of magnitude difference in the timescales of elastic strain accumulation and seismogenic strain release (e.g. Clark *et al.*, 2015; Craig *et al.*, 2016). The observation that groups of faults in eastern Australia (Phanerozoic SCR), together comprising a deforming region several hundred kilometres in extent, can turn 'on' and 'off' more or less simultaneously (e.g. Sandiford, 2003a; Quigley *et al.*, 2010b; Clark *et al.*, 2012), is broadly consistent with the latter hypothesis. However, in western and central Australia, the occurrence of 'one-off' events suggests caution in applying a contemporary elastic strain accumulation model (cf. Braun *et al.*, 2009; Clark, 2010). In what might be a special case, evidence for mid- to late Pleistocene relief-building on the Sanford River scarp (Mt Narryer region), at rates exceeding the local erosion rates, is interpreted in terms of the local faults having only recently 'turned on' in response to progressive southward extension of the West Australia Shear Zone in the Pleistocene (Whitney *et al.*, 2015).

Ideally, the question of whether the events recorded in the contemporary central and western Australian landscape (i.e. the one to three events in the last ~100 kyr on faults in neotectonic Domain 1 crust, and less than a dozen events for some faults in Domain 3 crust) are all that have occurred on those faults in neotectonic times, might best be decided by the investigation of faults that cut Tertiary paleovalleys (de Broeckert & Sandiford, 2005). Progressively greater displacements of older strata might indicate long term-strain accumulation and release episodically as large earthquakes, as assumed in the NSHA18. A pertinent question is what difference would it make to seismic hazard assessments if it were concluded from such a study that the concept of a long-term slip rate is not meaningful in Precambrian SCR crust (i.e. the current landscape expression relates to all the surface ruptures that have occurred on these structures in neotectonic times)?

To explore the sensitivity of seismic hazard estimates to the NSHA18 fault source model, seismic hazard with and without the NSHA18 seismotectonic source models is calculated for three localities within close proximity to neotectonic features: York, WA; Meckering, WA; Adelaide, SA, and; Morwell, VIC (Figure 4). Slip rates assigned to Precambrian SCR faults (near the town of York) in the NSHA18 are universally < 10 m/Myr. Even at longer return periods of interest to major engineering projects, these faults have little impact on hazard curves (Figure 4). Perhaps paradoxically, the seismic hazard is lower at York and Meckering when the fault sources are included. This is due to "moment balancing" procedures introduced in the seismotectonic source models in the complete NSHA18 computations that geometrically filter distributed earthquake ruptures that intersect earthquake sources in the fault-source model (Allen *et al.*, 2018a), which in this case is the Meckering fault scarp. At localities near neotectonic features with higher slip rates (i.e., Adelaide and Morwell), the seismotectonic source models have a greater influence on seismic hazard estimates at return periods of engineering interest, particularly for lower probabilities for exceedance (or longer return periods).

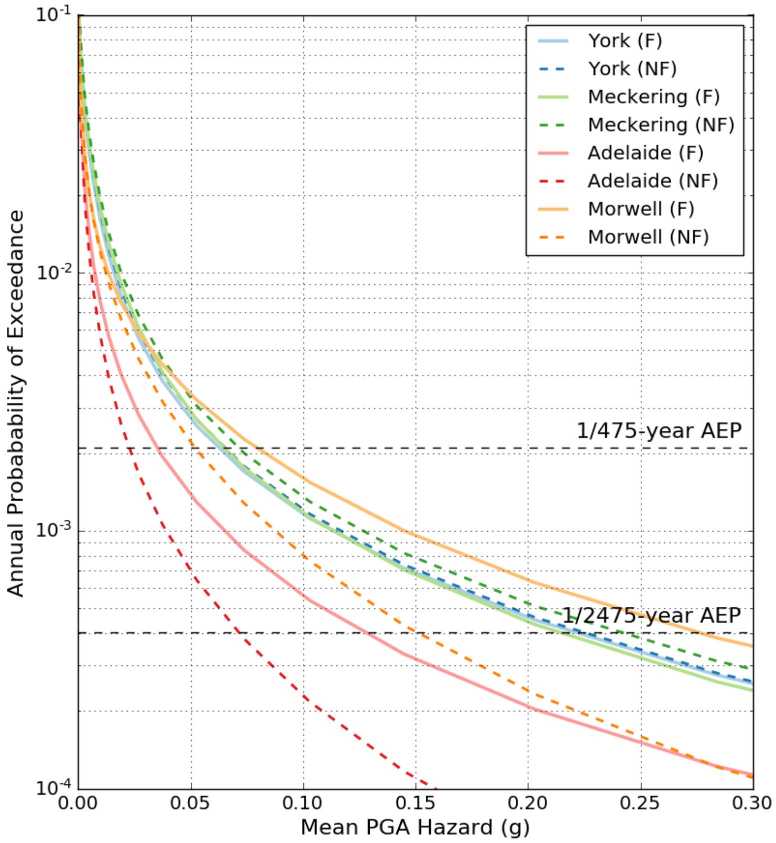

Figure 4: Mean PGA hazard curves for four locations showing the influence of fault sources. Adelaide is located within Phanerozoic SCR crust, Morwell in extended SCR crust, and the remainder in Precambrian SCR crust (cf. Figure 1). Curves denoted with "F" and "NF" indicate seismic hazard estimates with and without seismotectonic fault-source models, respectively.

From a neotectonic perspective, the hazard curves in Figure 4 present a paradox. An assessment of the landscape expression of large earthquakes (a proxy for hazard at long return periods, see also Figure 3) would rank the sites Morwell and Adelaide significantly above those from the Precambrian SCR. Yet the hazard curves for York and Meckering are only marginally less than for Morwell including faults, and are well above Adelaide. In the case of Meckering and York, which are located in the Southwest Seismic Zone (Doyle, 1971), several factors might be at play. The declustering algorithm used for the NSHA18 catalogue (Allen *et al.*, 2018b) considers both spatial and temporal proximity when determining which events might be dependent. The temporal proximity window triggering dependence is proportional to magnitude of the mainshock. A result of this is that most events since 1968 in the Meckering area have been classified as dependent and removed, whereas many events proximal to the smaller Cadoux and Calingiri mainshocks remain in the catalogue, and so contribute to recurrence statistics. Stein & Liu (2009) demonstrate proportionality between fault loading rate and the duration of aftershock sequences, with large intraplate events, such as those in Australia, potentially having aftershock sequences lasting thousands of years. Given the broad distribution of neotectonic fault scarps in the southwest of Western Australia, and the non-correlation of contemporary epicentres with most of those features (Clark, 2010), the general assumption in PSHA – that the historical seismic record is the best predictor of the next 50 years of seismicity – may break down at longer return periods should the contemporary seismicity migrate to a new centre within the broad region enveloping the neotectonic fault scarps. Where long return period hazard estimates are required (e.g. for critical infrastructure), modelling seismic hazard across a broad zone of distributed seismicity will tend to reduce possible seismic demand levels. Consequently, modelling hazard using deterministic scenarios or through the assignment of a minimum base shear design level (e.g. Humar, 2015), might provide a more appropriate minimum level of seismic protection. The take home message is that earthquake occurrence is typically more complicated than the models on which hazard maps are based, and that the available history of seismicity is almost always too short to reliably establish the spatiotemporal pattern of large earthquake occurrence (cf. Stein *et al.*, 2012).

CONCLUSIONS

Geological investigations of the nine historical surface rupturing earthquakes, which have all occurred in Precambrian SCR crust, found no evidence to suggest a prior event in the geologically recent past. The handful of paleo-earthquake scarps that have been investigated in the same setting show evidence for limited recurrence of large events (i.e. less than three to four events in the last 100 kyr, potential for previous events at times unspecified). Further research is required to determine if the events forming the current topography are the only events that have occurred on a given fault scarp (i.e are essentially one-off), or if they represent only the more recent of a protracted series of events (i.e. a long-term slip rate might be validly applied).

Based on our current understanding of earthquake recurrence on neotectonic faults in the Precambrian SCR crust, there appears to be limited advantage to including these features in seismotectonic source models for national-scale PSHAs. Low implied slip rates, and thus low rates of earthquake recurrence, have little effect on overall PSHA calculations at return periods of engineering interest. In contrast, neotectonic features in Phanerozoic and Extended SCR crust can influence seismic hazard at probabilities for exceedance of engineering interest. Consequently, whilst paleoseismic studies might be important in demonstrating whether long-term slip rates might be meaningfully assigned to Precambrian SCR faults, and in exploring the potential for non-stationary earthquake occurrence, it could be argued that instead of modelling fault sources, the seismic hazard could be modelled equally well using simple area-based distributed seismic source models. Furthermore, potentially greater benefits might be realised from investigations of neotectonic features in Phanerozoic SCR crust, which typically demonstrate higher slip rates and contribute more significantly to estimates of probabilistic seismic hazards at return periods of engineering interest.

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