

LARGE EARTHQUAKE RECURRENCE IN NEW SOUTH WALES: IMPLICATIONS FOR EARTHQUAKE HAZARD

D. J. Clark

Earthquake Hazard Project, Geoscience Australia

ABSTRACT

The Australian continent is actively deforming at a range of scales in response to far-field stresses associated with plate margins and buoyancy forces associated with mantle dynamics. On the smallest scale (10^1 km), fault-related deformation associated with far-field stress partitioning has modified surface topography at rates of up to ~100 m per million years. This deformation is evidenced in both the record of historical earthquakes and in the pre-historic record in the landscape. Palaeoseismological studies indicate that few places in Australia have experienced a maximum magnitude earthquake since European settlement because there are faults in most areas capable of hosting potentially catastrophic earthquakes with magnitudes in excess of 7.0. New South Wales is well represented in terms of its pre-historic earthquake record. Seismogenic faulting in the last 5-10 million years is thought to be responsible for locally generating up to 200 m of the contemporary topographic relief of the Eastern Highlands. Faults west of Sydney belonging to the Lapstone Structural Complex, and faults beneath the greater Sydney region, are associated with infrequent damaging earthquakes. Therefore, decisions relating to the siting and construction of the built environment should be informed using knowledge of local neotectonics.

1 AUSTRALIAN CRUSTAL STRESS FIELD

Over the last 45 million years the Australian continent has drifted ~3000 km to the north at a rate of ~6.5 cm/year - further and faster than any other continent. In contrast to other fast moving plates, such as the North and South American Plates, the maximum horizontal stress (S_{Hmax}) orientation within the Australian Plate is not parallel to the plate motion vectors (Figure 1) (Denham, Alexander and Worotnicki 1979, Denham and Windsor 1991, Coblenz, Sandiford, Richardson *et al.* 1995, Hillis and Reynolds 2000, Hillis and Reynolds 2003, Sandiford, Wallace and Coblenz 2004). This complex pattern has been satisfactorily modelled in terms of a balance between driving and resistive plate boundary forces (Coblenz, Sandiford, Richardson *et al.* 1995, Coblenz, Zhou, Hillis *et al.* 1998, Burbidge 2004, Sandiford, Wallace and Coblenz 2004, Dyksterhuis and Müller 2008, Hillis, Sandiford, Reynolds *et al.* 2008). Resistance to plate motion is seen in the mountain ranges of Papua New Guinea, the Himalaya and New Zealand, whereas slab pull along the Indonesian margin, and ridge push to the south along the Australia-Antarctic Discordance are drivers (Coblenz, Sandiford, Richardson *et al.* 1995, Coblenz, Zhou, Hillis *et al.* 1998, Hillis, Sandiford, Reynolds *et al.* 2008).

2 MANIFESTATION OF STRESS AS DEFORMATION

As the fastest, lowest, flattest and amongst the most arid of continents, Australia preserves a unique geomorphic record of intraplate tectonic activity, evidencing at least three distinct modes of surface deformation (Sandiford, Quigley, de Broekert *et al.* 2009, Sandiford and Quigley 2009). At long wavelengths (several 1000's of km) systematic variations in the extent of Neogene marine inundation imply the continent has tilted north-down, southwest-up. This is most convincingly seen along the southern Australian margin, where Miocene limestone of the Nullarbor Plain has been uplifted and subjected to marine erosion to form iconic cliffs. At intermediate-wavelengths (several 100's of km) several undulations of ~100-200 m amplitude have developed on the 1-10 Myr timescale, consistent with the buckling amplitude of the lithosphere. In the two most notable cases, the Lake Mackay palaeo-drainage is now internally draining in its northern reaches, and palaeo-lake Billa Kalina now sits high on a watershed (Sandiford, Quigley, de Broekert *et al.* 2009). At still shorter wavelengths (several 10's of km), fault related motion has produced local relief at rates of up to ~100 m/Myr over a period of several million years (Sandiford and Quigley 2009), for example in the Flinders Ranges (Quigley, Cupper and Sandiford 2006) and the Otway Ranges (Sandiford 2003). While it has been proposed that the second buckling mode of deformation is associated with contemporary seismicity in India (Vita-Finzi 2004), this link has not been proven in Australia. Hence it is the third mode that is of most interest in terms of assessing seismic hazard.

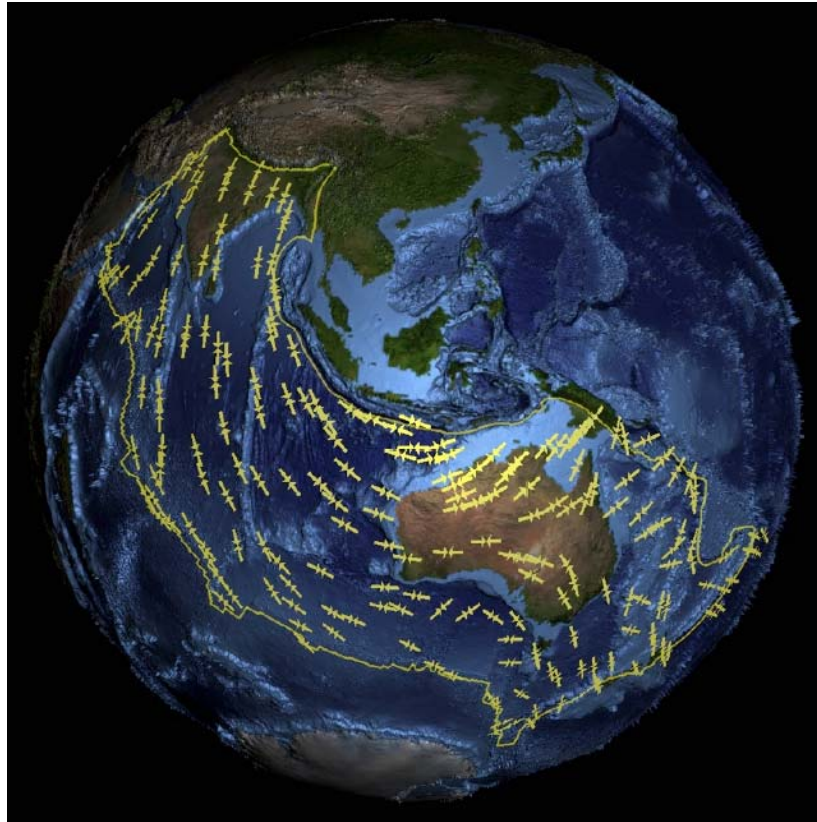


Figure 1. Modelled SHmax trends (Sandiford and Quigley 2009) for the Indo-Australian Plate adapted from solutions in Sandiford *et al.* (2004).

3 THE NEOTECTONIC ERA

Structural and sedimentary evidence from southeast Australian basins suggests that the current crustal stress regime was established in the interval 10-5 Ma (e.g. Dickinson, Wallace, Holdgate *et al.* 2001, Dickinson, Wallace, Holdgate *et al.* 2002, Sandiford 2003, Sandiford 2003, Sandiford, Wallace and Coblenz 2004, Hillis, Sandiford, Reynolds *et al.* 2008). A major unconformity related to substantial regional-scale tilting, uplift, folding and reverse faulting of late Miocene and older strata occurs in all southeast Australian basins (e.g. Gippsland and Otway Basins). Pliocene and Quaternary strata overlying the unconformity contain structures yielding palaeo-stress indicators consistent with the current *in situ* stress field, as determined from seismicity (Denham, Alexander and Worotnicki 1979, Denham and Windsor 1991, Leonard, Ripper and Li 2002) and down-hole stress determination techniques (e.g. Hillis and Reynolds 2000, Hillis and Reynolds 2003, Hillis, Sandiford, Reynolds *et al.* 2008). Here, the time over which the current stress field has pertained is defined as the Neotectonic Era, and a “neotectonic fault” is defined as a fault which has hosted displacement under conditions imposed by the current Australian crustal stress regime, and hence may move again in the future.

The term “active fault” as used in plate margin areas such as California, where a fault is classed as *active* if it has hosted a surface rupturing earthquake in the last 10 ka, is not useful in an intraplate context where large events might be spaced tens of thousands of years or more apart (Machette 2000, Clark 2009). Depending upon location and an understanding of patterns in episodic rupture, a fault or fault segment which has experienced a surface rupture in the last ten thousand years is likely to have expended a significant portion of its accumulated stress. Consequently it is unlikely to host a damaging event for many thousands of years into the future. Stress re-adjustments following a main shock may induce a temporally extended tail of smaller magnitude earthquakes that justifies consideration of the fault as active *sensu stricto*, but damaging aftershocks more than a year or two after the main shock are extremely unlikely, so the fault might defensibly be termed quiescent for seismic hazard purposes. Examples are to be found in the Tennant Creek and Meckering areas, which continue to experience micro-seismicity 21 and 41 years after the respective surface ruptures, but have not generated damaging earthquakes ($M > 5.5$) beyond a couple of years after the main shocks. The contribution to a hazard determination from a given neotectonic fault source, or combination of neotectonic fault sources, would be a more rigorous way to determine whether the intraplate fault(s) should be considered *active* (Somerville, Quijada, Thio *et al.* 2008). Relative contributions should ideally be defined on a local basis from neotectonic/palaeoseismic data,

and depend upon an understanding of the large earthquake recurrence behaviour of the local faults and the earthquake return period of interest (Clark 2009).

4 AUSTRALIA'S SEISMOGENIC NEOTECTONIC RECORD

Australia's rich neotectonic record provides an opportunity to understand the characteristics of seismogenic intraplate deformation, both at the scale of a single 'active' fault and at the scale of the entire continent (Figure 2). Over the last decade our knowledge of Australian intraplate seismogenic faults has advanced significantly, with the recognition that faults in different parts of the Australian continent respond in different fashions to the imposed stress. Six source zones (domains) spanning continental Australia have been proposed (Clark 2006, Clark, McPherson and Collins 2010) based upon neotectonic data (Figure 3a). A seventh offshore source zone is defined based upon analogy with the eastern United States (Johnston, Coppersmith, Kanter *et al.* 1994, Wheeler 1996, Wheeler and Frankel 2000). 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). These data, and conceptual and numerical models describing the nature of the seismicity in each source zone, have 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. This includes providing a means by which to estimate key parameters underpinning the next generation seismic hazard maps for Australia, such as maximum magnitude earthquake (M_{max}) (Figure 3b) and seismic source zone b values.

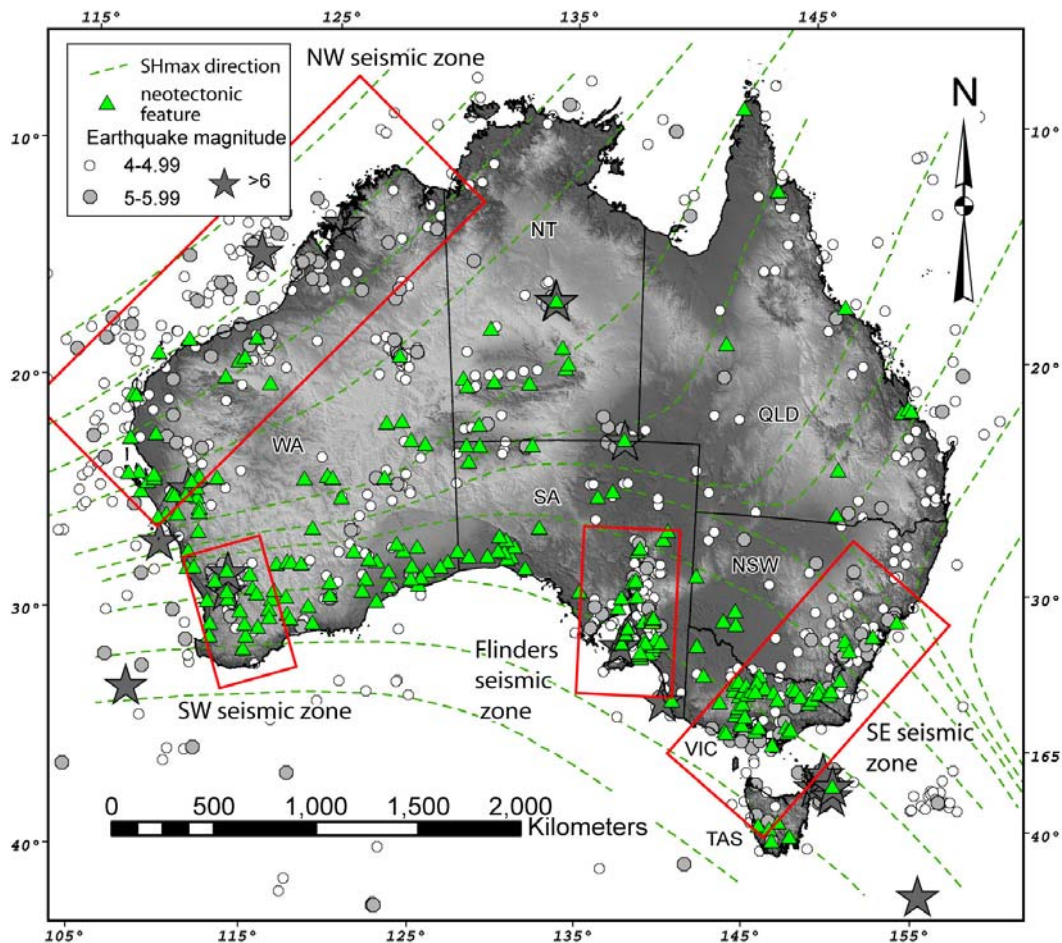


Figure 2: Earthquake epicentres, seismogenic neotectonic features, maximum horizontal stress vectors and zones of elevated seismicity (from Quigley *et al.* (2009)).

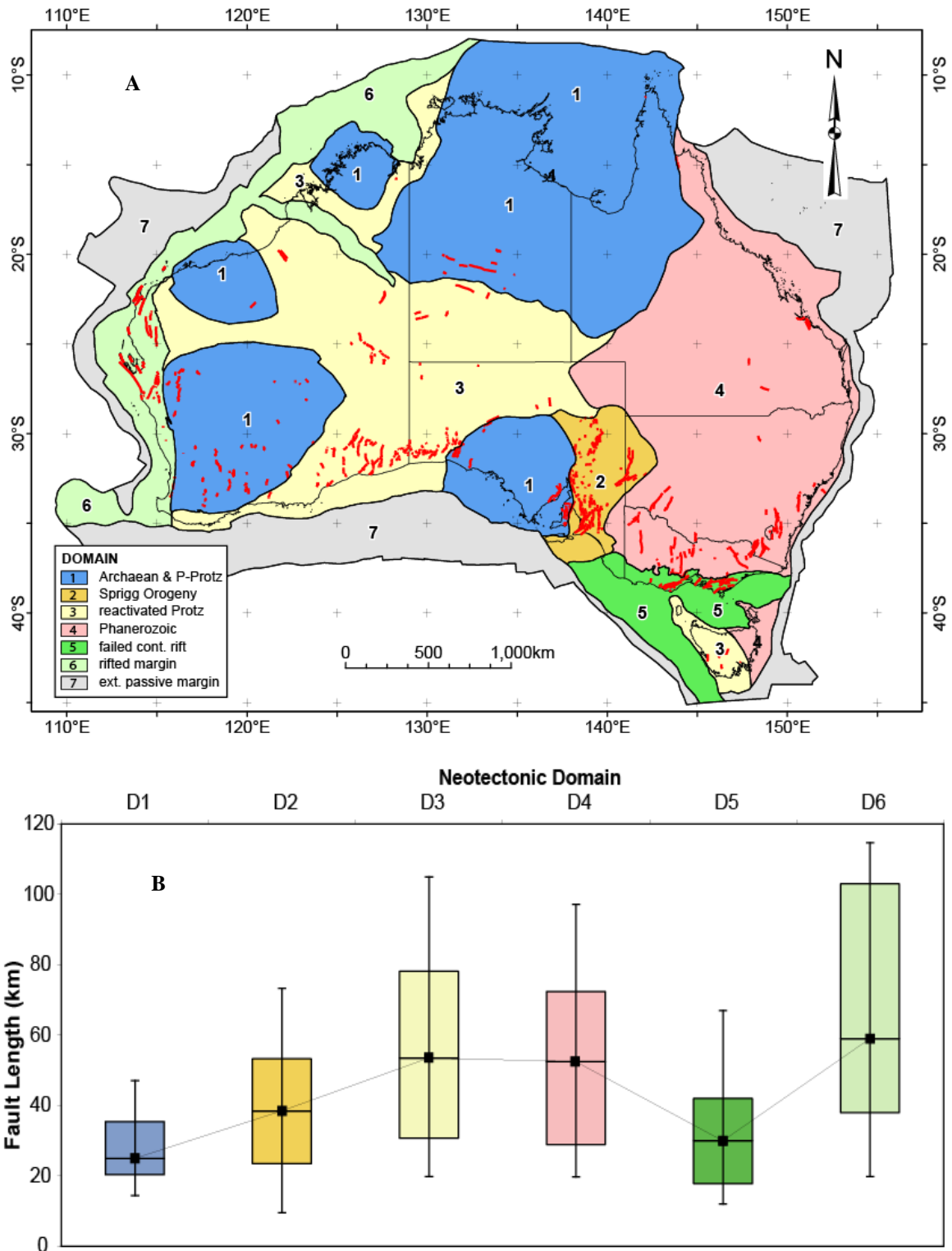


Figure 3: (a) Preliminary neotectonic domains with fault scarps from the Australian neotectonics database overlain, (b) statistics for fault length, which is a proxy for M_{max} . The 75th percentile value of 72 km for the Phanerozoic domain (D4) might be associated with an M_{max} of 7.3 ± 0.1 .

5 THE SEISMOGENIC NEOTECTONIC RECORD OF NEW SOUTH WALES

Known palaeo-earthquake scarps are largely confined to the southern half of New South Wales, in the Murray-Darling Basin (MDB) and the Eastern Highlands (Figure 4). Those in the topographically subdued MDB provide detailed insight into the characteristics of large earthquake occurrence in this domain. For example, west-up displacements across the 80 km long Cadell Fault have resulted in the formation of an up to 15 m high

scarp, diverting the course of the Murray River (Bowler and Harford 1966). The 3-4 m height of a tectonic terrace riser bordering the channel of the palaeo-Murray River in Green Gully, now an airgap, is consistent with entire scarp-length rupture (~Mw 7.2-7.3)(Clark, Van Dissen, Cupper *et al.* 2007). At least four earthquakes of this magnitude are required to produce the observed 14-15 m relief across the scarp. Perhaps a further two events of similar magnitude are required to account for 6 m of aggradation of the Barmah Fan, which buries the foot of the scarp (Stone 2006). These events occurred over a ca. 60 ka time interval between 80-20 ka, and involved a total slip in the order of 25 m (Clark, Van Dissen, Cupper *et al.* 2007). Seismic reflection data obtained over the scarp (Geoscience Australia, unpublished data) indicate only ~ 55 m of displacement of Neogene strata across a 50° west-dipping fault rooted into Lachlan Fold Belt basement rocks. The additional ~30 m of slip appears to have occurred largely in a discrete episode during the Pliocene sea-level high stand. Pronounced temporal clustering of events is implied, with long periods of inactivity separating short periods of scarp building (Clark, Van Dissen, Cupper *et al.* 2007). The topographically similar Danyo, Iona and Neckarboo Ridges in the central Murray Basin (Sandiford 2003) might be expected to have similar large earthquake recurrence characteristics.

Comparable bedrock erosion rates and tectonic relief production rates in the Eastern Highlands might be expected to result in low scarp survivability, bar exceptional circumstances. This expectation is borne out by examples such as the Khancoban-Yellow Bog Fault (Figure 4), which superposes Mesozoic granites over up to 500 m of Cenozoic fluvial gravels (Moye, Sharp and Stapledon 1963, Sharp 2004), yet has little topographic expression. This fault, which might be expected to be highly active, was only discovered as the result of tunnelling operations associated with the Snowy Hydro Scheme. In the Southern Tablelands, several faults are associated with prominent scarps. The Lake George Fault near Canberra began trapping sediments in the Late Miocene, and had completely beheaded the upper Lachlan River Catchment by the Pliocene (Coventry 1976, Singh, Opdyke and Bowler 1981, Abel 1985). It is not clear what relief existed across the fault prior to the neotectonic era, but it seems likely that much of the almost 200 m of vertical displacement across the fault was built in the interval 10-5 Ma associated with the reorganisation of the crustal stress field to its present configuration (Dickinson, Wallace, Holdgate *et al.* 2002, Sandiford, Wallace and Coblenz 2004, Hillis, Sandiford, Reynolds *et al.* 2008). The same may be true of the Lapstone Structural Complex, west of Sydney.

6 QUATERNARY FAULTING PROXIMAL TO SYDNEY

Faults of the Lapstone Structural Complex (LSC) underlie 100 km, and perhaps as much as 160 km, of the eastern range front of the Blue Mountains, west of Sydney (Branagan and Pedram 1990). More than a dozen major faults and monoclinial flexures have been mapped along its extent (Figure 5). The Lapstone Monocline is the most prominent of the flexures, and accounts for more than three quarters of the deformation across the complex at its northern end. The relief across the LSC has been equated with neotectonic activity on the underlying faults, and hence seismic hazard (IGNS 1999). An alternative viewpoint attributes the contemporary relief to the difference in erosion rates of sandstone on the western side, as opposed to relatively soft shale on the eastern side, of a pre-neotectonic LSC (Pickett and Bishop 1992).

The preliminary results of a palaeoseismic study of a fault-bound basin at Mountain Lagoon provide insight into the activity of the Kurrajong Fault (Geoscience Australia, unpublished data). The Kurrajong Fault forms one of the more prominent fault scarps in the LSC, involving 130 m of vertical displacement (Branagan and Pedram 1990), and so might be considered to be one of the more active faults in the complex. Drilling near the lagoon identified 15 m of fluvial, colluvial and lacustrine sediments overlying shale bedrock trapped behind a sandstone fault barrier corresponding to the fault. The age of the basal sediments which cover the floor of the lagoon behind this fault barrier provide quantitative constraint on the timing of fault movement, and suggests that impoundment commenced in the mid to late Miocene. Undeformed sediments that overlie the fault tip and fill the upper parts of the basin have Quaternary ages. This suggests that, barring any significant erosional loss, a maximum of 15 m of vertical displacement has occurred across the Kurrajong Fault in the current stress field. This is consistent with palaeomagnetic data, which indicate that folding and uplift relating to the Lapstone Structural Complex had largely ceased by late Pliocene (Bishop *et al.* (1982) with age recalculated by Pillans (2003)). If the 40 km length of the Kurrajong Fault is considered, our results suggest that maximum magnitude earthquakes of ~Mw 7.0 might occur with an average frequency of between 1-2 million years. The implication is that most relief at the eastern front of the Blue Mountains relates to erosional exhumation of 'old' structures (cf. Pickett and Bishop 1992).

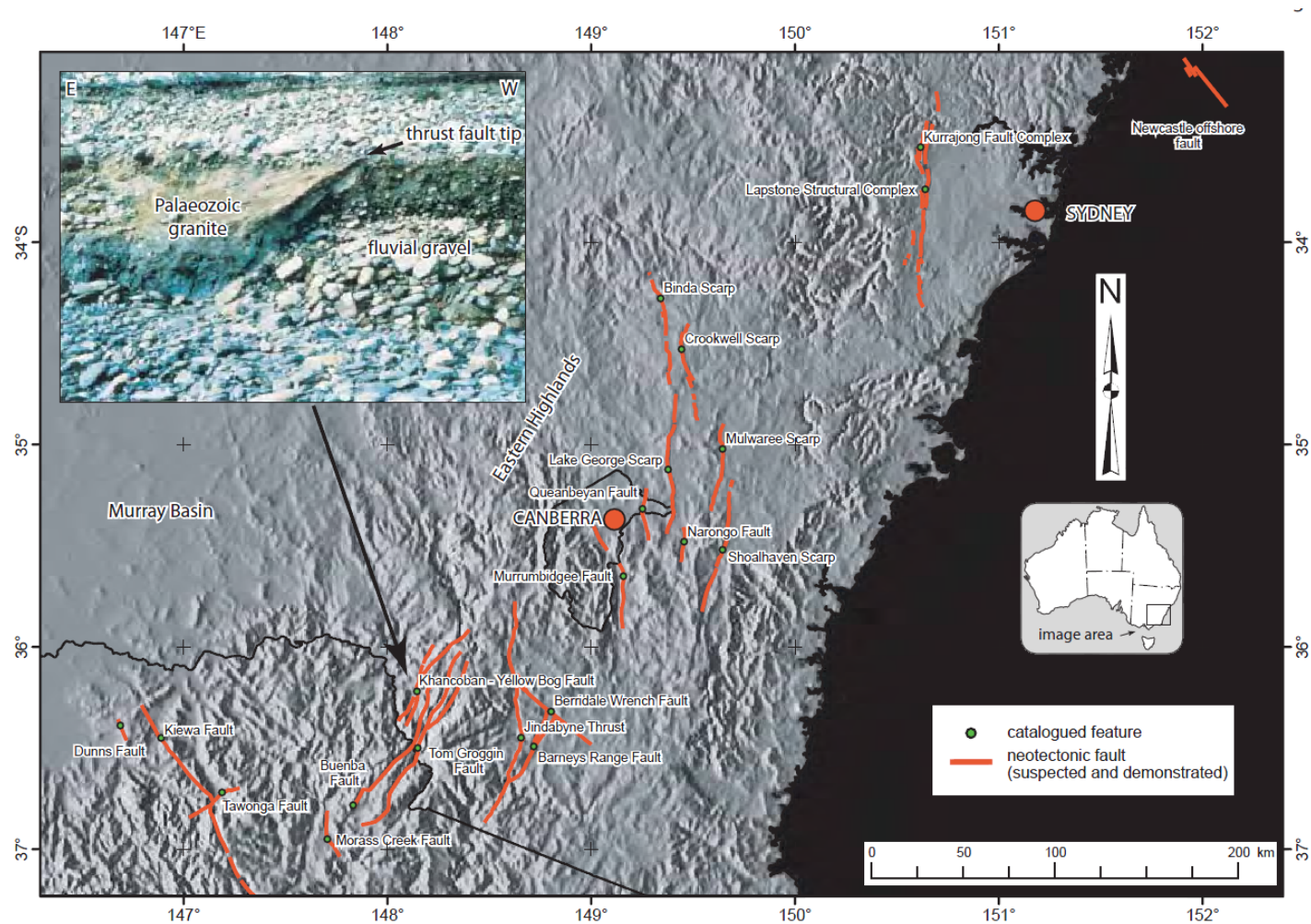


Figure 4: 90 m resolution SRTM DEM over the eastern highlands. Red lines denote fault scarps with suspected or demonstrated neotectonic movement (extracted from the Geoscience Australia neotectonics database, January 2010). Inset shows the Khancoban-Yellow Bog Fault as exposed in the bed of Khancoban Creek shortly after the Murray 1 power station was commissioned in the late 1960's. Inset image kindly provided by David Stapleton (formerly of Snowy Hydro).

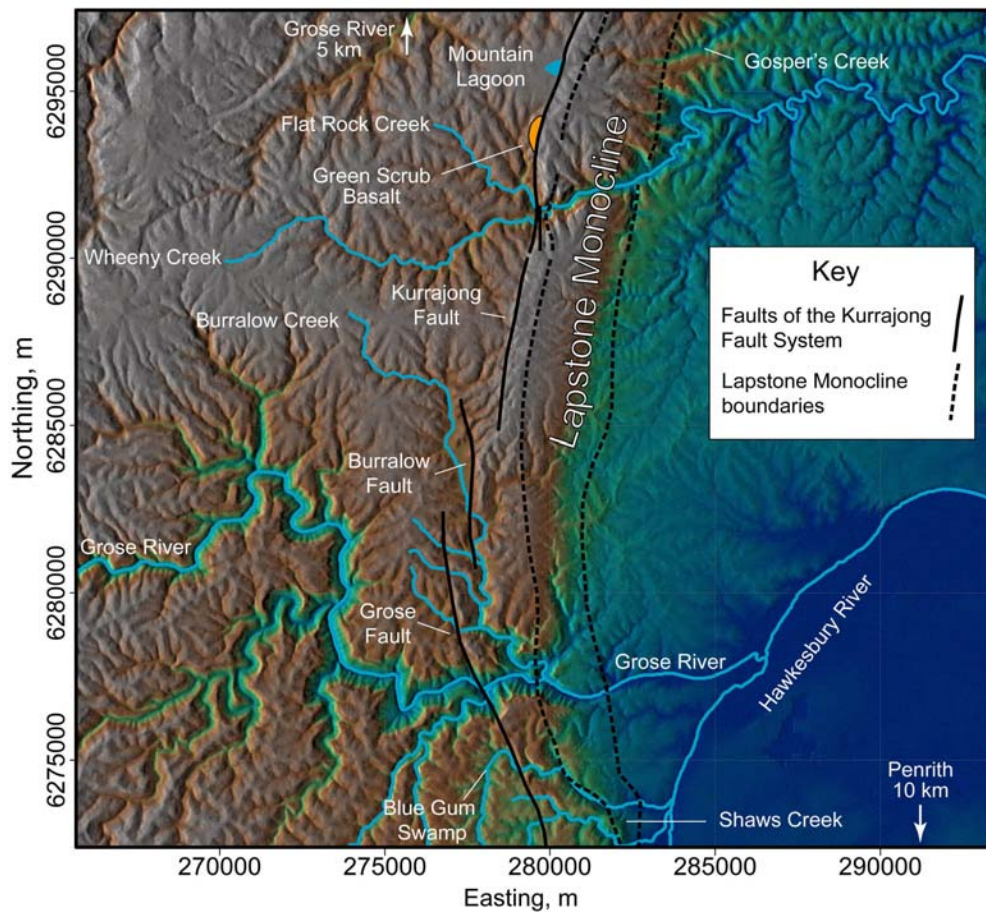


Figure 5: The northern Lapstone Structural Complex with major structures marked (from Kirkby *et al.* (2009)). Mountain Lagoon occurs against the Kurrajong Fault at the northern edge of the map.

Geologic and seismicity data collected as part of the seismic hazard investigation for the Lucas Heights Replacement Nuclear Reactor were used by Berryman *et al.* (2009) to estimate the recurrence for damaging earthquakes on individual faults within the Sydney Basin, excluding the Lapstone Structural Complex. Their findings are that M5.0-6.0 earthquakes occur on individual faults once every several million years. This estimate is consistent with the results from the Kurrajong Fault at Mountain Lagoon, indicating that the significant topographic relief across the Kurrajong Fault does not imply greater activity, again supporting the erosional exhumation model of Pickett & Bishop (1992).

At the northern margin of the Sydney Basin, where it is faulted against the New England Fold Belt, warping of Miocene strata during the Pleistocene has resulted in the formation of a monocline of 30 m amplitude (Huftile, Van Arsdale and Boyd 1999) (Figure 6). This ~30 km long northwest trending structure, denoted the Newcastle offshore fault, occurs along strike of the Hunter Thrust system, and close to the epicentre of the 1989 M5.6 Newcastle earthquake. While moderate earthquakes should not be assigned to particular faults (e.g. Clark 2009), an anomalously rich historic record of moderate earthquakes in the Newcastle region (M5.4, 1994; M5.6, 1989; M5.3, 1925; M5.3, 1868; M5.3, 1842; M4.9, 1841 and M5.0, 1837 (Sinadinovski, Jones, Stewart *et al.* 2002 and references therein)), when combined with the neotectonic evidence, provides a circumstantial case that the Hunter Thrust system may be more akin to faults such as Cadell or Khancoban-Yellow Bog than to the relatively quiescent faults of the Lapstone Structural Complex.

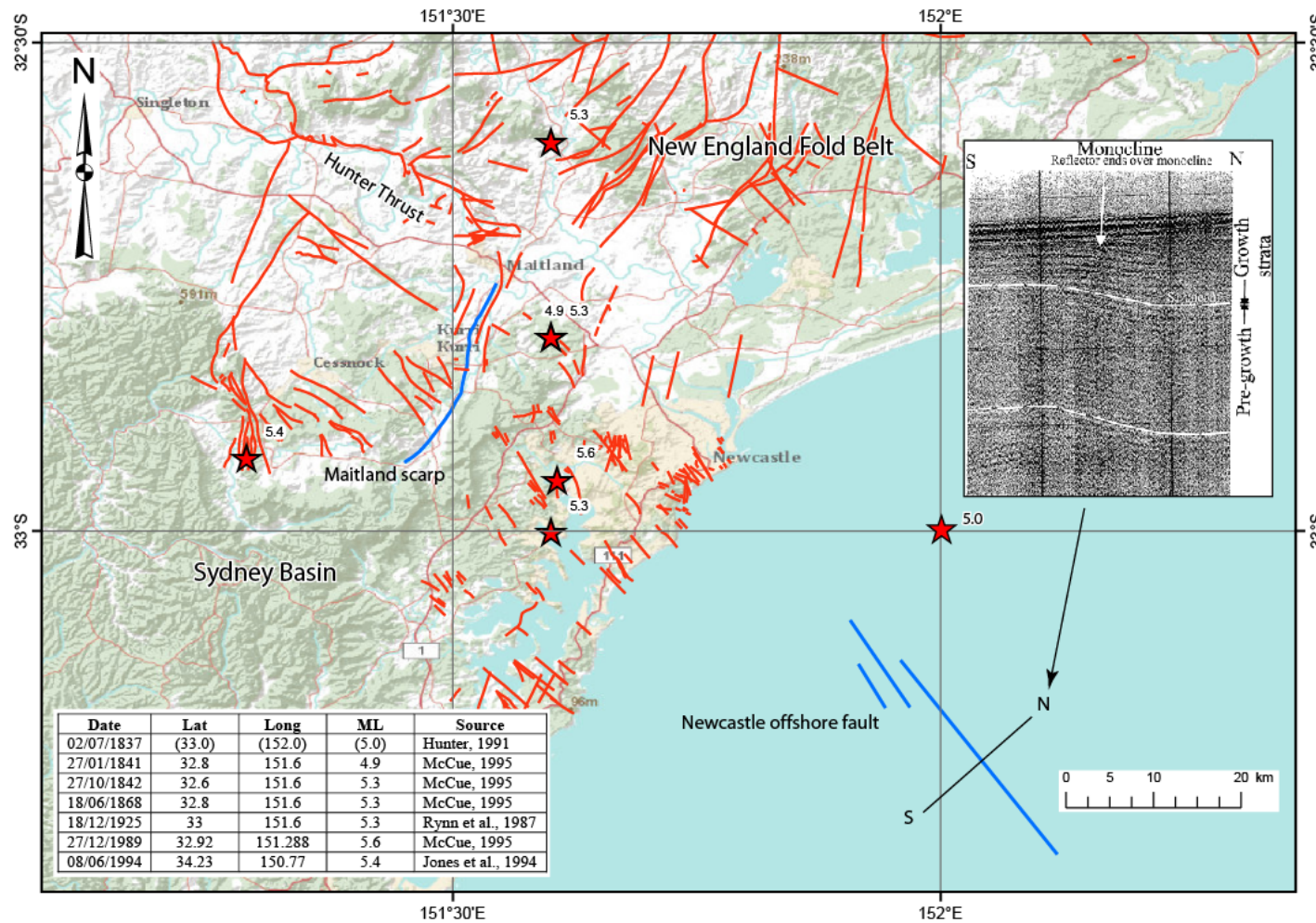


Figure 6: Historic earthquakes in the Newcastle region (error bars may be up to 50 km), fault scarps (from the GA neotectonics database) and mapped basement geology (red stars, blue lines and red lines respectively). Inset shows sparker profile after Huftile *et al.* (1999). The two white lines bracket Miocene strata. Pleistocene growth strata occurs above the upper white line. Exact location of the 1837 event is unknown and may be close to the 1841/42 events. (Kevin McCue pers. com., 2010).

7 CONCLUSIONS

Within the Australian intraplate context it has been demonstrated that active fault sources can contribute significantly to seismic hazard, even for return periods appropriate to residential construction design (e.g. Somerville, Quijada, Thio *et al.* 2008). Obtaining robust neotectonic data for faults of interest, or nearby analogous faults, is critical to assessing the contribution to hazard that these sources might make, and whether the faults should be considered to be “active” or not. Paradoxically for the Sydney Region, the faults with the most relief across them, those of the Lapstone Structural Complex, pose perhaps the least hazard. Others like the Hunter Thrust deserve further palaeoseismic investigation to quantify the potential hazard that they pose to nearby communities and infrastructure. In contrast to preliminary estimates of large earthquake recurrence in the order of one $M_w > 7.0$ event per 10-20 ka (IGNS 1999), new research suggests that the recurrence on individual faults is more likely to be in the millions of years (Berryman, Webb, Nicol *et al.* 2009, Clark, McPherson and Tomkins 2009). This implies a significant downgrading of the seismic hazard within the Sydney Basin.

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