What is an "active" fault in the Australian intraplate context? A discussion with examples from eastern Australia.

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A *neotectonic* fault is defined as one that has hosted measurable displacement in the current crustal stress regime (i.e. within the last 5-10 Ma (Sandiford *et al.* 2004)), and is therefore suitably oriented to host (or is *capable* of hosting) future displacement (Machette 2000). Evidence for palaeo-seismicity on a suspected neotectonic fault, potentially identified many thousands of years after the last large earthquake, can be used to confirm such a classification. Large earthquake behaviour on intraplate neotectonic faults, such as those in Australia, is highly non-Poissonian. The time between large ruptures varies considerably with time and is often highly episodic (Crone *et al.* 2003; Clark *et al.* 2007). Stress transfer can promote nearby faults towards failure leading to temporal patterns in rupture (e.g. Caskey & Wesnousky 1997). Consideration of neotectonic faults as *active* or quiescent in probabilistic hazard assessments is hence problematic.

The relevance of earthquake events on a given *neotectonic* fault is dependant upon the large earthquake recurrence interval on the fault and the return period being considered for hazard purposes. This in turn depends on the infrastructure being assessed. A static definition of an active fault, such as that used in interplate California, where a fault is defined as being active if it is associated with a *surface rupture* in the last 10,000 years, is clearly not useful to seismic hazard assessment in an intraplate setting like Australia. This is so because recurrence intervals for surface rupture on neotectonic faults in Australia are measured in the tens of thousands to hundreds of thousands of years or more (Clark & McCue 2003; Crone *et al.* 2003; Clark *et al.* 2007; Clark *et al.* 2008a). Depending upon location and an understanding of patterns in episodic rupture, a fault or fault segment having 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.

More rigorously, the contribution to a hazard determination from a given neotectonic fault source, or combination of neotectonic fault sources, will determine whether the fault(s) should be considered active (Somerville *et al.* 2008). Activity on a fault should be defined on a local basis from neotectonic data, depending upon the recurrence of the local faults and the return period of interest. For example, in a recent study of three faults in the Flinders Ranges (Somerville *et al.* 2008), it was found that for a 10,000 year return period, the faults contributed approximately 40%

of the hazard to nearby infrastructure, but only 25% of the hazard for a 2,500 year return period. This contribution reduced to <10% for a 500 year return period, where smoothed instrumental seismicity dominated the hazard. It might be concluded from this study that the three faults, in combination, could be considered to be active for the purposes of assessing critical infrastructure, but perhaps not for the purposes of typical residential and commercial construction. This approach is not without its complexities, potentially leading to a situation where a single fault in isolation is not considered active, but when viewed amongst a group of proximal contributing faults may be considered active. In addition, Somerville *et al.* used a slip rate averaged over the last 100,000 years (three seismic cycles). It is not clear how this slip rate relates to the longer term slip rate on the faults.

Those concerned with short-term seismic hazard often consider a fault to be *active* if it is associated with historic seismicity, which in the Australian context is restricted to the last ~100 years (Leonard 2008). However, in most intraplate areas worldwide, in the absence of surface rupture, historic seismicity does not have a clear and demonstrable relation to neotectonic faults. This is especially the case where instrumental earthquakes are small and the subsurface geology is incompletely known. Take for example the recent Korumburra sequence of events in the Gippsland region of eastern Victoria. These events, culminating in two magnitude 4.6 earthquakes on the 6th and 18th of March 2009, occurred at ~7-9 km depth (Gary Gibson, ES&S, personal communication, 2009) below an uplifted block between the Bass-Almurta Fault and the Kongwak Monocline (the Narracan Block, **Figure 1a**). Both faults are considered to be *neotectonic* as there is significant geologically recent topography associated with them (>100 m), but it would be bold to place the events on either fault on the basis of a spatial association with the surface trace alone. Assuming a square rupture, the rupture planes of the largest two events are unlikely to be larger than ~1.5 km on a side. The horizontal errors associated with the hypocentres are in the order of kilometres, and the vertical uncertainties of a similar order or greater. Furthermore, the subsurface geometry of neither fault is known. Convergent dips of between 45-60º in the upper five kilometres of crust are geologically reasonable (**Figure 1b**). By analogue with faults of the eastern Gippsland Basin, into which these faults link, dips might be expected to shallow markedly below 5 km depth (i.e. a listric geometry). A plausible fault geometry is depicted in **Figure 1c**, which superposes the structural geometry imaged by seismic reflection line BMR line 90/15 in the eastern Gippsland Basin (Williamson *et al.* 1991) onto the topography of the Narracan Block. Depending upon the preferred structural geometry, and the level of confidence placed in the hypocentral depths, one could develop a scenario where slip/creep on the Bass/Almurta Fault in the ductile lower crust stressed the hanging-wall block and triggered events on the fault underlying the Kongwak Monocline. Without high-precision seismic reflection data and accurate estimates of hypocentral locations this scenario remains speculative. For this reason it is not usually possible to confidently associate small to moderate earthquakes with particular structures, and hence assign an “active fault” label.

How might episodic rupture activity modify our perception of what might be considered an active fault? The Cadell Fault in southern NSW might be considered to be very active on the basis of having slipped in the order of 25 m in the last 70,000 years (Clark *et al.* 2007). However, detailed palaeoseismological data implies that this displacement occurred in the interval ~70,000-20,000 years ago, with an average

recurrence for M>7.0 earthquakes of ≤10,000 years. No large events have occurred for more than 2-3 average seismic cycles since 20,000 years ago. Seismic reflection profiling of the fault suggests that only one other similar period of activity, again involving in the order of 20 m of relief building (25 m of slip), has occurred on this fault in the last two million years (**Figure 2**). If this pattern were to continue, barring a last dying gasp of the recently past period of activity, we might not expect another large event on this fault for several hundreds of thousands of years. Consequently, a significant overestimation of hazard would result if a probabilistic hazard assessment used the average recurrence for this fault over the most recent active period, in the absence of information about the longer term rupture behaviour.

The situation is not often as clear cut as for the Cadell Fault, for the reason that Australia's neotectonic record is highly under-explored. For example, the Lake George Fault, 40 km east of Canberra, has experienced ~120-250 m of displacement in the current stress regime (Singh *et al.* 1981; Abel 1985). This implies a slip rate of ~12-25 m/Ma, and an average recurrence in the order of a hundred thousand years or more for M>7.0 events. With the exception of undeformed strandlines from palaeo-lake high-stands which suggest no rupture in the last 100,000 years (Kathryn Fitzsimmons, ANU, personal communication, 2008), nothing is known of this faults' rupture behaviour. Activity that might impact a seismic hazard assessment cannot be demonstrated with current knowledge. The Lapstone Structural Complex near Sydney might be assumed to be more active than the Lake George Fault by virtue of its >400 m high escarpment. However, recent work suggests that only ~10% of the relief across the feature formed as the result of neotectonic activity (Clark *et al.* 2008b). The average recurrence of M>7.0 events is in the order of millions of years. Hence, for most seismic hazard purposes this complex of faults must be considered quiescent, stressing the point that estimates of fault activity need to be based upon sound neotectonic data.

In light of the potential for pronounced episodic rupture behaviour on Australian faults (e.g. Crone *et al.* 1997; Crone *et al.* 2003; Clark *et al.* 2007; Clark *et al.* 2008a) (**Figure 2**) it is questionable whether long term slip rates (and the recurrence estimates based upon them) are everywhere (or anywhere) appropriate for probabilistic seismic hazard assessment. In the case of the Cadell Fault, the recurrence for surface rupture between periods of activity is essentially zero, while the recurrence in active periods is <10,000 years. As the duration of an active period can stretch to 100,000 years, it may be appropriate to use this "short-term" recurrence when assessing hazard of a fault in an active period, as Somerville et al. (2008) have done. The model presented in **Figure 2** helps to conceptualise the points critical to understanding the hazard posed by intraplate faults, and hence assess activity: (1) is the SCR fault in question about to enter an active period, in the midst of an active period, or in (or just entered) a quiescent period, and (2) if a fault is in an active period, what is the "average" recurrence interval and what is the variability around this average. This "average" could be incorporated statistically into probabilistic seismic hazard assessments (e.g. Somerville et al., 2008).

It is likely that faults in more neotectonically active areas, such as the Mount Lofty and Flinders Ranges, and the Otway, Bass and Gippsland Basins might individually, or in combination, be considered active for applications down to a 2500 year return period (c.f. Somerville *et al.* 2008). In Western Australia, where recurrence intervals

are very large and faults spatially isolated (e.g. Clark *et al.* 2008a), faults might not justifiably be termed active for all except studies relating to the most critical infrastructure.

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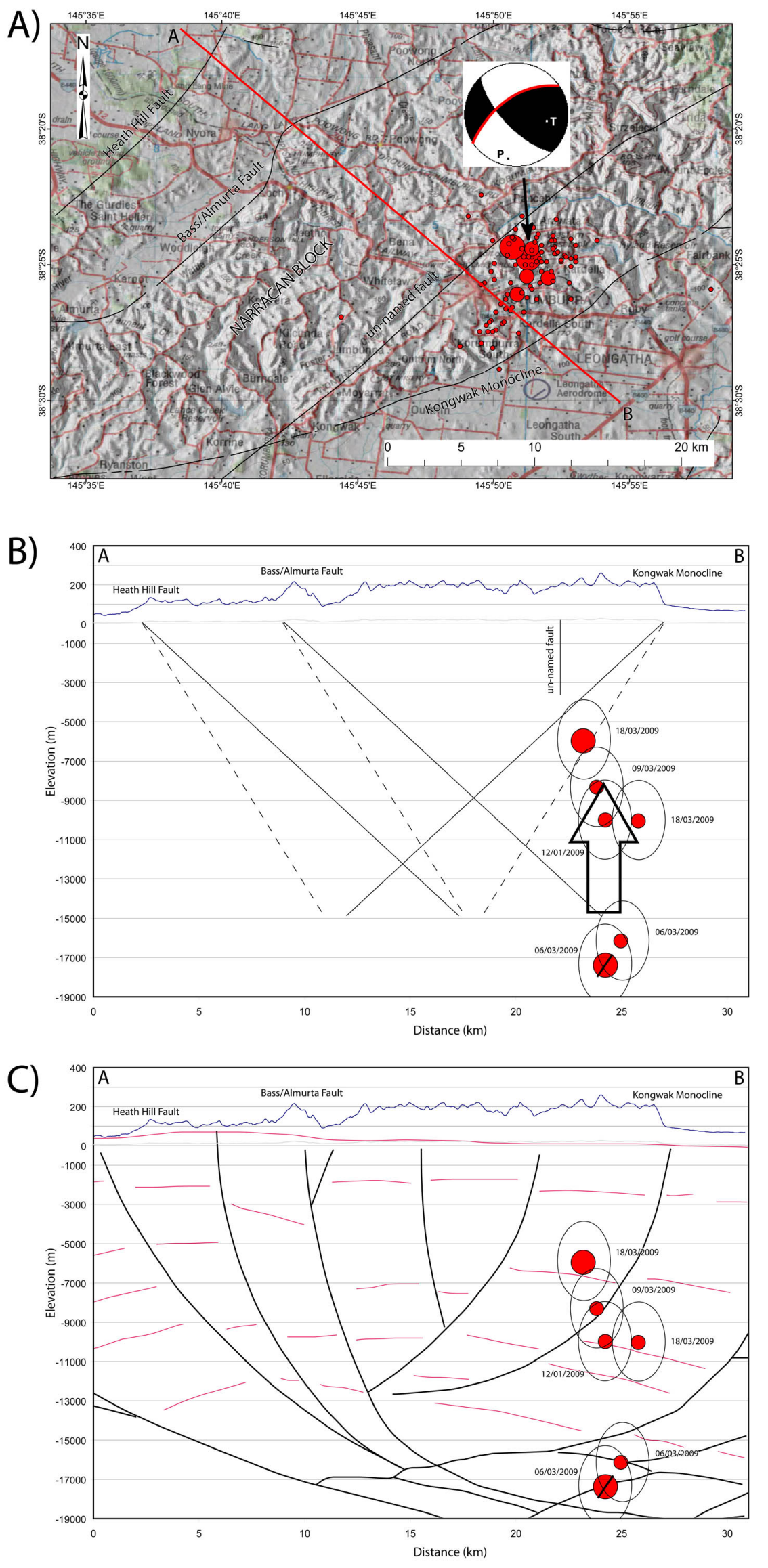
Figure Captions

Figure 1 – **a)** Plot of the epicentres of the largest of the March 2009 Korumburra earthquakes (courtesy of Wayne Peck at ES&S, 24/04/2009) overlaid onto 3 second SRTM DEM data with major fault traces marked. Focal mechanism courtesy of Kevin McCue (preferred nodal plane marked). **b)** Cross section A-B showing plausible subsurface envelopes of the major faults (45º and 60º dip) and hypocentre locations projected onto the section plane. Rupture width of the 06/03/2009 M4.6 event is shown oriented with the preferred nodal plane of the focal mechanism. Subsequent locations suggest that the 06/03/2009 events occurred at ~6 km depth (black arrow), **c)** Line drawing of BMR seismic line 90/15 from the eastern Gippsland Basin (Williamson *et al.* 1991) superimposed on the topography above the Korumburra earthquakes. Post Strzelecki Group sediments from the Gippsland Basin have been stripped from the line and the base of Latrobe Group used as a proxy for the ground surface near Korumburra. The master fault (and hence the asymmetry) is assumed to be the Bass/Almurta by analogy with the along-strike Yarragon fault. In b) and c) relief above sea level is exaggerated ten times. Relief at actual scale is shown by the grey line.

Figure 2 – Schematic diagram depicting clustered surface rupture behaviour modelled on the Cadell Fault. In an active period, the fault might host surface ruptures with a recurrence of <10,000 years. In intervening periods of quiescence the fault might be considered to be quiescent, depending upon the return period of interest.


A)
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A
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Heath Hill Fault
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un-named fault
Kongwak Monocline
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Poowong
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Korumburra
LEONGATHA
Leongatha Aerodrome
Leongatha South
Almurta
Almurta East
Blackwood Forest
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18/03/2009
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Elevation (m)
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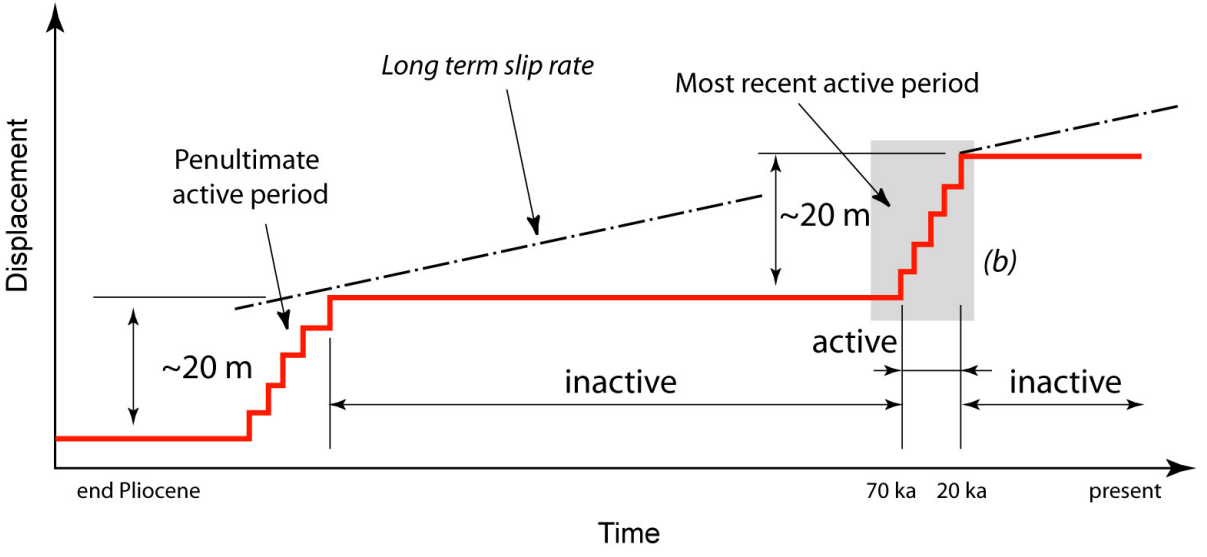
Displacement
Long term slip rate
Most recent active period
Penultimate
active period
~20 m
~20 m
(b)
active
inactive
inactive
end Pliocene
70 ka
20 ka
present
Time