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Incorporating fault sources into the Australian National Seismic Hazard Assessment (NSHA) 2018

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Abstract

Unique challenges are faced in modelling faults in intraplate regions for seismic hazard purposes. Low fault slip rates compared to landscape modification rates often leads to poor discoverability of fault sources, and results in incomplete characterisation of rupture behaviour. Regional and local test cases have demonstrated that fault sources assigned activity rates consistent with paleoseismic observations have the potential to significantly impact probabilistic seismic hazard assessments in Australia. To reflect this, the 2018 Australian NSHA will, for the first time, incorporate a fault source model. The model includes over 300 onshore faults, and a small number of offshore faults, which are modelled as simplified planes and assigned a general dip and dip direction. Dips are obtained preferentially from seismic-reflection profiles, or are otherwise inferred from surface geology and geomorphology, or estimated using fault geometries from similar neotectonic settings as a proxy. The base of faulting is generally taken as the regional maximum depth of distributed seismicity. Slip rates are calculated from displaced strata of known age, estimated from surface expression, or are again estimated by proxy from similar neotectonic settings. We construct a logic tree to capture epistemic uncertainty in fault source parameters, including magnitude frequency distribution, and the potential for periodic or episodic recurrence behaviour. This paper introduces the new fault source model, the fault source logic tree as it currently exists, and discusses uncertainty in and sensitivity to various elements of the proposed fault source input model.

Keywords: neotectonic**,** fault source model, NSHA

INTRODUCTION

It is standard practice in most plate margin regions to use a distributed seismicity model and a fault source model as input to national seismic hazard assessments (e.g. Petersen *et al.*, 2014; Stirling *et al.*, 2012). In stable continental regions (SCRs), low fault slip rates compared to landscape modification rates leads to poor discoverability of fault sources and incomplete characterisation of rupture behaviour (Clark & Leonard, 2015; Clark & Leonard, 2014). For this reason few SCR jurisdictions have included a fault source model in their national assessments, relying instead on short records of historical and instrumental seismicity (e.g. Leonard *et al.*, 2014).

Regional and local test cases have demonstrated that fault sources assigned activity rates consistent with paleoseismic observations have the potential to significantly impact probabilistic seismic hazard assessments in Australia (Clark & Leonard, 2015; Clark & Leonard, 2014; Somerville *et al.*, 2008). To reflect this, the 2018 Australian National Seismic Hazard Assessment (NSHA18) will, for the first time, incorporate a fault source model (FSM). The fault source model is a derivative of the Australian Neotectonic Features Database (ANFD, Clark *et al.*, 2012; Figure 1). The ANFD is a geospatial database containing observational information on faults, folds and other features within Australia that are believed to relate to large earthquakes during the Neotectonic Era (i.e., the past 5–10 million years). An important limitation of the database for seismic hazard assessment purposes is that it does not include seismicity source parameters (e.g. dip, slip rate) where those parameters have not been directly measured for a feature of interest. Simple, repeatable rules are used to populate required fields in the FSM where the data is not in the ANFD.

This contribution is divided into two parts. The first documents the process by which features in the ANFD were adapted to be suitable for inclusion into the FSM. The second part introduces the decision tree that forms the basis of the fault source model realisation in the OpenQuake software (Pagania *et al.*, 2014) utilised for the NSHA18. Conceptual models developed over the last decade describing large SCR earthquake recurrence behavior in space and time (Clark *et al.*, 2014a; Clark *et al.*, 2015; Clark *et al.*, 2012) have guided the construction of the FSM and the logic tree. These uniquely account for the defining features of SCR faults - episodic recurrence behavior, and variation in recurrence intervals, maximum magnitude (Mmax) and ground motion attenuation with intraplate geologic context.

THE AUSTRALIAN NEOTECTONIC FSM, PART 1: SOURCE GEOMETRY AND SLIP RATE

The FSM includes over 300 onshore faults, and a small number of offshore faults, which are modelled from ANFD surface traces as simplified planes and assigned a slip rate, generalised dip and dip direction. In line with the active fault model of New Zealand (Langridge *et al.*, 2016), the Australian FSM uses simplified fault traces; often only a handful of vertices per fault source (e.g. Figure 2). While the OpenQuake software can accommodate complex fault traces, fault plane dip is held constant in the NSHA18 realisation, precluding the inclusion of synthetic and antithetic splays. As such, the modelled faults do not have the intrinsic accuracy with respect to fault location compared to the ANFD, and so are not appropriate for fault offset or site specific studies.

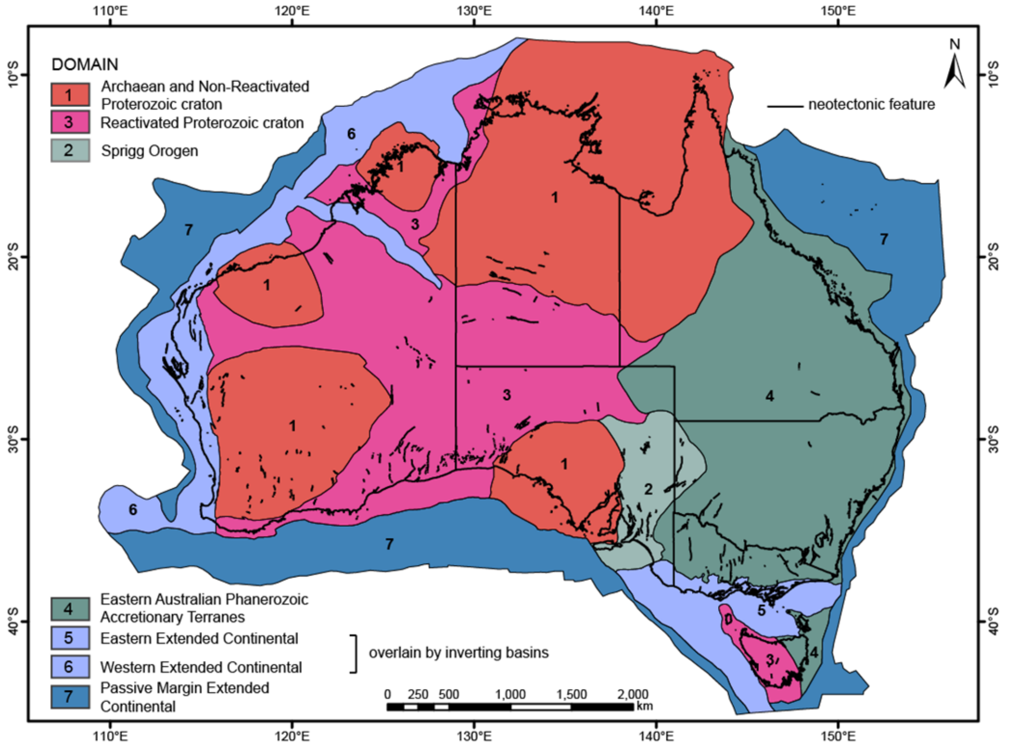

Figure 1: Neotectonic features from the Australian Neotectonic Features database (black lines) overlaid onto the neotectonic domains model of Clark et al. (Clark *et al.*, 2012).

Figure 2 highlights the differences in the spatial representation of a fault between the ANFD and the FSM. In most cases the ANFD and FSM surface traces differ by less than one kilometre. The 1988 Tenant Creek ruptures are chosen as an extreme case, where the difference between the actual and modelled surface trace is up to 6 km. Figure 2A shows the surface trace mapped from field observations (Machette *et al.*, 1991). While the complex surface scarp was the result of three large earthquakes within a 12 hour period (Bowman, 1991; Bowman, 1992; Choy & Bowman, 1990; Crone & Machette, 1997), the surface scarp is indistinguishable from a single source in the landscape. The current iteration of the FSM models this, and other ruptures with complex geometry (e.g. the 1968 Meckering scarp, Gordon & Lewis (1980)), by selecting the greatest tip to tip length with a common general dip direction. Antithetic structures are not at present modelled. It is unavoidable that some seismic moment is not modelled as a result of the reduction in total fault area in the simplification process. This might especially be the case for paleo-ruptures, which tend to be associated with simpler surface trace geometries than historic scarps, in some cases presumably as the result of erosion. The length of surface expression is assumed to approximate to the subsurface maximum rupture length. To account for poor discoverability of the tapered ends of a rupture, a length uncertainty of +5 km is reasonable.

Dips are obtained preferentially from seismic-reflection profiles, or are otherwise inferred from surface geology and geomorphology, or estimated using fault geometries from similar neotectonic or crustal stress regime settings as a proxy. Dips from the ANFD obtained from shallow paleoseismological investigations in soft sediments are generally not used, as significant change in fault dip might be expected between seismogenic depth and the near surface environment. It might be expected that the dip could reasonably vary by ± 10 degrees from the assigned value.

Moderate size earthquakes have a propensity to rupture to the surface in the cratonic domains (Domains 1 & 3, Figure 1) of the western two-thirds of Australia (e.g. Clark *et al.*, 2014b; Dawson *et al.*, 2008). In general, this characteristic reflects very shallow nucleation depths for most earthquakes in these domains (Choy & Bowman, 1990; Langston, 1987; Leonard, 2008). The top of faulting is hence taken as the ground surface. In Phanerozoic and extended domains (Domains 2 & 4-7), not all morphogenic earthquakes break the surface. For example, neotectonic deformation in the Gippsland Basin is defined by near surface folding overlying reactivated basin faults at depth. In these domains the top of faulting is varied from the ground surface to 1-2 km depth. The base of faulting is everywhere taken as the regional maximum depth of distributed seismicity (Balfour *et al.*, 2015; Leonard, 2008). We adopt the Leonard (2010) fault aspect ratio for the neotectonic domain Mmax – 0.5 magnitude units until the base of faulting is reached. Therafter OpenQuake extends only the fault length.

Modelling slip rates on Australian SCR faults prone to episodic rupture behaviour is the most scientifically challenging component of the FSM (Clark & Leonard, 2015; Clark & Leonard, 2014). The ANFD contains two measures that might be used to estimate fault slip rate. In a small number of instances slip rate data is available from paleoseismic trenching investigations (e.g. Clark *et al.*, 2015; Clark *et al.*, 2011; Quigley *et al.*, 2006). These data provide a snapshot of the last few events on the fault, and so typically capture slip rates during an ‘active period’ on the fault. Data from displaced strata or geomorphic surfaces of known age can provide fault slip estimates over longer time intervals, potentially spanning active and quiescent periods on the fault (i.e. long-term slip rates) (e.g. Gardner *et al.*, 2009; Sandiford, 2003). However, the majority of features within the ANFD are not associated with explicit fault displacement data. In these instances, the height of a scarp feature might be used as a proxy for vertical displacement, with guidance from better documented features within the same neotectonic domain as to how much expression is likely to be neotectonic. An understanding of the landscape modification rates (i.e. erosion and deposition) is crucial to accurate estimates of long term slip rates for these features. A +/-20% uncertainty is reasonable for slip rate estimates.

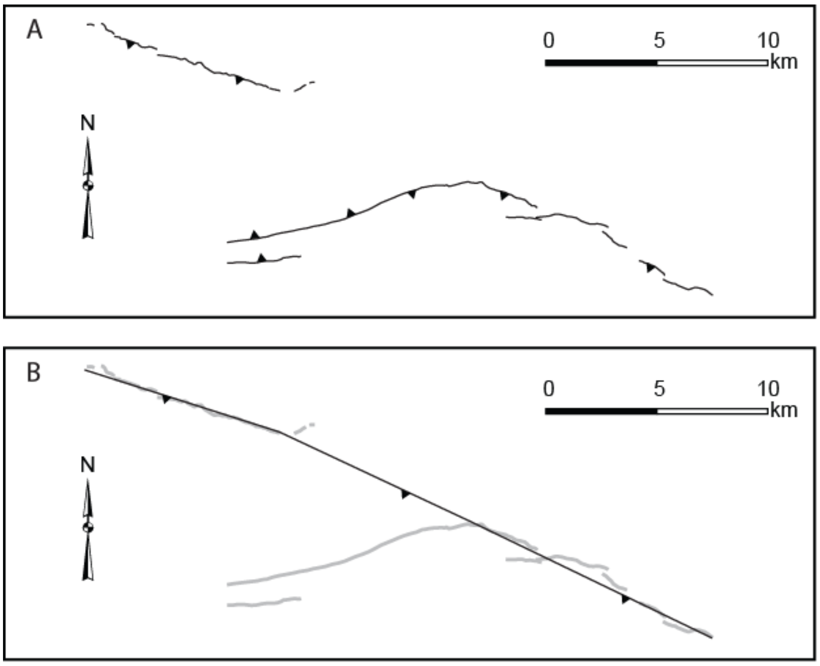

Figure 2 Example of simplification of fault trace geometry – the 1988 Tennant Creek Scarp as represented in the A) Australian neotectonic features database, B) Fault source model.

THE AUSTRALIAN NEOTECTONIC FSM, PART 2: THE LOGIC TREE

The use of OpenQuake modelling software allows epistemic uncertainty to be incorporated into the FSM. The alternative models that may be useful in representing fault behaviour can be visualised as a logic (or decision) tree, as presented in Figure 3. We adopt the interpretation of Musson (2012) that a logic tree weight represents the probability that the model in question is better than the others considered. Put a different way, the correct way to interpret the weights on each branch of a logic tree is as the estimate that it represents the best of the available 'useful' models. Only one branch can be the best one, and one branch must be the best one. Crosses on Figure 3 indicate weightings where the expert elicitation process will be used to populate values.

In this first implementation of the FSM, we adopt a pragmatic approach and focus on the few parameters that have the most impact, while accepting the tree might expand during the expert elicitation process. Below we discuss parameter uncertainty in the full tree (Figure 3a), and justifications for the simplifications adopted in the proposed tree (Figure 3b). It is worth noting that as the hazard is a function of moment rate, when a node has three branches, a mean and ±X, the two ±X branches largely cancel each other out for the mean hazard value if uncertainty is Gaussian (cf. Musson, 2012), although uncertainty bounds on the hazard value may then be underestimated. We use this reasoning, and sensitivity analysis (Griffin *et al.*, 2016) to justify using a 'best estimate' value only for parameters such as the top and base of faulting, fault dip, observed slip rate, shear modulus (μ) and b (i.e. the observed/inferred values in Figure 3a). For example, Leonard *et al.* (2014) demonstrated for source zones that varying Mmax by ± 0.4 had only a minor impact on the hazard and varying by ± 0.2 had a negligible impact. Similarly, Griffin *et al.* (2016) demonstrate that including a fault Mmax uncertainty of ± 0.2 also has a minor impact on the hazard, as does uncertainty in b (± 0.1) and fault dip (± 30°). Griffin *et al.* (2016) further demonstrate that different seismogenic depths of 10 km and 30km had a modest impact on the hazard. Consequently, we suggest that a model of 20±10 km with the 20km branch having a weight of 0.6 or more would likely only differ slightly from a model with a single 20km branch. For the simplified model earthquake magnitudes were calculated from the best estimate surface rupture length using scaling relationships proposed by (Leonard, 2014). The uncertainties used were those of the published study. Rupture length is limited by the regional Mmax for the neotectonic domain in which the fault resides (Leonard *et al.*, 2014). An Mmax rupture is allowed to 'float' on the plane of longer faults.

The hazard is most sensitive to two branches with quite distinct values of properties and moderately sensitive to three branches which are sufficiently distinct that the two end branches don't cancel each other out. For example, Clark & Leonard (2014) demonstrated that the choice of Characteristic Earthquake (CE) or Gutenberg-Richter (GR) made a major difference to the hazard. In general, paleoseismic data cannot discriminate between Gutenberg-Richter and Characteristic magnitude frequency distributions on Australian faults (Clark & Leonard, 2015). Consequently, both models are considered as logic tree branches. Restricting only the larger earthquakes to the fault, by increasing Mmin on both CE and GR faults, also makes a major difference to the hazard (Clark & Leonard, 2014). The neotectonic domains model (Clark *et al.*, 2012) might be used as a guide to spatial variation in Mmin.

Clark & Leonard (2014) demonstrated that hazard was very sensitive to slip-rate. As mentioned above, most slip rate estimates from the ANFD span time periods sufficiently long to include both active and quiescent periods on a fault that is episodically active. In such circumstances, it is questionable whether a ‘long-term’ slip rate is a meaningful quantity for seismic hazard purposes as the fault is either ‘on’ (i.e. slipping at much greater than this rate) or ‘off’ (slipping at a fraction of this rate) (cf. Clark & Leonard, 2014). A model that recognises that long-term slip rates are often the only data available for a group of Australian faults, and includes weighted branches for active period, quiescent period and long-term slip rates, has been used for hazard assessment in the Otway Basin with some success by Stirling et al. (Stirling *et al.*, 2011). Herein we adopt a similar modelling strategy.

As only a handful of faults have been the subject of a paleoseismological investigation we cannot discount the possibility that periodic rupture (i.e. the average return period derived from the long term slip rate assuming a Poisson distribution) occurs on some faults and/or in some settings. We therefore include a decision tree branch that allows that a fault is slipping at the long term average rate as well as branches for episodic rupture behaviour. Where only a long term slip rate is available, we weight branches where the fault is slipping at either 10 times or 0.1 times the long term average rate. 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 (Clark *et al.*, 2008; Clark *et al.*, 2014a; Clark *et al.*, 2015; Crone *et al.*, 2003). We therefore justify the use of a FSM that lacks spatial completeness (cf. Clark & Leonard, 2014, Figure 2). In regions of higher neotectonic uplift rate, such as the inverting Mesozoic basins (Otways, Gippsland, Carnarvon; Domains 5&6, Figure 1), active period relief may not be completely removed in a quiescent period, but the youthfulness of the relief will be noticeably degraded. Where paleoseismological data is available for the last few events on a fault we adopt the approach used in the 2014 USNSHM for the Meers Fault (Petersen *et al.*, 2014), which effectively weights the active period (short-term) slip rates calculated by the study.

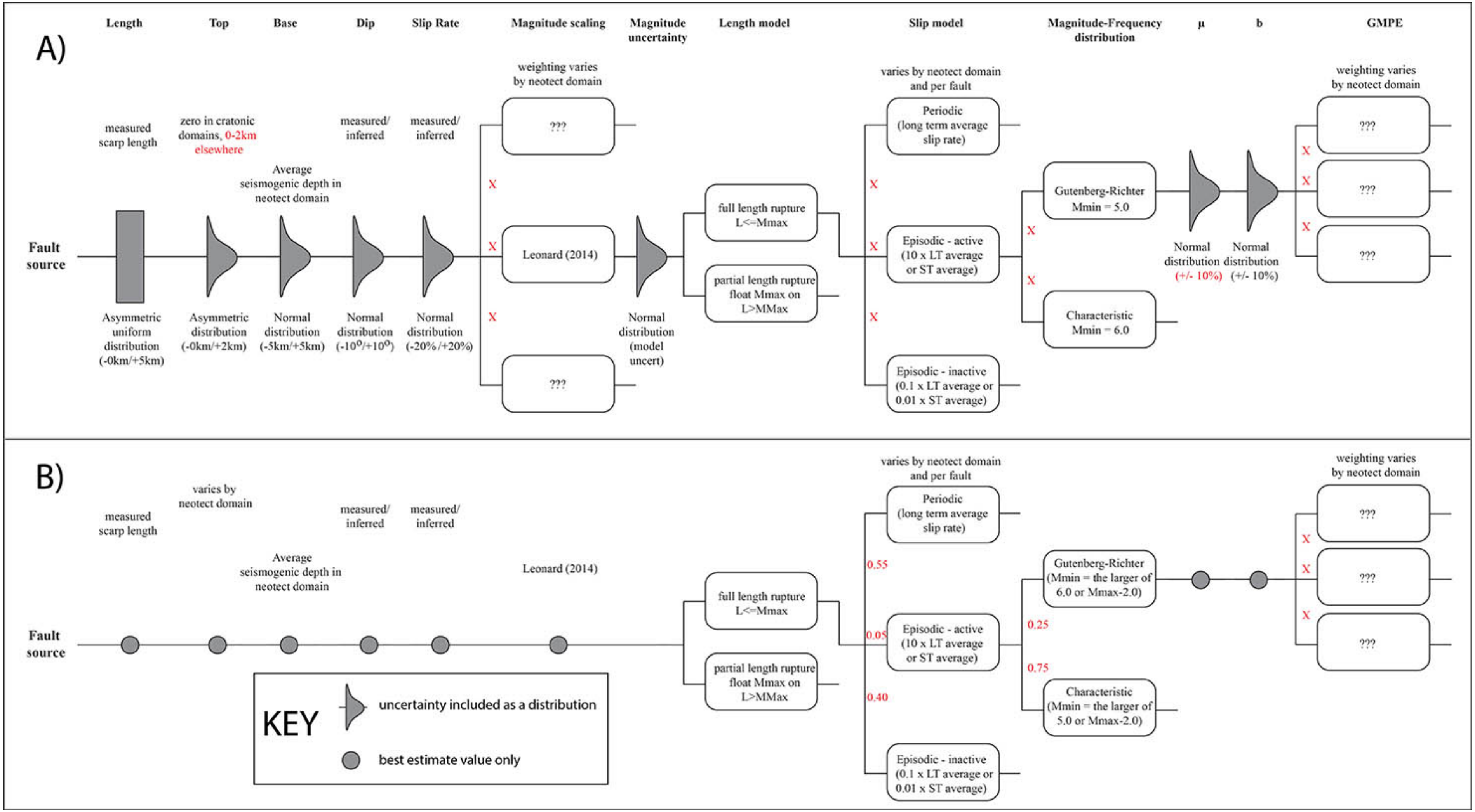

Figure 3: Fault source model logic tree. (A) Complete model, (B) simplified model with example weightings for a fault in an unknown activity phase.

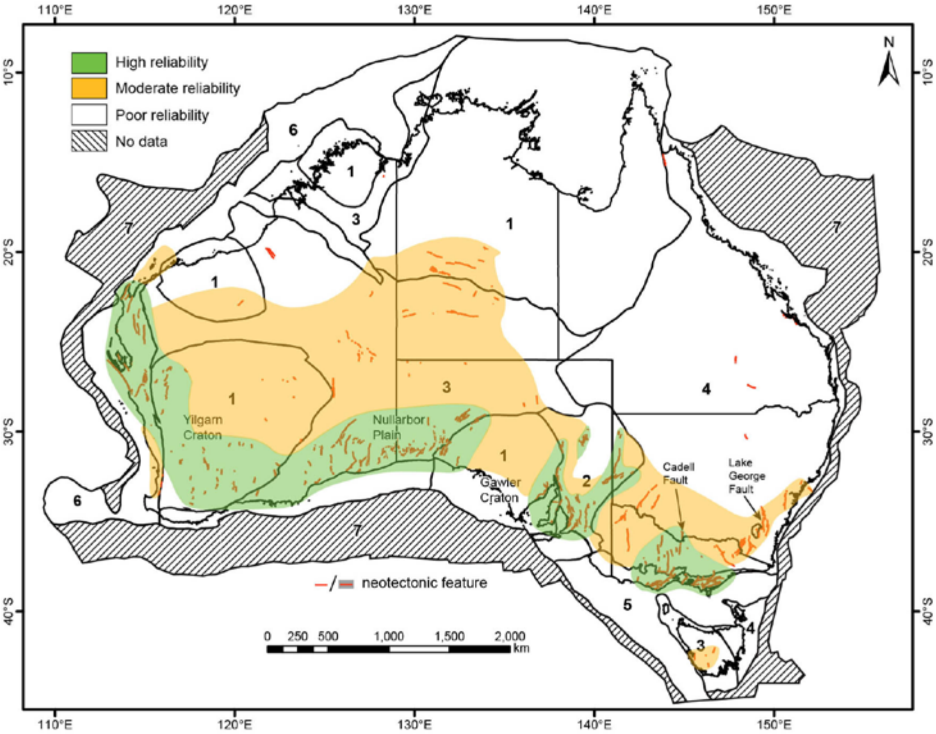

Figure 4: Schematic map depicting the completeness/reliability of the ANFD. High reliability implies that 75% or more of features relating to Mw>6.5 earthquakes that have occurred in the last *ca.* 100 kyr are thought to be known. Moderate and poor reliability relate to 50-75% and <50% thresholds respectively (reproduced from Clark & Leonard, 2014).

DISCUSSION

Dataset completeness

It is very likely that the incompleteness of the neotectonic catalogue (Figure 4) would result in an under-estimate of the hazard, especially in regions where landscape modification rates (erosion/deposition) are comparable to or exceed the rates of tectonic relief building (cf. Clark & Leonard, 2014). However, 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 much of catalogue of neotectonic faults (e.g. Chéry & Vernant, 2006; So & Capitanio, 2016), presents a mitigating factor. The comparatively rapid relief-building on intra-plate faults during active periods leads to greatly enhanced discoverability (cf. Figure 4). It may be inferred that a large percentage of those faults 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. All of the earthquakes that have produced surface ruptures in historic times, including the 21st May 2016 Petermann Ranges earthquake, are of this kind. In eastern Australia we can be less confident that relief across a neotectonic fault is exclusively associated with recent activity. While the Cadell Fault built ~20 m of relief in the last 70 kyr (Clark *et al.*, 2015), only ~10% of the relief across the Lapstone Structural Complex, west of Sydney, was found to be neotectonic (McPherson *et al.*, 2014).

Combining the FSM with the distributed seismicity source model in the NSHA18

Mixed seismicity source models require care in specifying earthquake frequencies and maximum magnitudes in order to avoid double-counting of earthquake occurrences. Perhaps the simplest method of combining a distributed seismicity source model and a fault source model is to define a separate set of minimum and maximum magnitudes for each model. Typically, the area source zone is treated as a region of background seismicity in which small to moderate sized events are modelled as random events up to a maximum magnitude threshold, above which most faults might be expected to surface rupture in the particular neotectonic domain. Recurrence frequency is statistically determined from the instrumental earthquake catalogue. Above the threshold magnitude, larger earthquakes are modelled as occurring on the defined faults, with recurrence frequency defined from the fault geometry and slip rate as per, for example, Figure 3. For characteristic faults (cf. Youngs & Coppersmith, 1985), Clark & Leonard (2014) concluded that at 500 and 2500 year return periods the final hazard computed from the combined fault source and distributed seismicity models is most sensitive to changes in the Mmin of the fault sources rather than changes to Mmax of the source zone. 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)).

The 21st May 2016 Mw6.0 Peterman Ranges earthquake was the latest in a series of surface rupturing earthquakes in the cratonic parts of Australia where little evidence was found for prior events on the rupturing fault (i.e. all the historic surface ruptures). We must therefore expect M≥6 earthquakes to occur as part of the background seismicity within Australia; and not exclusively on faults. Except in the case of the historical surface ruptures (Clark *et al.*, 2014b), the spatial correlation between contemporary seismicity and known neotectonic faults over much of the continent appears to be poor (Clark *et al.*, 2012). For this reason, a combined model where earthquakes above a certain magnitude in the historic catalogue (or extrapolated from the historic catalogue) are assumed to occur on known faults, is inappropriate.

Further, Leonard and Clark (2011) show that, despite the widely accepted predictive power of small earthquakes, the rate of contemporary seismicity in the southwest of Western Australia is much greater than that required to build the 100,000 year catalogue of surface ruptures. 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. We contend that the case exists for simply adding the fault model to the distributed seismicity model. Given that most areas in Australia are unlikely to have experienced an earthquake approaching Mmax, there is little chance of double counting moment.

CONCLUSIONS

We have presented the process by which we have taken the Australian Neotectonic Features Database and developed a preliminary fault source model that includes a logic tree to capture the epistemic uncertainty of the most important parameters. This fault source model forms the basis of the model that, after an expert elicitation process, will become the fault source model of the 2018 national seismic hazard assessment.

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