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Large earthquake recurrence in the Adelaide region: a palaeoseismological perspective

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Abstract

The Mount Lofty and Flinders Ranges of South Australia are bound on the east and the west by reverse faults that thrust Proterozoic and/or Cambrian basement rocks over Quaternary sediment. These faults range from a few tens to almost one hundred kilometres in length, and tend to be spaced significantly less than a fault length apart. In the few instances where the thickness of overthrust sediment can be estimated, total neotectonic throws are in the order of 100-200 m. Slip rates on individual faults range from 0.02-0.17 mm/a, with one unconfirmed estimate as high as 0.7 mm/a. Taking into account the intermittent nature of faulting in Australia, it has been suggested that 30-50% of the present-day elevation of the Flinders and Mount Lofty Ranges relative to adjacent piedmonts has developed in the last 5 Ma. Uplifted last interglacial shorelines (*ca.* 120 ka) along the southern coast of the Mount Lofty Ranges indicate ongoing deformation.

Palaeoseismological investigations provide important insight into the characteristics of the large earthquakes responsible for deformation events. Single event displacements of 1.8 m have been measured on the Williamstown-Meadows Fault and the Alma Fault, with the former relating to a surface rupture length of a least 25 km. Further to the south in Adelaide’s eastern suburbs, a 5 km section of scarp, potentially relating to a single event slip on the Eden-Burnside Fault, is preserved in *ca.* 120 ka sediments. Where the Eden-Burnside Fault meets the coast at Port Stanvac 20 kilometres south, the last interglacial shoreline is uplifted by 2 m relative to its expected position. At Normanville, on the uplifted side of the Willunga Fault, the last interglacial shoreline is over 10 m above its expected position, implying perhaps five or more surface rupturing events in the last *ca.* 120 ka on this >50 km long fault. On the eastern range front, a very large single event displacement of 7 m is inferred on the 54 km long Milendella Fault, and the 79 km long Encounter Fault displaces last interglacial shorelines by up to 11 m.

There is abundant evidence for large surface-breaking earthquakes on many faults within 100 km of the Adelaide CBD. Slip rates are low by plate margin standards, implying a low rate of recurrence for M7+ events on individual faults (perhaps 10,000 years or more). However, a proximal moderate-sized event or even a large event at distance has the potential to cause significant damage to Adelaide, particularly given its construction types and local site conditions.

Keywords: seismic hazard, neotectonics, earthquake, palaeoseismology, slip rate

Neotectonics of the Mount Lofty Ranges

The Mount Lofty and Flinders Ranges is experiencing an ongoing period of uplift (‘mountain building’), referred to as the Sprigg Orogeny (Sandiford 2003). The ranges form the main topographic axis of the orogen, and are bound by N-S to NE-SW trending fault scarps (Fig. 1). These scarps are testimony to the role of neotectonic faulting in shaping the present landscape.

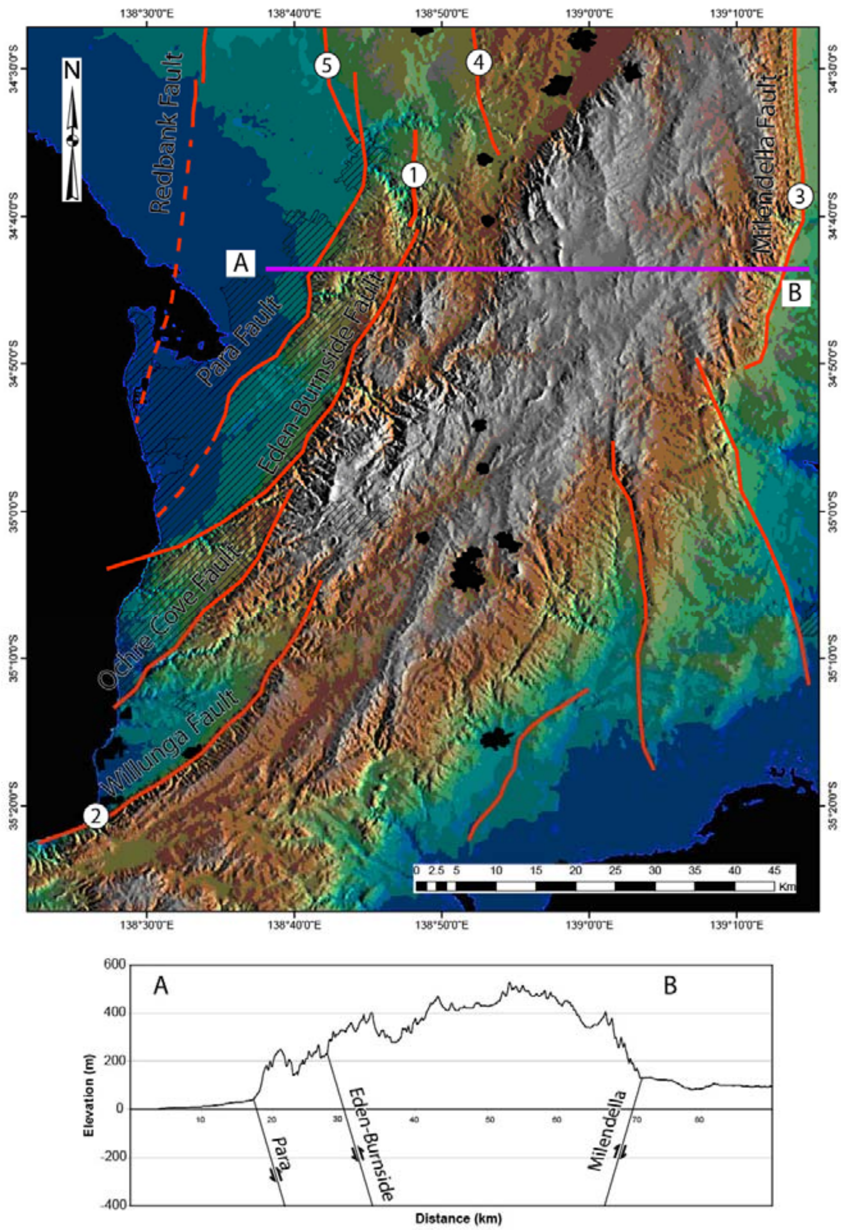

Figure 1. Major neotectonic faults and associated scarps in the Mount Lofty Ranges (Adelaide region stippled), and schematic cross section derived from 90 m SRTM DEM. Fault exposures marked (1-3) show that the range bounding faults are reverse oriented and dip beneath the range: (1) - Concordia/Gawler Fault (Quigley *et al.* 2009); (2) - Willunga Fault (Sandiford 2003); (3) - Milendella fault (Bourman & Lindsay 1989). Points (4) and (5) mark the Williamstown-Meadows and Alma Faults, which were trenched in 2010 at locations north of this image (Geoscience Australia, unpublished data).

Motion on these structures has juxtaposed ancient (>500 million year old) basement rock above alluvial and colluvial sediments shed from the developing upland systems in the last 1-2 million years (Fig. 2b-d) (e.g. Williams 1973; Bourman & Lindsay 1989; Sandiford 2003; Quigley *et al.* 2006). Fault-slip kinematics are consistent with the structures having formed in response to the current stress regime, with S_{Hmax} trending between N080°E and N125°E (Quigley *et al.* 2006). This motion is consistent with a subset of earthquake mechanisms, which show both reverse and strike slip failure for this region (Clark & Leonard 2003).

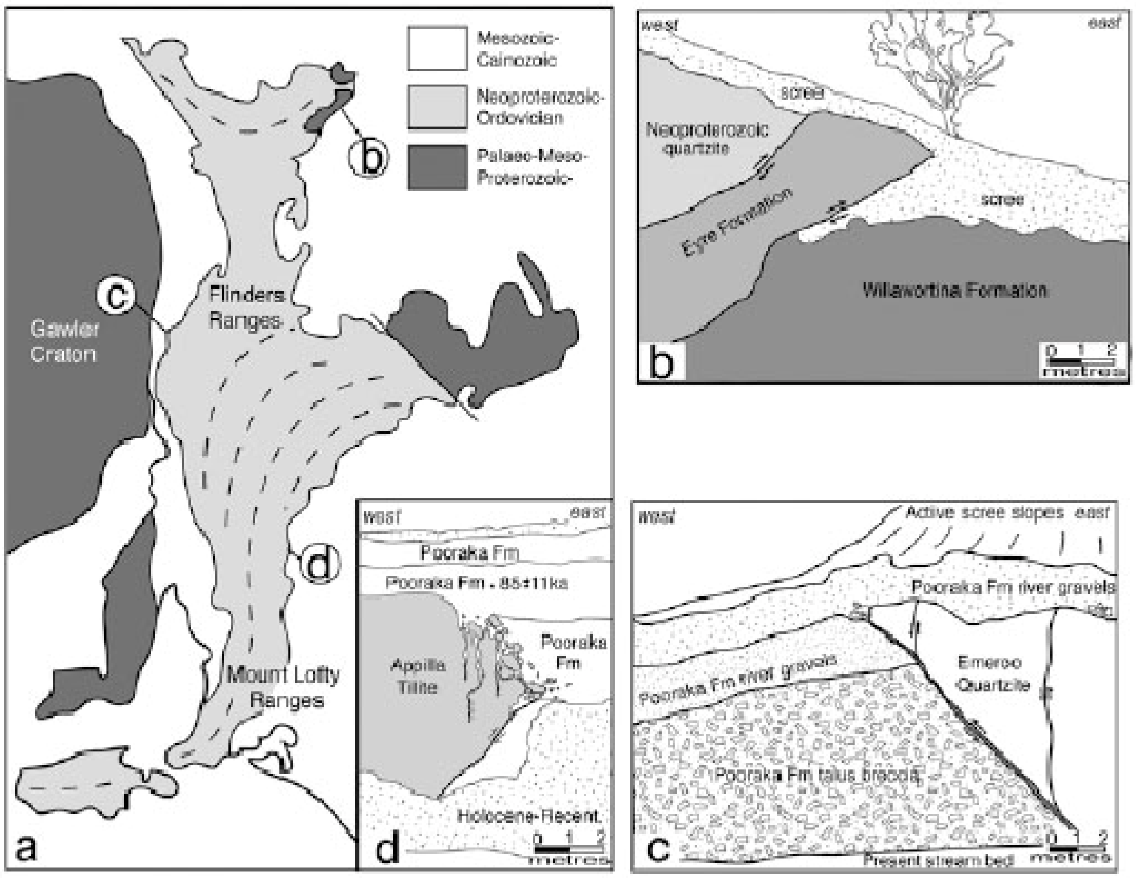

Figure 2. (a) Simplified geological map of the Flinders and Mount Lofty Ranges region. Basement rocks are shaded while younger sediments are in white. Insets show sketches of exposures of range-bounding thrust faults from **(b)** Paralana, **(c)** Wilkatana and **(d)** Burra. Note that all faults are reverse and dip beneath the ranges (after Celerier *et al*. 2005).

A number of major neotectonic faults are located within 50 km of the Adelaide urban area (e.g. Para, Eden-Burnside, Ochre Cove-Clarendon, Willunga, Milendella, Palmer, Bremer (see Fig. 1); cf. Sandiford 2003). Several more occur to the north between Adelaide and Port Augusta (e.g. Alma, Redbanks, Williamstown-Meadows, Wilkatana, Crystal Brook, Nectar Brook; cf. Somerville *et al.* 2008). Exposures of the range-bounding faults near Adelaide are rare, but where identified they invariably show evidence for moderate to steep angle reverse faults which dip beneath the ranges (Fig. 2; cf. Flöttmann & James 1997).

Palaeoseismological evidence for large earthquakes

The cumulative vertical displacement on the fault network that forms the western front of the Mount Lofty Ranges is estimated to be ~240 m, of which ~80 m represents offset of early Quaternary (*ca.* 1.6 million year old) strata (Sandiford 2003; Sandiford & Quigley 2009). Stratigraphic relations implying that the total displacement has accumulated in the last 5-6 million years (Sandiford *et al*. 2004) give time-averaged displacement on bounding faults of approximately 40-50 m/Ma, in line with that inferred from historical seismicity rates (Sandiford & Quigley 2009). Palaeoseismological studies show maximum probable magnitude (M_{max}) earthquake events of moment magnitude (M*w*) 7.3–7.5 with recurrence intervals in the order of 10^4 years, averaged over several seismic cycles (Quigley *et al*. 2006; Somerville *et al*. 2008).

Recent investigation of the Williamstown-Meadows Fault near Tarlee (Fig. 1, point 4; Fig. 3a) has revealed evidence for a 1.8 m single event reverse displacement which vertically offsets a Quaternary alluvial fan (probably Pooraka Formation) by 1.5 m (Geoscience Australia, unpublished data). This data is consistent with a M_W 6.8 earthquake, a recurrence of which would be catastrophic given its location proximal to the northern end of the Adelaide urban corridor. Investigations across the Alma Fault near Hoyleton revealed a similar single event slip, and hence earthquake event (Fig. 1, point 5; Fig. 3b).

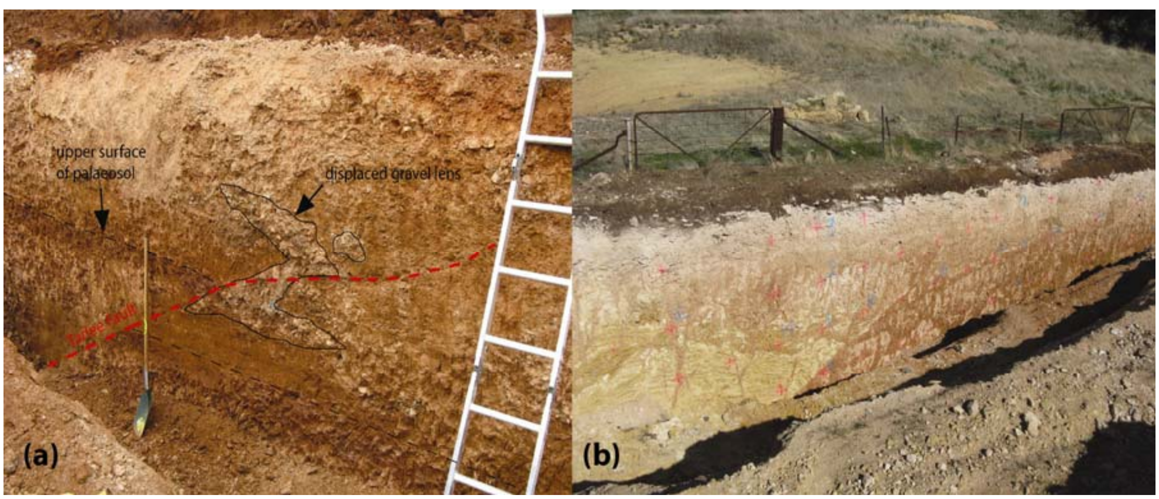

Figure 3. (a) Williamstown-Meadows Fault near Tarlee, showing deformed gravel lens and displaced palaeosol; **(b)** Alma Fault near Hoyleton, showing weathered bedrock (yellow) thrust over younger sediments (red).

Fairburn (2004) describes a previously recognised but little documented feature in the eastern suburbs of Adelaide, where Adelaidean outcrop exhibits a linear termination against younger sediments and coincides with a small westerly dipping scarp [1.5-2.0 m high and ~5 km long]. This feature might be associated with the Hope Valley Fault (Fairburn 2004), or relate to a pre-historic rupture on a splinter of the Eden-Burnside (cf. Limb 1980).

Numerous studies (e.g. Belperio *et al*. 1995, Murray-Wallace 1995; Bourman *et al*. 1999) have demonstrated displacement of the last interglacial shoreline in the Adelaide region by up to 10 m relative to its expected position (Fig. 4). Bourman *et al*. (1999) identify tectonic dislocation of Miocene and early Pleistocene marine units, and demonstrate differential uplift of the Fleurieu Peninsula along with up to ~10 m of depression in the Adelaide area and Murray Basin in the past 125 ka.

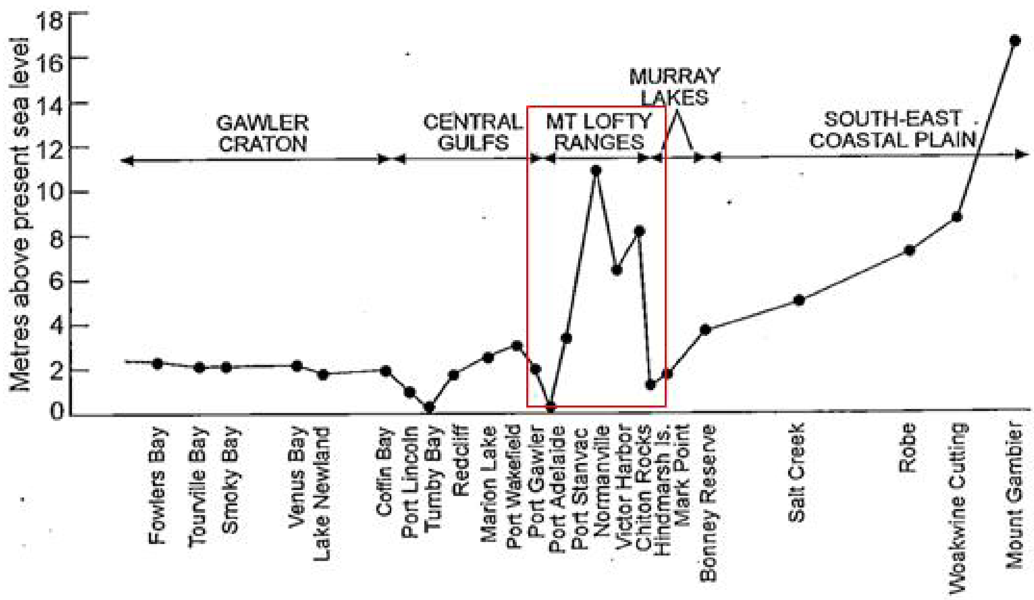

Figure 4. Altitude of last interglacial intertidal facies in southern South Australia (from Bourman *et al.* 1999). Note significant elevation difference relative to sea level for points on the southern Mount Lofty Ranges.

An interesting implication of the reverse faulting geometry of the ranges is that the 1954 M5.4 Adelaide earthquake may have occurred at depth on the Para Fault, rather than on the Eden-Burnside Fault, as is more commonly thought (Fig. 5). The Para Fault is of particular significance for seismic hazard assessment as it is runs beneath the greater Adelaide urban area and is associated with a prominent scarp developed in Quaternary sediments (Fig. 5 inset). Borehole data suggest a 27 m offset of the Late Pleistocene Pooraka Formation (Bourman *et al.* 1997) across the Para Fault (Sheard & Bowman 1996), equating to a slip rate in the order of 0.2-0.8 mm/yr over the last 35-125 ka. The top of underlying Hindmarsh Clay (age >500 ka) is displaced by a similar amount, suggesting that the displacement relates to a recent pulse of activity, similar to that seen in the last *ca.* 67 ka on the Wilkatana Fault (Quigley *et al.* 2006). The borehole records further indicate that the underlying Pliocene Hallett Cove Sandstone has been displaced across the Para Fault by <200 m, implying longer term slip rates at least 2-5 times smaller than since the mid-Quaternary. If the borehole data is valid, and the Para Fault remains in an active period commensurate with the last 35-125 ka, recurrences for earthquakes much larger than the 1954 event could be <10 ka, and perhaps as little as a few thousand years.

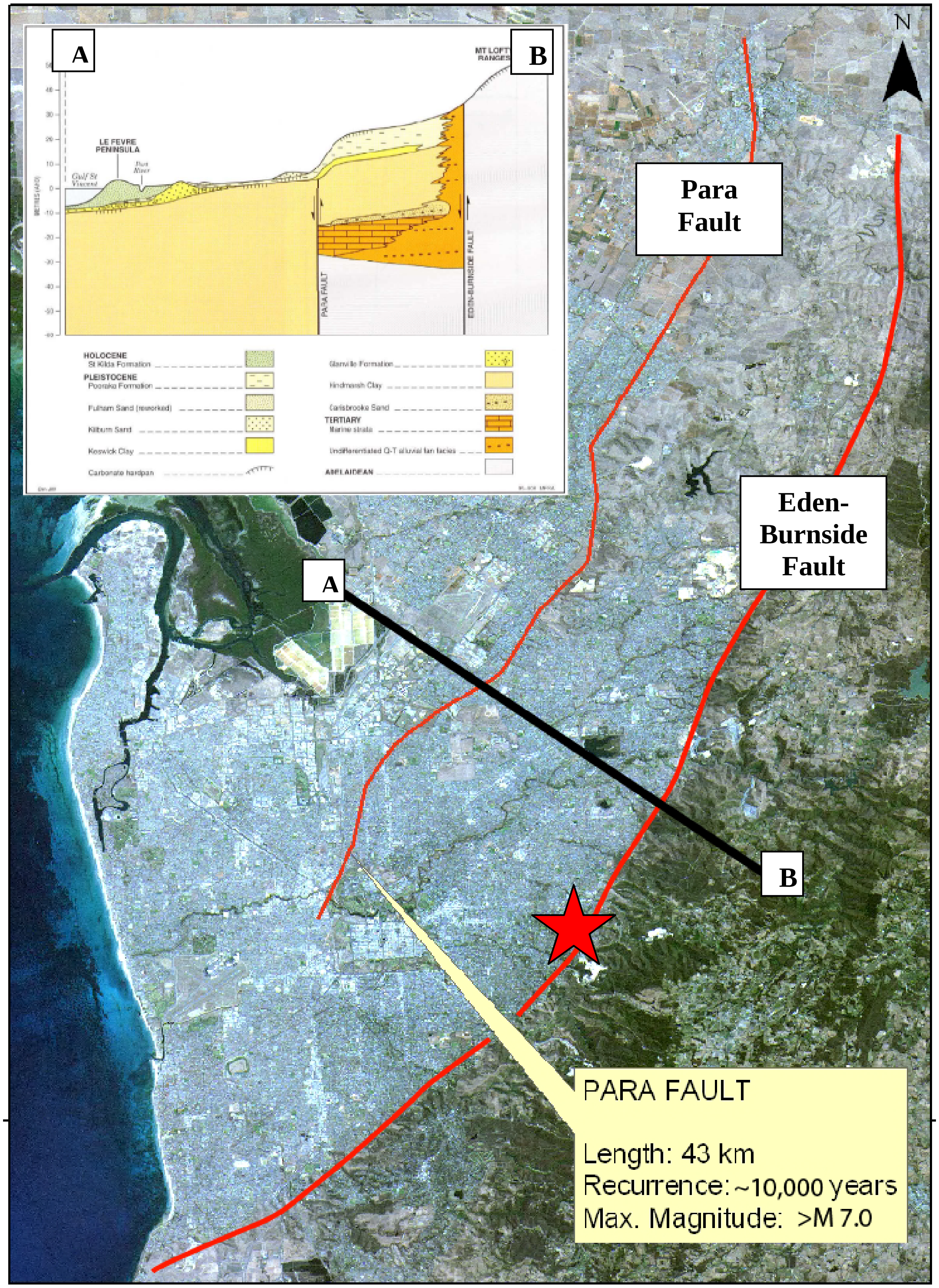

Figure 5. Surface traces and schematic section through the Para and Eden-Burnside Faults in the vicinity of Adelaide. Inset: cross section A-B showing that the Para Fault displaces the Quaternary (mid-Pleistocene) Hindmarsh Clay (yellow unit) by tens of metres (inset from Belperio 1995). Red star marks the estimated epicentre of the 1954 M5.4 Adelaide earthquake (McCue 1996).

Implications for seismic hazard

As implied previously, there are several sources of seismic hazard to Adelaide that should be considered in conjunction with a relatively infrequent maximum magnitude rupture on the Para Fault. This becomes intuitive when it is considered that the damage radius of a relatively modest magnitude 6.5 earthquake is approximately 50 km. Somerville *et al.* (2008) demonstrate that the contribution from several nearby neotectonic fault sources in the central Flinders Ranges are greater than distributed seismicity (i.e. the historic earthquake record) in hazard calculations for return periods of 475 years and longer. For critical infrastructure (return periods of 10,000 years and greater) the hazard from neotectonic fault sources dominates. A similar scenario might be expected for the Adelaide area given the great density of neotectonic faults (see Fig. 1). The Para, Eden-Burnside, Ochre Cove/Clarendon, Willunga, Alma, Williamstown-Meadows and Milendella faults all have M_{max} values exceeding M_W 7.0. While specific recurrence data for many of these structures is still elusive, a large rupture on any of these faults has the potential to seriously impact Adelaide and the surrounding region (e.g. Sinadinovski *et al.* 2006). More frequent, less than M_{max} events (e.g. 1954 M5.4 Adelaide earthquake) on faults of the western range front and beneath the coastal plain (e.g. Redbank Fault, which is considered to extend south beneath Port Adelaide – Fig. 1; cf. Flöttmann *et al.* 1998), also have the potential to cause significant damage.

It has been demonstrated that neotectonic faults can contribute significantly to seismic hazard, even for return periods appropriate to residential construction design (e.g. Somerville *et al.* 2008). Obtaining robust neotectonic data for faults of interest, or from nearby analogous faults, is critical to assessing the contribution that neotectonic faults might make to hazard. For the Adelaide region, recurrence data for such faults is sparse and significant additional data is required to reduce uncertainties in estimates of M_{max}.

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