Potential geologic sources of seismic hazard in Australia's south-eastern highlands: what do we know?

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Abstract

Many mapped faults in the south-eastern highlands of New South Wales and Victoria are associated with apparently youthful topographic ranges, suggesting that active faulting may have played a role in shaping the modern landscape. This has been demonstrated to be the case for the Lake George Fault, ~25 km east of Canberra. The age of fluvial gravels displaced across the fault indicates that relief generation of approximately 250 m has occurred in the last *ca.* 4 Myr. This data implies a large average slip rate by stable continental region standards (~90 m/Myr assuming a 45 degree dipping fault), and begs the question of whether other faults associated with relief in the region support comparable activity rates. Preliminary results on the age of bedrock terraces on the Murrumbidgee River proximal to the Murrumbidgee Fault are consistent with tens of metres of fault displacement in the last *ca.* 200 kyr. Further south, significant thicknesses of river gravels are over-thrust by basement rocks across the Tawonga Fault and Khancoban-Yellow Bog Fault. While these sediments remain undated, prominent knick-points in the longitudinal profiles of streams crossing these faults suggest Quaternary activity commensurate with that on the Lake George Fault. More than a dozen nearby faults with similar relief are uncharacterised.

Recent seismic hazard assessments for large infrastructure projects concluded that the extant paleoseismic information is insufficient to meaningfully characterise the hazard relating to regional faults in the southeast highlands, despite the potential for large recurrent earthquakes alluded to above. Fault locations and extents are inconsistent across scales of geologic mapping, and rupture lengths and slip rates and behaviours remain largely unquantified. A more comprehensive knowledge of these faults will be required to support renewed interest in nation-building infrastructure, and the expansion of major population centres, in the eastern highlands.

Keywords: Lake George, seismic hazard, earthquake, paleoseismology

INTRODUCTION

In contrast to plate margin regions, such as neighbouring New Zealand, Australian geological maps typically do not explicitly include active/neotectonic faults, their properties, and potential complexities (cf. Rattenbury & Isaac, 2012), and there are many inconsistencies on published maps. For example, the trace of the Livingstone Creek Fault in the Snowy Mountains deviates by up to 2.5 km between 1:250,000 scale (VandenBerg, 1997) and 1:50,000 scale (e.g. VandenBerg *et al.*, 1998; Willman *et al.*, 1998) mapping. Furthermore, the northern extent of the fault is named the Saltpetre Gap fault in 1:50,000 scale mapping. A similar situation exists for the Deakin Fault, near Canberra, as mapped at 1:250,000 scale (Best *et al.*, 1964). The extension of the fault is mapped as the Devils Pass fault on the Goulburn 250,000 sheet to the north (Johnston *et al.*, 2010). At 1:100,000 scale the northern and southern segments appear to be distinct (Abell, 1991), and truncate against the Winslade Fault.

In common with New Zealand (Langridge *et al.*, 2016), and the United States (https://earthquake.usgs.gov/hazards/qfaults/), Australia has adopted a digital format active (Neotectonic or Quaternary-active) faults database (Clark *et al.*, 2012), to be used for hazard modelling, geological research, infrastructure planning and provision of information to the general public. In many cases, inconsistencies in naming and trace location have been ironed out in this database. Knowledge of Australian seismogenic faults has advanced in recent years to the stage where faults are more commonly being explicitly included in probabilistic seismic hazard assessments at scales from site specific to national (e.g. Somerville *et al.*, 2008; Clark *et al.*, 2016; Griffin *et al.*, 2016). However, despite the advances, most faults in Australia remain poorly characterised in terms of their paleoseismology, and in many cases, their geometry. Hence, hazard modellers face significant uncertainty in assigning rupture geometry, segmentation behaviours, and recurrence behaviours.

Some of Australia's highest bedrock erosion rates are found in the elevated areas of the eastern highlands: up to 30–50 m/Ma (Weissel & Seidl, 1998; Heimsath *et al.*, 2000; Heimsath *et al.*, 2001; Wilkinson *et al.*, 2005; Tomkins *et al.*, 2007; Heimsath *et al.*, 2010). That the eastern highlands contain faults associated with modest topographic ranges (e.g. Lake George Fault, Murrumbidgee Fault) suggests that tectonic uplift rates may locally exceed erosion rates (Figure 1). Slip rates of this order have been shown to contribute significantly to probabilistic seismic hazard assessments (e.g. Clark & Leonard, 2014; Clark *et al.*, 2016). Consequently, the faults may pose a seismic hazard to proximal communities and infrastructure. Mapping and characterising potentially active faults is particularly challenging in such an environment of high relief, high erosion rates and extensive vegetation cover, and is a process that is far from complete. Indeed, recent seismic hazard assessments for large infrastructure projects concluded that the extant paleoseismic information is insufficient to meaningfully characterise the hazard relating to regional faults in the southeast highlands, despite the potential for recurrent large earthquakes alluded to above.

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 ~100-200 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 faults. This is especially the case where instrumental earthquakes are small and the subsurface geology is incompletely known (e.g. Clark, 2009). In this contribution we therefore focus on the landscape record of fault displacement. A brief synopsis of instrumental seismicity in the south-eastern highlands, and potential relationships to faulting is presented in the Appendix.

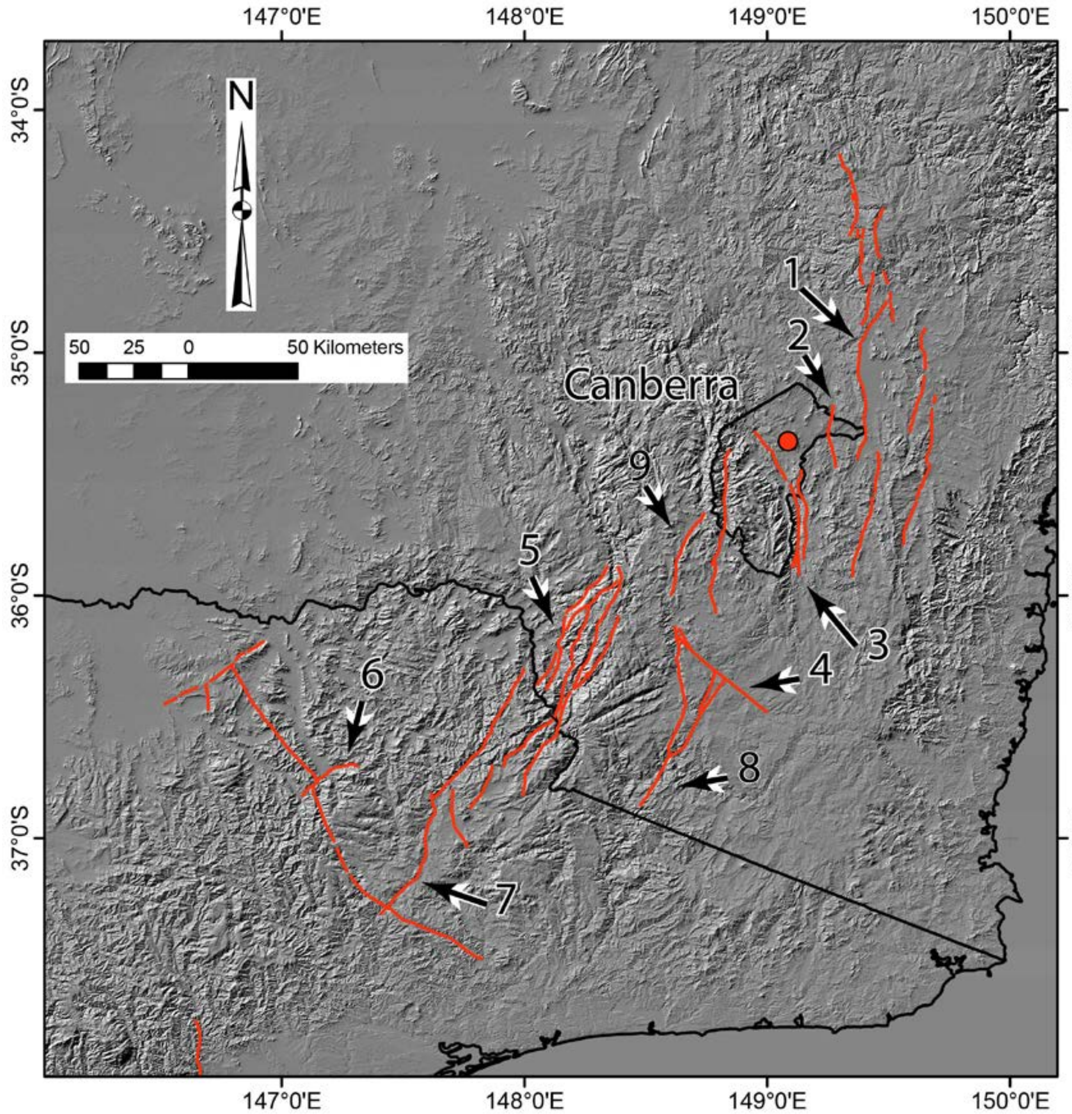


Figure 1: Neotectonic features in the eastern highlands (red lines) from the Australian Neotectonic Features database (after Clark *et al.*, 2012). Faults mentioned in the text: 1. Lake George, 2. Queanbeyan, 3. Murrumbidgee, 4. Berridale Wrench, 5. Khancoban-Yellow Bog, 6. Tawonga, 7. Livingstone Creek, 8. Jindabyne, 9. Tantangarra. Base map is SRTM DEM topography.

Epeirogenic vs seismogenic relief generation and maintenance in the eastern highlands

Evidence is widespread amongst southeast Australia's offshore basins for a Late Miocene to Pliocene tectonic event which resulted in the formation of a pronounced angular unconformity marking the onset of the extant crustal stress regime (Dickinson *et al.*, 2002; Sandiford *et al.*, 2004). Pliocene and younger strata overlying the unconformities are gently deformed (folded and faulted), consistent with indicators for neotectonic activity throughout Australia (Sandiford, 2003; Quigley *et al.*, 2010; Clark *et al.*, 2012; Clark *et al.*, 2014a). The question as to what extent this tectonic event affected the eastern highlands of Australia, and to what extent the basin record may be used as an analogue for the current potential for seismicity, has been a topic of debate over the last several decades.

Holdgate *et al.* (2008) present evidence from the Victorian part of the south-eastern highlands consistent with a punctuated uplift ‘event’ – the post-Eocene Kosciuszko Uplift (Andrews, 1910; Sprigg, 1945; Browne, 1967) – that continued into the Late Pliocene and potentially into the Pleistocene (see also Sharp, 2004; Greenwood *et al.*, 2017). Up to ~1000 m up uplift is ascribed to this event. The authors interpret lineaments visible in SRTM DEM data as faults upon which this uplift was achieved, though few of the northeast-trending lineaments have been confirmed as faults with Neogene displacement. More recently, Muller *et al.* (2016) used a plate-mantle convection model to show how movement of a continental edge over sinking slabs, and large-scale mantle upwellings can drive punctuated dynamic topographic uplift of margin highlands. They argue that while uplift due to intraplate stress changes through time can be accompanied by significant crustal deformation, it is readily observed in regions where it is the primary driver of uplift, as along the Flinders Ranges in South Australia (Sandiford, 2003; Celerier *et al.*, 2005; Quigley *et al.*, 2006). Seeing no such deformation in the eastern highlands (i.e. range bounding faults with significant throw), Muller *et al.* (2016) appeal to an alternative hypothesis involving dynamic topographic processes to explain the majority of Cenozoic uplift.

There are, however, many reports of faults demonstrating late Cenozoic displacement within the south-eastern highlands, stretching from Victoria into southern New South Wales (e.g. Beavis, 1960; Morand & Gray, 1991; Joyce *et al.*, 2003; Paine *et al.*, 2004; Holdgate *et al.*, 2006; Holdgate *et al.*, 2008; VandenBerg, 2010; Robson & Webb, 2011; Webb *et al.*, 2011). These occur mainly along the continental divide, where elevation is highest. A handful of fault systems with structural relief on the order of a few hundreds of metres or more are also documented, consistent with the hypothesis of Hillis *et al.* (2008) that neotectonic activity is responsible for adding a couple of hundred metres to the elevation of the eastern highland.

The record of Neogene and younger faulting in the eastern highlands

Perhaps the best documented examples of faults with displacement in the order of hundreds of metres in the eastern highlands are the Tawonga fault (Beavis, 1960; Beavis, 1962) and the Khancoban-Yellow-Bog fault (Moye *et al.*, 1963; Sharp, 2004). As part of works for the Snowy Mountains Hydro-electric Scheme, both faults were demonstrated to juxtapose Lachlan Fold Belt basement rocks over Cenozoic stream gravels. In the case of the Tawonga Fault, the No. 4 tailrace tunnel followed gravel some 200 m beneath a thrust tip of basement gneiss (Beavis, 1960). Drilling in the footwall of a surface exposure of gneiss thrust over gravel across the Khancoban-Yellow-Bog fault encountered a similar amount of overthrust gravel (Moye *et al.*, 1963; Ken Sharp, Pers. Comm. 2002). Pronounced knickpoints in stream bed profiles constructed upstream of both faults imply a punctuated uplift history (e.g. Figure 2). The age of overthrust gravels, and the timing of knickpoint initiation, are unknown. Hence the slip history (including rates) of these faults are unknown.

Fault traces cutting up from basement into undated unconsolidated sediments are documented from the Providence Portal, proximal to the Jindabyne Thrust/Tantangara Fault (Moye *et al.*, 1963). The Berridale Wrench Fault is associated with ~3 m high linear scarps in undated alluvial deposits, and very active springs (Lambert & White, 1965). Nearby candidates for similar activity include, but are not limited to, the Graben Gullen, Crookwell, Binda, Queanbeyan, Shoalhaven, Mulwaree, Tumut Ponds, Long Plain, Buenba, Lake George and Murrumbidgee Faults. These faults are associated with prominent bedrock scarps. However, exposures of faulted late Cenozoic sediments are not known, and have not been systematically searched for.

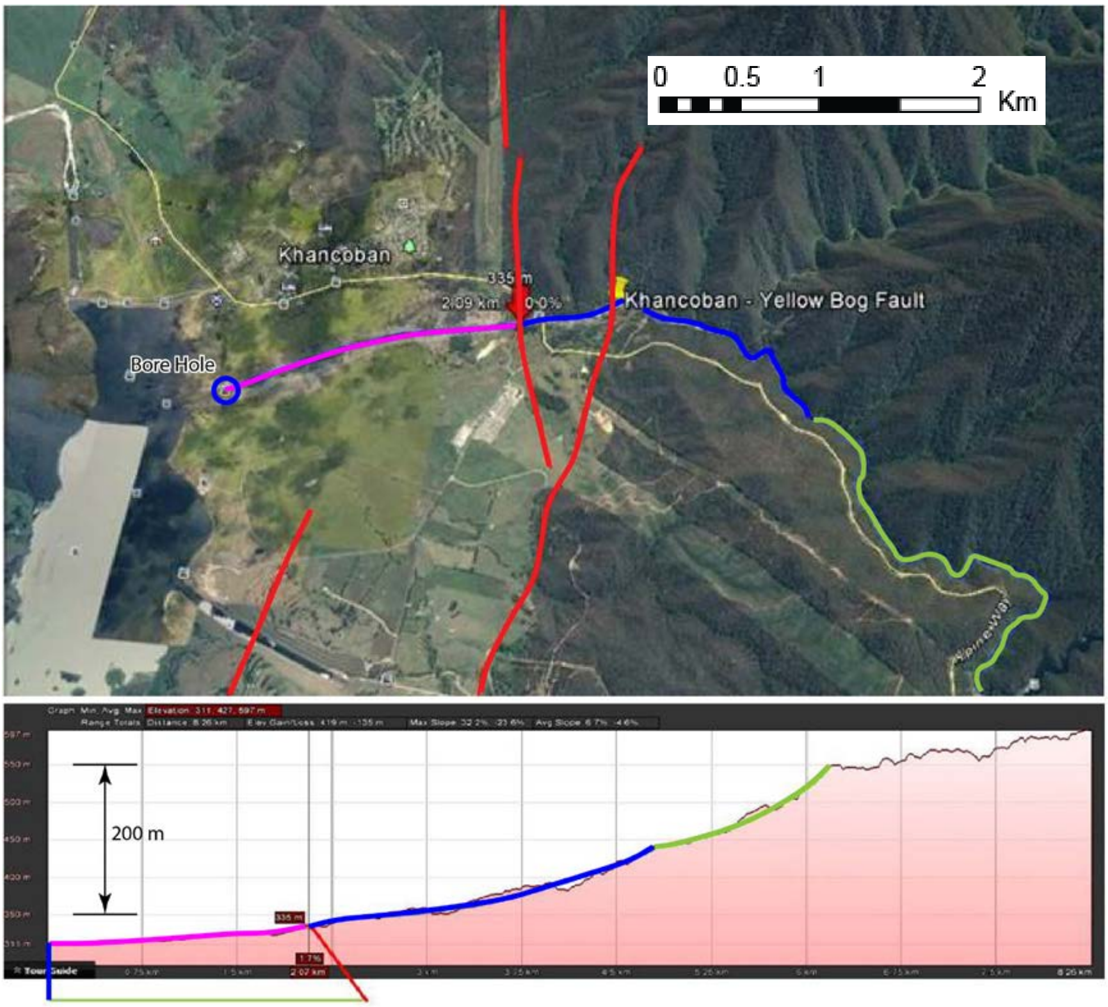


Figure 2: Google Earth image and stream profile across the Khancoban-Yellow Bog Fault near Khancoban. Notethat ~200 m high kickpoint upstream of the fault is facetted, implying a multistage uplift history. Borehole data from the Snowy Hydro Electric Scheme (Moye *et al.*, 1963) suggests a further >100 m of uplift is concealed by sediments in the footwall.

PALEOSEISMIC CASE STUDIES

Two faults in the region have been the subject of paleoseismic investigation to determine slip history, the Lake George and Murrumbidgee faults.

The Lake George Fault

The Lake George Basin formed as the result of west-dipping reverse faulting and associated fault propagation folding at the eastern margin of the Lake George Range in the interval between *ca.* 3.93 Ma and the present (Macphail *et al.*, 2015). Assuming that elevated gravels in the former outlet (Geary's Gap) are correlative with similar lithology at the base of the basin (Taylor, 1907; Browne, 1969), vertical displacement on the order of 250 m has occurred in this time interval (Figure 3). Averaged over a timescale of several million years, this is one of the larger rates of displacement recorded for an Australian intraplate fault (e.g. ~90 m/Myr assuming a 45 degree dipping Lake George fault) (cf. Clark *et al.*, 2011; Clark *et al.*, 2012). Three prominent angular unconformities, separating packages of approximately parallel strata, indicate that deformation was episodic, with up to 1 million years separating active periods on the fault. The most recent episode of deformation most likely occurred immediately prior to the current normally-polarised magnetochron (i.e. <780 ka).

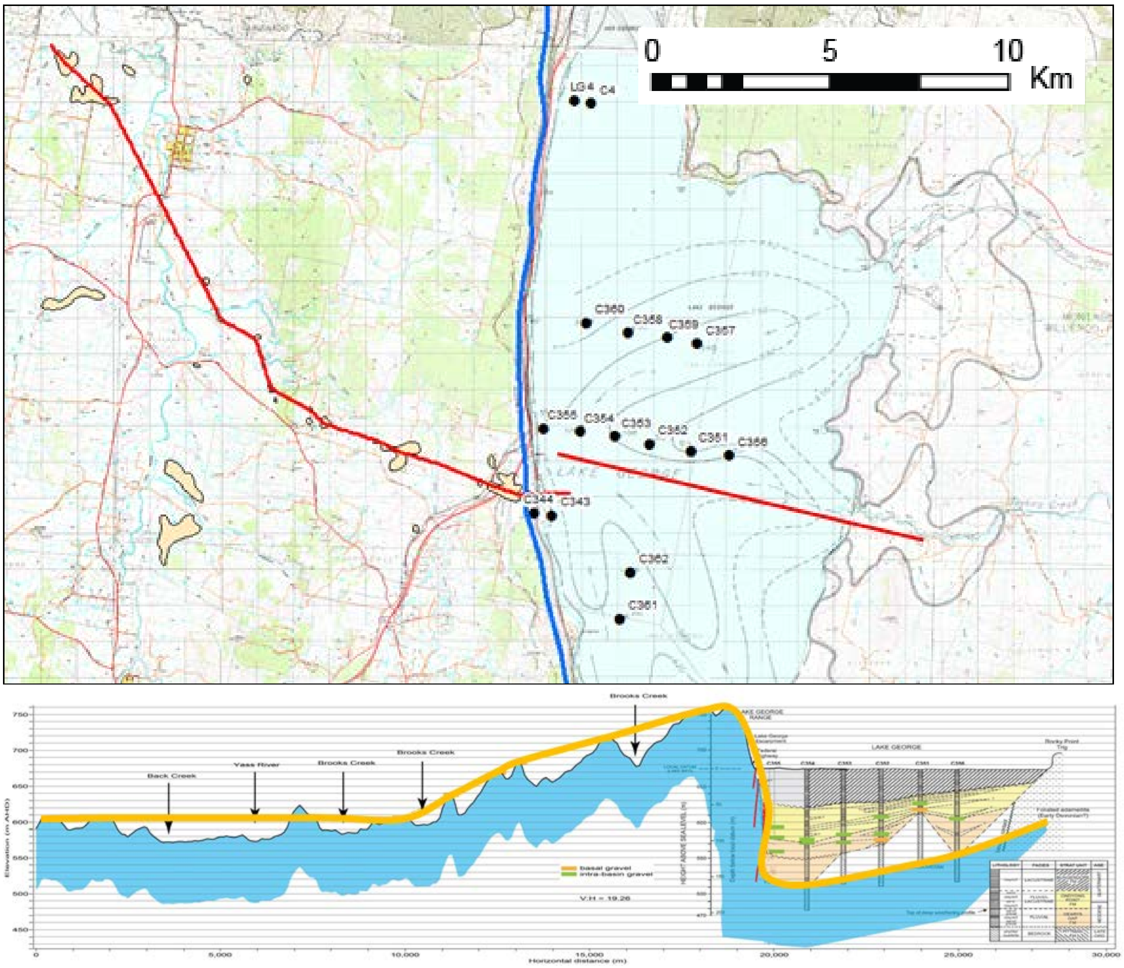


Figure 3: Central part of the Lake George Basin. The trace of the Lake George Fault is marked in blue, and uplifted fluvial gravels to the west of the fault are marked in orange. Borehole locations and contours for the base of the basin are drawn after Abell (1985). The section line (red line in upper panel) allows for the deformation envelope to be recovered by linking uplifted gravels with those intersected in boreholes at the base of the basin.

The Lake George Range is the eastern boundary of an uplifted block, known as the Cullarin Block, that extends to the west facing Queanbeyan scarp (Figure 4). As it is likely the east-dipping Queanbeyan Fault likely links into the west-dipping Lake George Fault at depth, it may have been active at the same time as the Lake George Fault.

Preliminary results from the Murrumbidgee Fault

The west dipping Murrumbidgee Fault is associated with a prominent east facing scarp over more than 70 km. The northern ~25 km of the scarp forms the western margin of the conurbation of Canberra (Figure 4). The Murrumbidgee River enters a contriction known as the Red Rocks Gorge at a location where the main fault splays and steps to the left. Bedrock terraces within the gorge record changes in the river profile which can be related to the vertical displament history on the Murrumbidgee Fault. Preliminary results dating the onset of terrace formation suggests a period of displacement on the fault, involving at least 15 m of vertical displacement of the river profile, starting at around 200 ka.

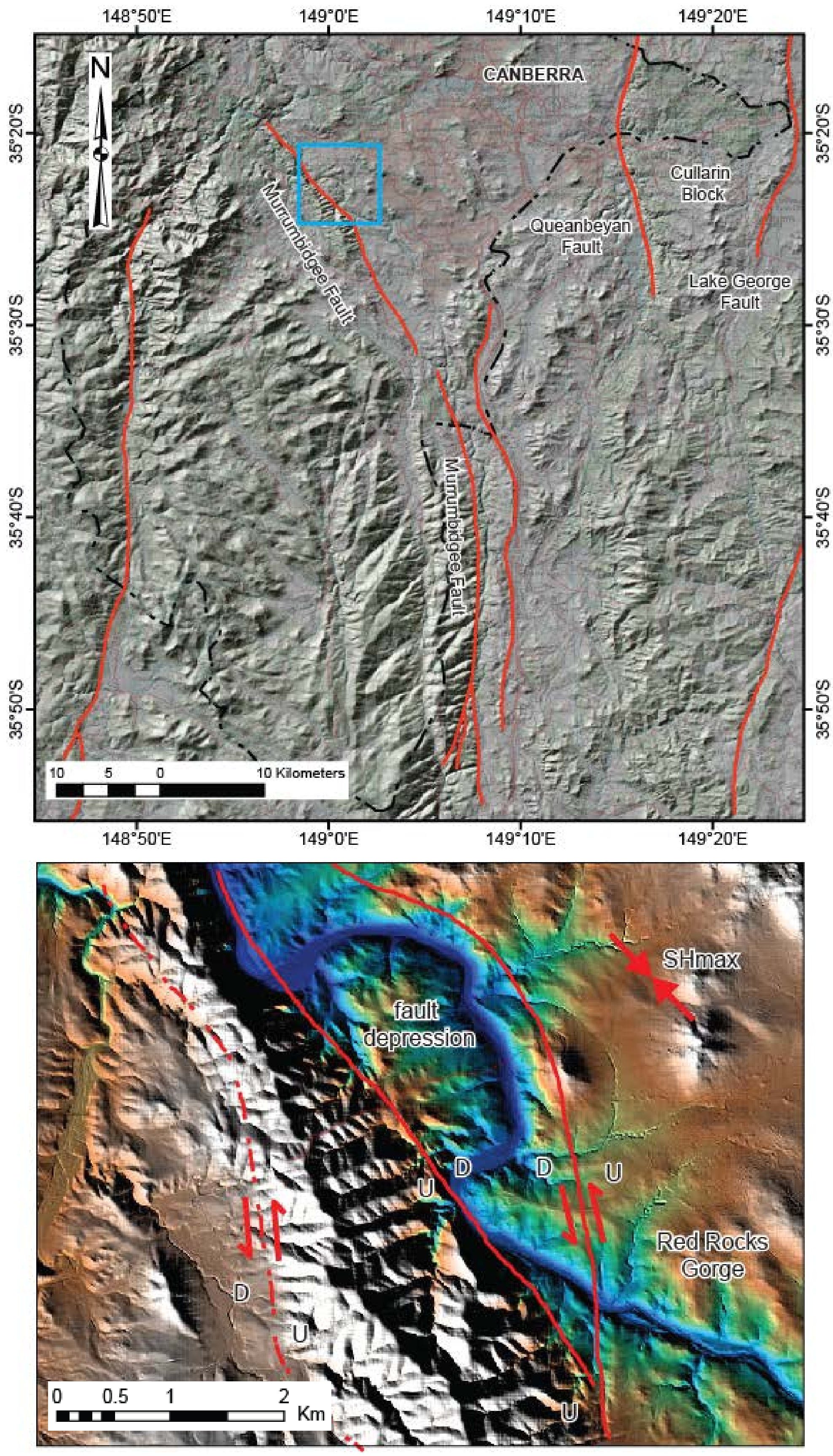


Figure 4: Map showing the location of the Murrumbidgee Fault, west of Canberra. The fault at this location is almost parallel to the regional stress field, which favours strike slip motion (but still with a compressive component). Inset shows a left stepping extensional jog. Subsidence within the jog initiated a base level drop on the Murrumbidge River and the formation of the Red Rocks Gorge.

DISCUSSION

A belt of faults associated with modest ranges straddles the continental divide of the eastern highlands from north of Goulburn in New South Wales to south of Mount Beauty in northeast Victoria (Figure 1). It is perhaps not coincidental that this belt of faults, and the continental divide that they straddle, trends perpendicular to the local maximum horizontal crustal stress orientation (Rajabi *et al.*, 2016; Rajabi *et al.*, 2017). This geometry favours reverse failure with the maximum vertical component to displacement. On individual faults, the magnitude of the vertical component of displacement over the time that the current stress condition has pertained (<8-4 Ma, Dickinson *et al.*, 2002) appears to be less than a few hundreds of metres. When it is compared with the estimate of ~1000 m of post Eocene uplift ascribed to the Kosciuszko uplift event (Holdgate *et al.*, 2008; Greenwood *et al.*, 2017), this finding favours a hypothesis where the the role of active faulting in relief generation and maintenance in the eastern highlands is subordinate to other mechanisms (Hillis *et al.*, 2008; Müller *et al.*, 2016). That is not to say that there is no seismic hazard.

Near the northern extent of the belt, the Lake George and Murrumbidgee faults are associated with uplift rates of 60-75 m/Myr (albeit calculated over different time ranges). Uplift on the Lake George Fault is found to be episodic, with active periods on the fault involving tens of metres of uplift being separated by quiescent periods of up to ~1.3 Myr. Slip rates in active periods may be ten times the long term average, as is seen for the Cadell Fault in the Murray Basin to the west (Clark *et al.*, 2015). The timing of the most recent active period on the Murrumbidgee Fault (<0.2 Ma), compared to the Lake George Fault (>0.78 Ma), suggests that periods of activity are asynchronous on proximal large faults.

Further south, the Khancoban Yellow-Bog Fault juxtaposes basement gneiss over more than a hundred metres of unconsolidated gravels, and is associated with a prominent disequilibrium stream profile indicative of punctuated uplift. At the southern mapped end of the belt, the Tawonga Fault also juxtaposes basement rocks over unconsolidated gravels, and is associated with a prominent disequilibrium stream profile indicative of punctuated uplift. The faults in between the above examples are typically associated with similar topographic expression, but are otherwise uncharacterized. It is not unreasonable to suspect activity rates similar to the characterized faults. If this is the case, a significant geologic source of seismic hazard exists in the southeast highlands, potentially commensurate with that in the Gippsland Basin to the south, or the Mt Lofty/Flinders Ranges to the west (cf. Clark & Leonard, 2014).

CONCLUSIONS

A belt of more than two dozen faults associated with modest ranges straddles the continental divide of the eastern highlands of Australia (Figure 1). These structures are largely uncharacterized in terms of seismogenic potential. The few faults that have been studied are associated with uplift rates of ≤60-75 m/Myr, and have accrued a few hundred metres of vertical displacement over the past 8-4 Myr. Evidence from the Lake George Fault suggests that slip is not evenly distributed in time, and that activity rates can be ten times the long term average in ‘’ periods. Faults may not synchronise in terms of the timing of active periods. A more comprehensive knowledge of these faults will be required to support renewed interest in nation-building infrastructure, and the expansion of major population centres, in the eastern highlands. Obtaining even partially complete displacement histories from these faults will be challenging, but opportunities exist to gather this information with modest effort from industry and regulators, at least for the Tawonga and Khancoban-Yellow Bog Faults.

ACKNOWLEDGEMENTS

The authors would like to thank Trevor Allen and Jonathan Griffin for making comments on an early version of this manuscript, and two anonymous reviewers for their thoughtful reviews. This article is published with the permission of the CEO of Geoscience Australia.

REFERENCES

Abell, R.S. 1985. Geology of the Lake George Basin, NSW. *Bureau of Mineral Resources, Geology and Geophysics Record 1985/4*: 57.

Abell, R.S. 1991. Geology of the Canberra 1:100 000 sheet area. *Bureau of Mineral Resources Bulletin*, 233: 135pp.

Andrews, E.C. 1910. Geographical unity of eastern Australia in late and post Tertiary time with applications to biological problems. *Journal and Proceedings of the Royal Society of New South Wales*, 44: 420-480.

Beavis, F.C. 1960. The Tawonga Fault, northeast Victoria. *Proceedings of the Royal Society of Victoria*, 72: 95-100.

Beavis, F.C. 1962. The geology of the Kiewa area. *Proceedings of the Royal Society of Victoria*, 75: 349-410.

Best, J.G., D'Addario, G.W., Walpole, B.P. & Rose, G. 1964. *Canberra 1:250 000 Geological Sheet SI/55-16, 2nd edition*. Geological Survey of New South Wales, Sydney.

Bock, G. & Denham, D. 1983. Recent earthquake activity in the Snowy Mountains region and its relationship to major faults. *Journal of the Geological Society of Australia*, 30: 423-429.

Browne, W.R. 1967. Geomorphology of the Kosciusko block and its north and south extensions. *Proceedings of the Linnean Society of New South Wales*, 92: 117-144.

Browne, W.R. 1969. General notes on the geomorphology of New South Wales. *Journal of the Geological Society of Australia*, 16: 559-569.

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

Clark, D. 2009. What is an "active" fault in the Australian intraplate context? A discussion with examples from eastern Australia. *Australian Earthquake Engineering Society Newsletter* http://www.aees.org.au/wp-content/uploads/2013/11/AEES_2009_2.pdf, June 2009: 3-6.

Clark, D., Griffin, J., Stirling, M., Leonard, M. & Volti, T. 2016. *Incorporating fault sources into the Australian National Seismic Hazard Assessment (NSHA) 2018, Australian Earthquake Engineering Society 2016 Conference, Nov 25-27*, Melbourne, Vic.

Clark, D., McPherson, A. & Allen, T. 2014a. Intraplate earthquakes in Australia. In: P. Talwani (Editor), Intraplate Earthquakes. Cambridge University Press, New York, pp. 8-49.

Clark, D., McPherson, A., Allen, T. & De Kool, M. 2014b. Co-seismic surface deformation relating to the March 23, 2012 MW 5.4 Ernabella (Pukatja) earthquake, central Australia: implications for cratonic fault scaling relations.

Bulletin of the Seismological Society of America, 104(1): 24-39, doi: 10.1785/0120120361.

Clark, D., McPherson, A. & Collins, C.D.N. 2011. Australia’s seismogenic neotectonic record: a case for heterogeneous intraplate deformation. *Geoscience Australia Record*, 2011/11: 95 p.

Clark, D., McPherson, A., Cupper, M., Collins, C.D.N. & Nelson, G. 2015. The Cadell Fault, southeastern Australia: a record of temporally clustered morphogenic seismicity in a low-strain intraplate region. In: A. Landgraf, S. Kuebler, E. Hintersburger and S. Stein (Editors), Geological Society, London, Special Publication *Seismicity, Fault Rupture and Earthquake Hazards in Slowly Deforming Regions*.

Clark, D., McPherson, A. & Van Dissen, R. 2012. Long-term behaviour of Australian Stable Continental Region (SCR) faults. *Tectonophysics* 566-567: 1-30, http://dx.doi.org/10.1016/j.tecto.2012.07.004.

Clark, D.J. & Leonard, M. 2014. Regional variations in neotectonic fault behaviour in Australia, as they pertain to the seismic hazard in capital cities. *Australian Earthquake Engineering Society 2014 Conference, Nov 21-23, Lorne, Vic*, http://www.aees.org.au/wp-content/uploads/2015/06/44-Clark.pdf: paper 44.

Cleary, J.R. 1967. The seismicity of the Gunning and surrounding areas, 1958-1961. *Journal of the Geological Society of Australia*, 14(1): 23-29.

Cleary, J.R., Doyle, H.A. & Moye, D.G. 1964. Seismic activity in the snowy mountains region and its relationship to geological structures. *Australian Journal of Earth Sciences*, 11(1): 89-106.

Denham, D., Weekes, J. & Krayshek, C. 1981. Earthquake evidence for compressive stress in the southeast Australian crust. *Journal of the geological Society of Australia*, 28: 323-332.

Dickinson, J.A., Wallace, M.W., Holdgate, G.R., Gallagher, S.J. & Thomas, L. 2002. Origin and timing of the Miocene-Pliocene unconformity in southeast Australia. *Journal of Sedimentary Research*, 72(2): 288-303.

Greenwood, D.R., Keefe, R.L., Reichgelt, T. & Webb, J.A. 2017. Eocene paleobotanical altimetry of Victoria's Eastern Uplands. *Australian Journal of Earth Sciences*, 64(5): 625-637, DOI: 10.1080/08120099.2017.1318793.

Griffin, J., Volti, T., Clark, D., Ghasemi, H., Leonard, M. & Allen, T. 2016. *Development of the Australian National Seismic Hazard Assessment (NSHA) 2018*, *Australian Earthquake Engineering Society 2016 Conference*, Nov. 25-27, Melbourne, Victoria.

Heimsath, A.M., Chappell, B.W. & Fifield, K. 2010. Eroding Australia: rates and processes from Bega Valley to Arnhem Land. *Geological Society of London Special Publication*, 346: 225-242.

Heimsath, A.M., Chappell, J., Dietrich, W.E., Nishiizumi, K. & Finkel, R.C. 2000. Soil production on a retreating escarpment in southeastern Australia. *Geology*, 28(9): 787-790.

Heimsath, A.M., Chappell, J., Dietrich, W.E., Nishiizumi, K. & Finkel, R.C. 2001. Late Quaternary erosion in southeastern Australia: a field example using cosmogenic isotopes. *Quaternary International*, 83-85: 169-185.

Hillis, R.R., Sandiford, M., Reynolds, S.D. & Quigley, M.C. 2008. Present-day stresses, seismicity and Neogene-to-Recent tectonics of Australia’s ‘passive’ margins: intraplate deformation controlled by plate boundary forces. In: H. Johnson, A.G. Dore´ , R.W. Gatliff, R. Holdsworth, E.R. Lundin and J.D. Ritchie (Editors), The Nature and Origin of Compression in Passive Margins. Geological Society, London, Special Publications, pp. 71-90.

Holdgate, G.R., Wallace, M.W., Gallagher, S.J., Wagstaff, B.E. & Moore, D. 2008. No mountains to snow on: major post-Eocene uplift of the East Victoria

Highlands; evidence from Cenozoic deposits. *Australian Journal of Earth Sciences*, 55: 211-234.

Holdgate, G.R., Wallace, M.W., Gallagher, S.J., Witten, R.B., Stas, B. & Wagstaff, B.E. 2006. Cenozoic fault control on 'deep lead' palaeoriver systems, Central Highlands, Victoria. *Australian Journal of Earth Sciences*, 53(3): 445-468.

Johnston, A.J., Scott, M.M., Thomas, D.J., Pogson, D.J., Warren, A.Y.E., Sherwin, L., Colquhoun, G.P., Watkins, J.J., Cameron, R.G., MacRae, G.P. & Glen, R.A. 2010. Goulburn 1:250 000 Geological Sheet SI/55-12, provisional 2nd edition. Geological Survey of New South Wales, Orange.

Joyce, E.B., Webb, J.A., Dahlhaus, P.G., Grimes, K.G., Hill, S.M., Kotsonis, A., Martin, J., Mitchell, M.M., Neilson, J.L., Orr, M.L., Peterson, J.A., Rosengren, N.J., Rowan, J.N., Rowe, R.K., Sargeant, I., Stone, T., Smith, B.L. & White, S. 2003. Geomorphology. In: W.D. Birch (Editor), Geology of Victoria. Geological Society of Australia, pp. 533-561.

Lambert, I.B. & White, A.J.R. 1965. The Berridale Wrench fault: A major structure in the Snowy Mountains of New South Wales. *Australian Journal of Earth Sciences*, 12(1): 25-33.

Langridge, R.M., Ries, W.F., Litchfield, N.J., Villamor, P., Van Dissen, R.J., Barrell, D.J.A., Rattenbury, M.S., Heron, D.W., Haubrock, S., Townsend, D.B., Lee, J.M., Berryman, K.R., Nicol, A., Cox, S.C. & Stirling, M.W. 2016. The New Zealand Active Faults Database. *New Zealand Journal of Geology and Geophysics*, 59(1): 86-96, 10.1080/00288306.2015.1112818.

Leonard, M. 2008. One hundred years of earthquake recording in Australia. *Bulletin of the Seismological Society of America*, 98: 1458-1470.

Macphail, M., Fifield, L.K., Pillans, B., Davies, M. & Hope, G. 2015. Lake George revisited: New evidence for the origin and evolution of a large closed lake, Southern Tablelands, NSW, Australia. *Australian Journal of Earth Sciences*, 10.1080/08120099.2015.1108365.

McCue, K. 1989. A century of earthquakes in the Dalton-Gunning region of New South Wales. *BMR Journal of Australian Geology & Geophysics*, 11(1): 1-9.

McCue, K. 2004. Australia: historical earthquake studies. *Annals of Geophysics*, 47(2/3): 387-397.

McCue, K. 2011. *The 1959 Berridale NSW Earthquake Revisited, Australian Earthquake Engineering Society 2011 Conference, Nov 18-20* Australian Earthquake Engineering Society Barossa Valley, South Australia, pp. paper 36.

McCue, K. 2012. Historical earthquakes in NSW. *AEES Newsletter*, http://www.aees.org.au/wp-content/uploads/2013/11/McCue_NSW_EQs.pdf.

McCue, K.F. 1980. Magnitudes of some early earthquakes in Southeastern Australia. *Search*, 11(3): 78-80.

Michael-Leiba, M.O. 1994. Fluctuations in seismicity in the Dalton area, NSW, Australia, and their relevance to earthquake forecasting. *AGSO Journal of Australian Geology and Geophysics*, 15(3): 329-333.

Morand, V.J. & Gray, D.R. 1991. Major fault zones related to the Omeo Metamorphic Complex, northeastern Victoria. *Australian Journal of Earth Sciences*, 38: 203-221.

Moye, D.G., Sharp, K.R. & Stapledon, D.H. 1963. Geology of the Snowy Mountains Region. *Snowy Mountains Hydro-electric Authority, Cooma* (unpubl.: held in Geological Survey of New South Wales Library).

Müller, R.D., Flament, N., Matthews, K.J., Williams, S.E. & Gurnis, M. 2016. Formation of Australian continental margin highlands driven by plate–mantle interaction. *Earth and Planetary Science Letters*, 441: 60-70, http://dx.doi.org/10.1016/j.epsl.2016.02.025.

Paine, M.D., Bennetts, D.A., Webb, J.A. & Morand, V.J. 2004. Nature and extent of Pliocene strandlines in southwestern Victoria and their application to Late Neogene tectonics. *Australian Journal of Earth Sciences,* 51(3): 407-422.
Quigley, M.C., Clark, D. & Sandiford, M. 2010. Tectonic geomorphology of Australia. *Geological Society, London, Special Publications*, 346(1): 243-265.
Quigley, M.C., Cupper, M.L. & Sandiford, M. 2006. Quaternary faults of south-central Australia: palaeoseismicity, slip rates and origin. *Australian Journal of Earth Sciences*, 53: 285-301.
Rajabi, M., Tingay, M. & Heidbach, O. 2016. The present-day stress field of New South Wales, Australia. *Australian Journal of Earth Sciences*, 63(1): 1-21, 10.1080/08120099.2016.1135821.
Rajabi, M., Tingay, M., Heidbach, O., Hillis, R. & Reynolds, S. 2017. The present-day stress field of Australia. *Earth-Science Reviews*, 168: 165-189, 10.1016/j.earscirev.2017.04.003.
Rattenbury, M.S. & Isaac, M.J. 2012. The QMAP 1:250 000 Geological Map of New Zealand project. *New Zealand Journal of Geology and Geophysics*, 55(4): 393-405, 10.1080/00288306.2012.725417.
Robson, T.C. & Webb, J.A. 2011. Late Neogene tectonics in northwestern Victoria: Evidence from the Late Miocene–Pliocene Loxton Sand. *Australian Journal of Earth Sciences*, 58(6): 579-586.
Sandiford, M. 2003. Neotectonics of southeastern Australia: linking the Quaternary faulting record with seismicity and in situ stress. In: R.R. Hillis and D. Muller (Editors), Evolution and dynamics of the Australian Plate Geological Society of Australia Special Publication, pp. 101-113.
Sandiford, M., Wallace, M. & Coblentz, D. 2004. Origin of the in situ stress field in southeastern Australia. *Basin Research*, 16: 325-338.
Sharp, K.R. 2004. Cenozoic volcanism, tectonism and stream derangement in the Snowy Mountains and northern Monaro of New South Wales. *Australian Journal of Earth Sciences*, 51(1): 67-83.
Somerville, P., Quijada, P., Thio, H.K., Sandiford, M. & Quigley, M. 2008. Contribution of Identified Active Faults to Near Fault Seismic Hazard in the Flinders Ranges. *Australian Earthquake Engineering Society Meeting*, Paper 45.
Sprigg, R.C. 1945. Some aspects of the geomorphological of portion of the Mount Lofty Ranges. *Transactions of the Royal Society of South Australia Department of Mines Report Book*, 69: 277-304.
Taylor, T.G. 1907. The Lake George Senkungsfeld, a study of the evolution of Lakes George and Bathurst. *Proceedings of the Linnean Society of N. S. W.*, 32: 325-345.
Tomkins, K.M., Humphreys, G.S., Wilkinson, M.T., Fink, D., Hesse, P.P., Doerr, S.H., Shakesby, R.A., Wallbrink, P.J. & Blake, W.H. 2007. Contemporary versus long-term denudation along a passive plate margin: the role of extreme events. *Earth Surface Processes and Landforms*, 32: 1013-1031.
VandenBerg, A.H.M. 1997. *Tallangatta SJ 55-3 Edition 2, 1:250 000 Geological Map Series*, *1:250 000 geological map*. Geological Survey of Victoria.
VandenBerg, A.H.M. 2010. Paleogene basalts prove early uplift of Victoria's Eastern Uplands. *Australian Journal of Earth Sciences*, 57(3): 291 - 315.
VandenBerg, A.H.M., Magart, A.P.M., Simons, B.A., Willman, C.E. & Hendrickx, M. 1998. *Benambra. 1:50 000 geological map*. Geological Survey of Victoria.
Webb, J.A., Gardner, T.W., Kapostasy, D., Bremar, K.A. & Fabel, D. 2011. Mountain building along a passive margin: Late Neogene tectonism in southeastern Victoria, Australia. *Geomorphology*, 125: 253-262.

Weissel, J.K. & Seidl, M.A. 1998. Inland propagation of erosional escarpments and river profile evolution across the southeast Australian passive continental margin. In: K.J. Tinkler and E.E. Wohl (Editors), Geophysical Monograph. American Geophysical Union, pp. 189-206.

Wilkinson, M.T., Chappell, J., Humphreys, G.S., Fifield, K., Smith, B. & Hesse, P. 2005. Soil production in heath and forest, Blue Mountains, Australia: influence of lithology and palaeoclimate. *Earth Surface Processes and Landforms*, 30: 923-934.

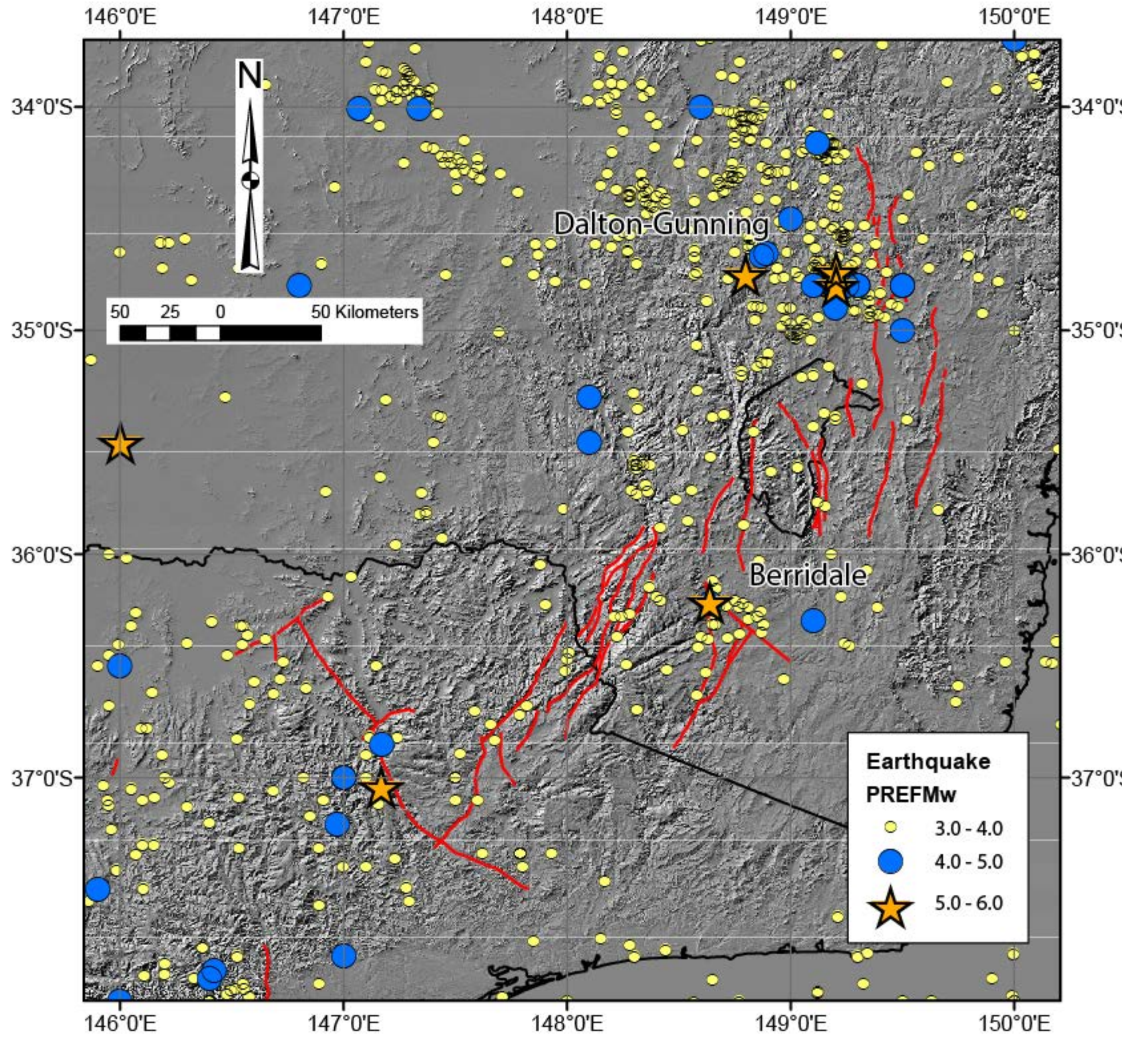
Willman, C.E., Magart, A.P.M., Simons, B.A., Hendrickx, M. & VandenBerg, A.H.M. 1998. *Gibbo. 1:50 000 geological map*. Geological Survey of Victoria.

APPENDIX - INSTRUMENTAL SEISMICITY IN THE SOUTH-EASTERN HIGHLANDS, AND POTENTIAL RELATION TO FAULTING

The south-eastern highlands lie within the southeast Australia seismic zone of Leonard (2008), one of four broad regions of elevated seismicity within the Australian continent. The region has been one of the better monitored in Australia by virtue of the former ANU seismograph network, elements of the Geoscience Australia National Seismic Network, and seismograph networks installed in association with large infrastructure, and operated by Environmental Systems and Services (e.g. http://www.esands.com/pdf/Seismology/ESS_Seismic_Network_Report_2009.pdf). Consequently, hypocentral uncertainties are some of the lowest in the country, ranging from approximately one kilometre to ten kilometres. Seismicity occurs in a broad NE-trending band that follows the axis of the highlands, and extends onto the plains to the west (Appendix Figure 1). The rate of seismicity appears to have been roughly steady over at least the last 100 years (Leonard 2008). The instrumental catalogue has been enhanced through the study of historical events, adding several dozen events (McCue, 1980; McCue, 1989; McCue, 2004; McCue, 2012).

In detail, concentrations of epicentres are associated with the Dalton-Gunning (Cleary, 1967; McCue, 1989; Michael-Leiba, 1994) and Berridale (Cleary *et al.*, 1964; Bock & Denham, 1983; McCue, 2011) areas. The latter activity was tentatively associated with faults in the area, though landscape evidence is equivocal (Lambert & White, 1965; Bock & Denham, 1983; McCue, 2011). Although linear trends in earthquake epicentres are sometimes apparent (e.g. Cleary *et al.*, 1964; Bock & Denham, 1983), correlation to a particular "active" structure remains a speculative process in the absence of surface rupture. Seismologists, and professionals 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 ~100-200 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 faults. This is especially the case where instrumental earthquakes are small and the subsurface geology is incompletely known (e.g. Clark, 2009). For example, take one of the larger of the events shown on Appendix Figure 1, the 1959 M_L~5 Berridale earthquake. The depth of this ~3 km x 3 km rupture is reported as 17 km and uncertainties on the location of the event are reported as ± 1 km horizontal and ± 2 km vertical (Cleary *et al.*, 1964). Nominally, the epicenter is located near to the intersection of the sub-vertical and NW-trending Berridale wrench fault, the north-trending and moderately east-dipping Jindabyne Thrust, and ~ 18 km northwest of the moderately northwest-dipping Barneys Range Fault. The pure thrust focal mechanism constructed for the event (Denham *et al.*, 1981) excludes the Berridale wrench fault as host. The uncertainty ellipse on the event does not intersect the east dipping Jindabyne Thrust at hypocentral depths, and the geometry of the Barney's Range fault in plan view suggests that it is a splay branching off the larger Jindabyne Thrust, and so terminates at depth >8-10 km east of the epicenter. thereby excluding that structure. As concluded by Bock & Denham (1983), the event appears to have occurred on an unmapped fault. Depending upon the preferred structural geometry, and the level of confidence placed in the horizontal location and hypocentral depths, the same argument can be made for other events in the Snowy Mountains. Ruptures need not occur on structures associated with a surface fault trace.

The Activity in the Dalton-Gunning region is of particular interest in this respect. The earthquake hypocentres appear to have occurred predominantly in the upper 10 km of the crust, with most occurring at much shallower depth (e.g. McCue, 1989). No potential candidate fault structures are known from the epicentral area. However, epicentres conspicuously occur to the west of a north-south line marked by the Lake George, Graben Gullen and Cullerin Faults (Appendix Figure 1). Recent work on the Lake George Fault suggests it is a relatively shallow west dipping structure, and so may underly the epicentral area at depth. This raises the possibility that compressive stresses developed in the hangingwall of the larger faults may lead to failure on minor structures. An analogous situation may be the case with the 1987 Marryat Creek, 2012 Ernabella, and 2016 Petermann Ranges all occurring in the immediate hanging wall of the crustal scale Woodroffe thrust (e.g. Clark *et al.*, 2014b).



Appendix Figure 1: Map showing the location of faults in the eastern highlands with seismicity of magnitude M>3 overlain (Geoscience Australia NSHA2018 catalogue).