A seismic source zone model based on neotectonics data

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Introduction

Australia's rich neotectonic record provides an opportunity to understand the characteristics of intraplate deformation, both at the scale of a single 'active' fault and at the scale of the entire continent. Over the last decade our knowledge of Australian intraplate faults has advanced significantly (e.g. Crone et al., 1997, 2003; Clark & McCue, 2003). Herein, six preliminary seismicity source zones spanning continental Australia, and based upon neotectonics data, are proposed. Each source zone contains active faults that share common recurrence and behavioural characteristics, in a similar way that source zones are defined using the historic record of seismicity. The power of this domain approach lies in the ability to extrapolate characteristic behaviours from well-characterised faults (few) to faults about which little is known (many). This data, and conceptual and numerical models describing the nature of the seismicity in each source zone, has the potential to significantly enhance our understanding of seismic hazard in Australia at a time scale more representative than the snapshot provided by the historic record of seismicity.

Australia's neotectonic record

Herein, an "active fault" is one which has hosted displacement under conditions imposed by the current Australian crustal stress regime, and hence may move again in the future. Similarly, "neotectonic deformation" is defined as deformation under conditions imposed by the current crustal stress regime. Estimates of 10-5 Ma for the establishment of the current crustal stress regime (e.g. Sandiford et al., 2004) are based upon several lines of evidence. A major unconformity related to uplift, gentle folding and reverse faulting of late Miocene strata in all southeastern Australian basins is constrained to the period 10-5 Ma (Dickinson et al., 2002; Sandiford, 2003), and Pliocene and Quaternary strata overlying this unconformity contain structures consistent with the current stress field. This time interval also corresponds to the initiation of the current phase of uplift in the Southern Alps of New Zealand (Sutherland, 1996) and in Papua New Guinea (Hill & Raza, 1999). Hence, neotectonic displacement is defined as faulting that has occurred in the last 10-5 Ma, and an "active" fault one that has hosted displacement since that time. In practice, the footprint of individual seismic events might only be recognisable in the landscape for several tens of thousands of years to a few hundreds of thousands of years. Consequently the vast majority of known active faults have hosted surface breaking earthquakes in the last 100 kyr.

Figure 1 presents the more than 200 instances of potential neotectonic deformation (predominantly active 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. Verifying the features as active faults is an ongoing process, but has thus far had a high success rate (e.g. Sandiford, 2003; Celerier et al., 2005; Clark, 2005; Quigley et al., 2006; Clark et al., in press; Estrada et al., this volume).

The catalogue of active faults varies in completeness as sampling is biased by the available datasets (e.g. DEMs, mine records, state survey records), by the extent of unconsolidated sedimentary cover on the surface, the rate of landscape processes relative to the rate of tectonic processes etc. Large swathes of northern Australia have not yet been examined. The catalogue is most complete in the southwest of Western Australia (Clark, 2005), where it might be expected that most surface ruptures relating to greater than Mw6.5 earthquakes having occurred in the last 100ka are represented. The Mount Lofty Ranges in South Australia is similarly complete, and perhaps also the Nullarbor Plain.

Less than a dozen faults, mainly from southern Australia, have been quantitatively examined to determine source parameters (e.g. timing of events, recurrence, magnitude, Fig. 2). Two important characteristics of Australian intraplate faults are revealed in the extant data:

1. recurrence of surface breaking earthquakes on a single fault is typical (ie. areas hosting active fault scarps are earthquake-prone).
2. temporal clustering of events apparent on some faults (ie. large earthquake recurrence in 'active' phases might be much less than during 'inactive' phases).

This is not the sum total of our knowledge as slip rates on faults can be estimated from offset units of known age without knowing about specific seismic events (e.g. Sandiford et al., 2003). Furthermore, if the data in Fig. 2 is combined with information such as the total displacement across faults in the current stress regime, fault length and distribution, relationship to contemporary seismicity, and to topography and landscape etc, the analysis can be taken further by grouping faults sharing common traits into domains.

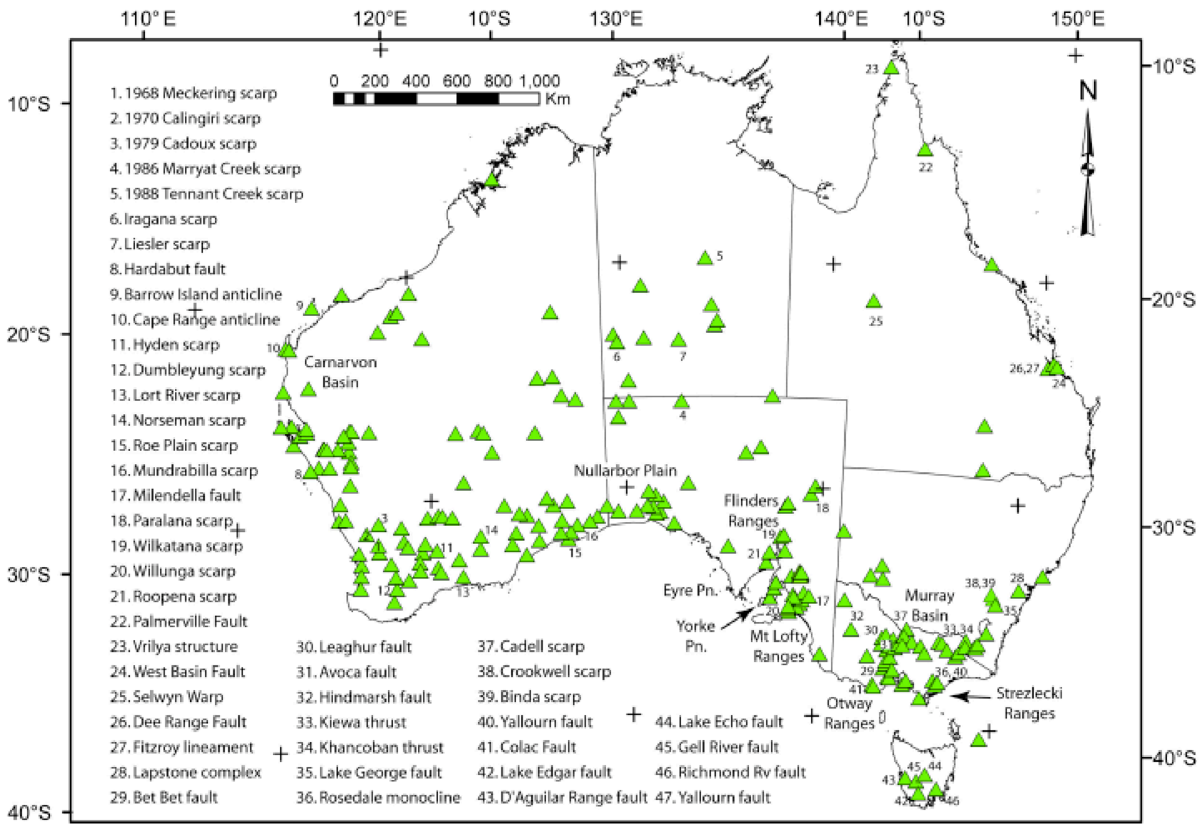


Figure 1. Location of neotectonic features from the GA Australian Neotectonics Database. A selection of the better known scarps have been named.

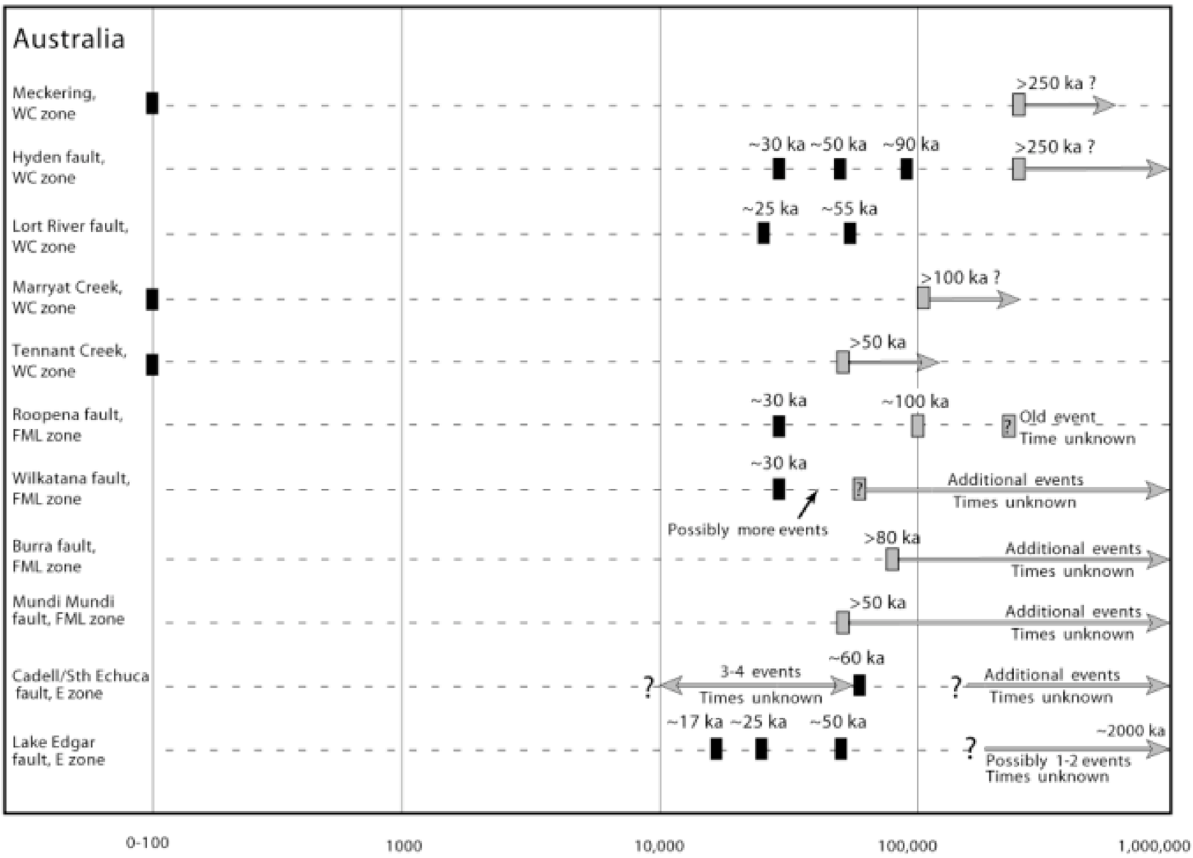


Figure 2. Recurrence data for Australian faults. WC=Western and Central domain, FML=Flinders/Mt Lofty Ranges domain, E=Eastern domain.

Preliminary Seismicity Source Domains based upon neotectonic data

A cursory examination of the landscape and faults in Western Australia and South Australia reveals a marked disparity in the crustal response to imposed stresses (Fig. 3). For example, active faults in Western Australia are typically widely spaced, are not associated with historic seismicity and displace a low undulating landscape by less than 10 m (Fig. 3a). In contrast, faults in the Mt Lofty Ranges are closely spaced, are commonly associated with historic seismicity, and host neotectonic displacements of up to a couple of hundred metres (Fig. 3b).

A summary of the fault characteristics data from across Australia is presented in Table 1. The primary thesis of this study is that Australia may be divided into a number of domains which are distinguished by differing active fault characteristics (Fig. 4). To a large degree the differing active fault characteristics may be related to gross geologic setting (e.g. Archaean craton cf. Proterozoic mobile belt cf. Palaeozoic/Mesozoic arc complex). A consequence of this is that data from a Western Australian fault may not necessarily be directly applied to understand the rupture behaviour of an eastern Australian fault.

In general, known active fault density is low in the Western and Central and Nullarbor domains, high in the Flinders/Mt Lofty Ranges Domain, and intermediate in the Eastern Australia Domain. Neotectonic displacements on individual active faults are typically in the order of ten metres or less in the Western and Central Domain, less than a few tens of metres in the Nullarbor Domain, and up to a couple of hundred metres in the Flinders/Mt Lofty and Eastern Australia domains. A belt of faults with anomalously large displacements for the Western and Central Domain (several tens of metres) occurs in the Carnarvon Basin. These faults fringe the Archaean Yilgarn and Pilbara cratons which may focus strain in this belt. Active fault length is variable within domains and is not diagnostic between domains. Faults longer than 50 km occur in each domain, suggesting that earthquakes of greater than Mw7.0 are possible Australia wide.

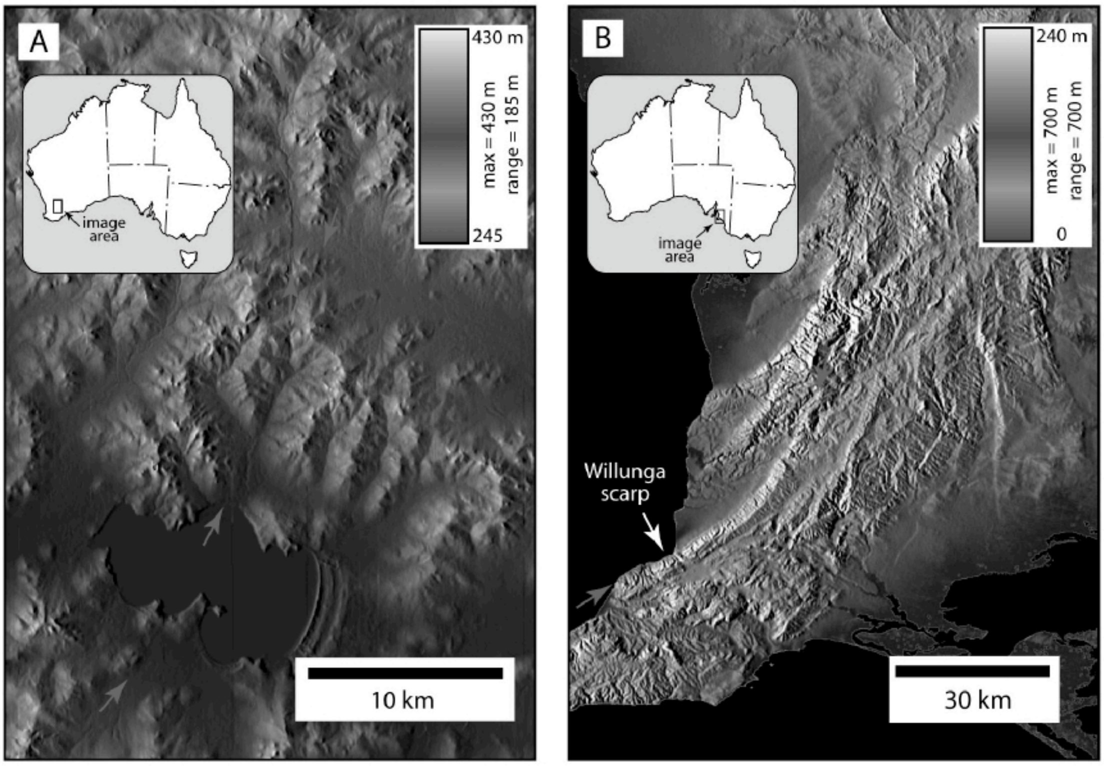


Figure 3. Colour draped shuttle radar 90 m digital elevation model images. (A) Dumbleyung Fault scarp, wheatbelt southwest Western Australia. (B) the Willunga Fault scarp, western range front of the Mt Lofty Ranges, South Australia.

Earthquake recurrence appears to be highly temporally clustered in the Western and Central domain, with events in active periods being separated by several tens of thousands of years, and intervening quiescent periods lasting hundreds of thousands to millions of years. Temporal clustering of events also seems likely for faults on the western margin of the Flinders/Mt Lofty Ranges Domain, but recurrence may be more regular for the faults associated with the greatest uplift in the domain (e.g. Wilkatana Fault, Quigley et al., 2006). The one fault for which data is available in the Eastern Australia domain, the Cadell Fault, demonstrates very marked temporal clustering of events. Three periods of activity since the mid Eocene are imaged in seismic data, each building several tens of metres of relief. The last (current?) period of activity generated 15 m of relief in the last 60 ka, indicating a slip rate for periods of activity at least two orders of magnitude greater than the long term slip rate. Only in the Flinders/Mt Lofty Ranges Domain is there compelling evidence for significant relief relating to active faulting (ie. range building). This domain also bears the clearest relationship between contemporary seismicity and active faulting (with the exception of the five historic surface ruptures in the Western and Central Domain). In most domains, the bulk of active faults are not associated with contemporary seismicity. The Queensland Domain is too poorly known to meaningfully characterise at present.

Table 1 Characteristic of active faults and their relationship to the record of seismicity in the five domains.

Neotectonic region	Western and central Australia[$]	Nullarbor	Flinders/Mt Lofty Ranges	Queensland	Eastern Australia	Tasmania[#]
Completeness of active fault dataset	high in SW, low elsewhere	moderate	high in Mt Lofty and northern Flinders Ranges, moderate elsewhere	low	moderate to high in victoria, moderate to low elsewhere	low
Number of known active faults*	~80-100	5-15	20-30 (a dozen more occur on the Eyre and Yorke peninsulas)	<5	~50-70^	~5
Relative density of known active faults	low to moderately high	low	moderate to high	very low	low to high	moderate
Relationship between active faults to building of ranges	no relation between active faults and large-scale topography, except perhaps in the Carnarvon Basin	no relation between active faults and subdued large-scale topography	ranges bound by active faults	no relation between active faults and large-scale topography	typically no relation between active faults and large-scale topography, but locally some active faults do bound ranges	typically no relation between active faults and large-scale topography, but locally some active faults do bound ranges
Relative historic seismicity rate	moderate to high in SW, low elsewhere	very low	high	very low	moderate	moderate
Relationship of historic seismicity to known active faults	concentrated where there have been historic surface ruptures, rarely associated with pre-historic fault scarps	no association with pre-historic scarps	well defined belt of high seismicity, locally associated with pre-historic fault scarps	no association with pre-historic scarps	no clear association with pre-historic fault scarps	no clear association with pre-historic fault scarps
Post ca. 9 Ma displacement on known active faults	10 m or less	10 m or less	many with displacements up to ~100 m	less than 10 m ?	many less than 10 m, some up to 100 m	some less than 10 m, some up to 100 m
Number of post ca.10Ma ruptures on an individual fault	<4	no data	many	no data	few to many	few to many
Examples	Hyden, Meckering, Lort River	Roe Plain, Mundrabilla	Wilkatana, Roopena	Palmerville	Khancoban, Cadell, Lake George	Lake Edgar, D'Aguilar Range

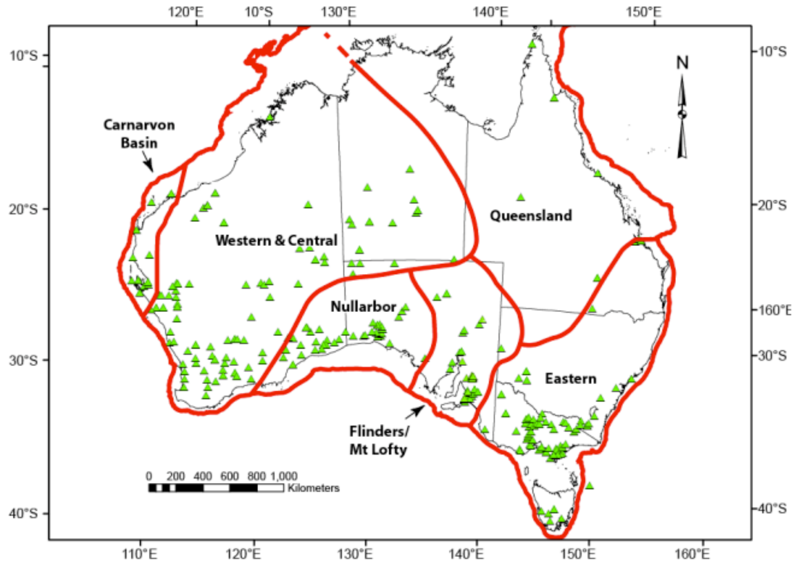
* most regions are under explored, and the level of study is not homogeneous within and between regions. For example, large areas of NW Western Australia are shown as having no active faults. This may largely be a consequence of the area having not been studied.

[#] subset of eastern Australia neotectonic region

[$] relationships based upon the better-studied SW portion of this region

^ several features in Victoria are based upon subsurface mine records of faulted Late Tertiary (10-3 Ma) basalts, where faulting has no surface expression. Further records associate concentrations of small earthquakes with large scarps.

Figure 4. Preliminary neotectonic source domains. Outer boundary is the 200 m isobath. Future refinements will concentrate on refining the basis for the domains with additional neotectonic information. For example, the Queensland domain is almost completely unquantified. The eastern coast of this domain is similar in landscape character to parts of the Eastern domain. Similarly the central Australian orogenic belts (Arunta, Musgrave, Strangways) are of similar geologic character to the seismogenic basement beneath the Nullarbor domain, potentially requiring a redefinition of boundaries.



Discussion: Applications to seismic hazard assessment

In general, Australia is under-explored in terms of its neotectonic record. As a consequence, important conclusions regarding the seismic activity of a region and the characteristics of faults within a region are necessarily based upon incomplete data. However, neotectonic data, and the neotectonic source domains proposed above, has the potential to contribute to seismic hazard assessment in a number of important ways.

1. Improved source parameters for seismicity-based source zones, and a neotectonics-based seismicity source zone map

Neotectonics data provides information about the larger infrequent earthquakes that dominate the moment release budget. Consideration of active fault scarp height and length provides robust estimates of Mmax, and palaeoseismological investigations provide recurrence data. Active fault magnitude-recurrence data for the southwest of Western Australia (Clark, 2005) has already been combined with data from the historic record of seismicity to generate a Gutenberg-Richter relationship which extends out to magnitude Mw7.5 (Leonard & Clark, this volume). The a and b values derived thereby might be applied to the entire Western and Central Source Domain. A similar exercise might be undertaken in other domains as further neotectonics data becomes available, thereby generating a neotectonics seismicity source map that might be included in a weighted logic tree containing seismicity based source zone models for generation of the next national seismic hazard map. Such neotectonics-based models might be expected to better reflect the long-term pattern of seismicity than those based upon the historic record, and hence are appropriate for consideration when designing or assessing critical infrastructure.

In addition, earthquake prone regions may be defined based upon the presence of active fault scarps upon which recurrence can be demonstrated, potentially affecting the background value of hazard for seismicity-based source zones.

2. Active fault source zones for use in the national hazard map

Faults with well understood activity (e.g. Lake Edgar, Cadell) will be included into the next generation hazard model by defining small source zones around the faults which accommodate the larger (>~M6) earthquakes, surrounded by a general zone which accommodates the smaller earthquakes. Parameters from known faults might be extrapolated to faults within the same neotectonic source zone inferred to be active but lacking in detailed recurrence information. Palaeoseismicity data from a representative suite of faults from each source zone will be required to assess the validity of such extrapolations.

3. Active fault source zones for site specific hazard assessment.

A limited number of rupture scenarios have been run for well-characterised active faults (e.g. Cadell Fault, Echuca; Morwell Fault, La Trobe Valley; Lapstone Fault, western Sydney) in order to assess the impact of a recurrence of an event in the palaeo-record (e.g. Dhu et al., 2006). The results indicate impacts of far greater magnitude than those experienced as a result of events in the historic catalogue (e.g. the 1989 Newcastle event). For example, a simulated rupture of the Cadell Fault, generating a Mw7.2 earthquake has been modelled as causing greater than 50% total loss over a 6800 km2 area.

4. Modelling of hazard based upon neotectonic seismicity models and strain rate data.

An alternative approach, perhaps further from realisation, involves the development of hazard maps largely independent of historic seismicity data by using neotectonics data as constraint on numeric crustal strain models. If each active fault is modelled using a generic (or specific) behaviour model derived from the available palaeoseismological data, then a hazard map for larger events might be constructed using the appropriate neotectonics seismicity model for the domain in which the faults occur (ie. uniform strain distribution at long time frames in the Western and Central Domain, Clark, 2005). For the southwest of Western Australia, a model of uniform fault distribution may be adopted with a fault behaviour model involving temporal clustering of events. Each event would collectively sum to a strain rate estimated from GPS, seismic moment release, or finite element crustal strain modelling, with constraint from the landscape character (ie. mountain ranges are not building). Similar scenarios may be run for the Flinders Ranges neotectonic source zone, based upon the neotectonic seismicity model of Celerier et al. (2005).

Conclusions

The neotectonics source zones proposed in this paper are a first attempt to group active faults of like characteristics. With more paleoseismic data (to capture variability in source behaviour) and refinement of neotectonic source zones, extrapolations may be made from well-known faults to other faults, and models describing the long term seismic behaviour of the Australian crust developed. The potential exists thereby to overcome the limitations of the short historic record of seismicity in Australia, upon which all current hazard assessments are based.

References

Celerier J., Sandiford M., Hansen D.L. and Quigley M., 2005. Modes of active intraplate deformation, Flinders Ranges, Australia. Tectonics 24, doi:10.029/2004&C001679.

Clark D.J. and McCue K., 2003, Australian Palaeoseismology: towards a better basis for seismic hazard estimation: Annales of Geophysics, 46, 1087-1105.

Clark D., 2005. A preliminary seismicity model for southwest Western Australia based upon neotectonic data. Proceedings of the Australian Earthquake Engineering Society 2005 meeting, Albury Australia. Paper 22, 1-6.

Clark D.J., Cupper M., Sandiford M., and Kiernan K., 2004, Style and timing of late Quaternary faulting on the Lake Edgar Fault, southwest Tasmania, Australia: implications for hazard assessment in intracratonic areas: Geological Society of America Special Publication, in press.

Crone A J, Machette M N, and Bowman J R, 1997, Episodic nature of earthquake activity in stable continental regions revealed by palaeoseismicity studies of Australian and North American Quaternary faults.: Australian Journal of Earth Sciences, 44, 203-214.

Crone A J, de Martini P M, Machette M N, Okumura K, and Prescott J R, 2003, Paleoseismicity of aseismic Quaternary faults in Australia Implications for fault behaviour in stable continental regions: Bulletin of the Seismological Society of America, 93, 1913-1934.

Dhu T, Robinson. D., McPherson A. Leonard M., Sinadinovski C., Cummins P. & Schneider, J., 2006. Earthquake Risk in Australia. Proceedings Volume of the Australian Earth Science Convention 2006. Melbourne, Australia. p144.

Dickinson J.A. Wallace M.W., Holdgate G.R., Gallagher S.J. and Thomas L., 2002. Origin and timing of the Miocene–Pliocene unconformity in southeast Australia. Journal of Sedimentary Research, 72, 288-303.

Estrada B., Clark, D., Wyrwoll K.-H. & Dentith M., 2006. Palaeoseismic investigation of a recently identified Quaternary fault in Western Australia: the Dumbleyung Fault, this volume.

Hill K.C. and raza A., 1999. Arc-continent collision in Papua New Guinea: constraints from fission track thermochronology. Tectonics, 18, 950-966.

Leonard. M. & Clark D., 2006. Reconciling neotectonic and seismic recurrence rates in SW WA., this volume.

Quigley, M., Cupper, M., Sandiford, M, 2006. Quaternary faults of southern Australia: palaeoseismicity, slip rates and origin. Australian Journal of Earth Sciences 53, 285-301.

Sandiford M, 2003. Neotectonics of southeastern Australia: linking the Quaternary faulting record with seismicity and in situ stress: In: eds Hillis R.R. & Muller D, Evolution and dynamics of the Australian Plate, Geological Society of Australia Special Publication 22, 101-113.

Sandiford, M., Wallace, N., Coblentz, D, 2004. Origin of the in situ stress field in southeastern Australia, Basin Research 16, 325-338.

Sutherland R., 1996. Transpressional development of the Australia-Pacific plate boundary through southern South Island New Zealand: constraints from Miocene-Pliocene sediments, Waiho-1 borehole, South Westland. New Zealand Journal of Geology and Geophysics 39, 251-264.