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Neotectonics and landscape evolution of southeastern Australia: establishing a geologic context for contemporary seismicity

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ABSTRACT
Southeastern Australia contains a rich geologic record of Plio-Quaternary reverse faulting and associated landscape evolution that can be used to provide geologic constraints on historical seismicity. The Mt Lofty-Flinders Ranges-eastern Gawler Craton region and Eastern Highlands are characterized by high fault density, "youthful" geomorphology, and high seismic activity relative to most of Australia, including the intervening Murray Basin. Inferred ~east-west directed maximum compressive paleostress orientations derived from Plio-Quaternary faults are generally consistent with ~east-west to ~southeast-northwest maximum compressive stress orientations derived from historical earthquake focal mechanisms, providing a link between the neotectonic record, seismicity, and *in situ* stress. Plio-Quaternary fault slip rates along range-bounding reverse faults range from 20 to 150 m per million years (m Myr^{-1}). Coupled with slow bedrock erosion rates at range summits, this suggests a minimum of 100 m of surface uplift has occurred over considerable areas of southeastern Australia since the Miocene. Estimates of recurrence interval of large magnitude, surface rupturing earthquakes along individual faults range from ~ 22 000 to ≥ 83 000 years. Single-event fault displacements may have reached up to 8 m in total fault offset. The data acquired from neotectonic investigations bear heavily on the modes, mechanisms, and seismic risk associated with the active regional deformation of southeastern Australia, including the Sydney Basin.

INTRODUCTION

Although records of historical earthquakes provide cursory information on active crustal deformation and seismic risk, recurrence intervals of large earthquakes in many intracontinental regions commonly surpass the life span of these records by orders of magnitude, defining the need for fault studies over geologic time-scales. The neotectonic record of prehistoric faulting provides an important source of information on the long-term behaviour of intracontinental faults, especially where it can be linked to contemporary seismicity. Australia is particularly well-suited to study these structures as much of the continent is relatively arid and has remained immune from Quaternary glaciations, resulting in high preservation levels of faults and associated landforms.

In southeastern Australia, distribution patterns of contemporary seismicity closely overlap with topographically high regions containing increased concentrations of neotectonic faults and rugged "youthful" geomorphology, implying a casual link between active deformation and landscape evolution (Fig. 1). Considerable progress has been made towards a better understanding of the dynamics, rates, and landscape manifestations of this modern tectonic regime through recent neotectonic, geomorphic, and geodynamic studies. In this paper, we briefly summarize this progress and provide a regional geologic context for southeastern Australian earthquakes.

ACTIVE DEFORMATION OF SOUTHEASTERN AUSTRALIA

Seismicity and *in situ* stress

Southeastern Australia is one of the most seismically active parts of the continent, with distributions of historical (~1850 A.D. to present) earthquakes up to Richter Magnitude ~6.4 extending from the eastern Gawler Craton to the Eastern Highlands (Fig. 1). Approximately 7000 earthquakes were

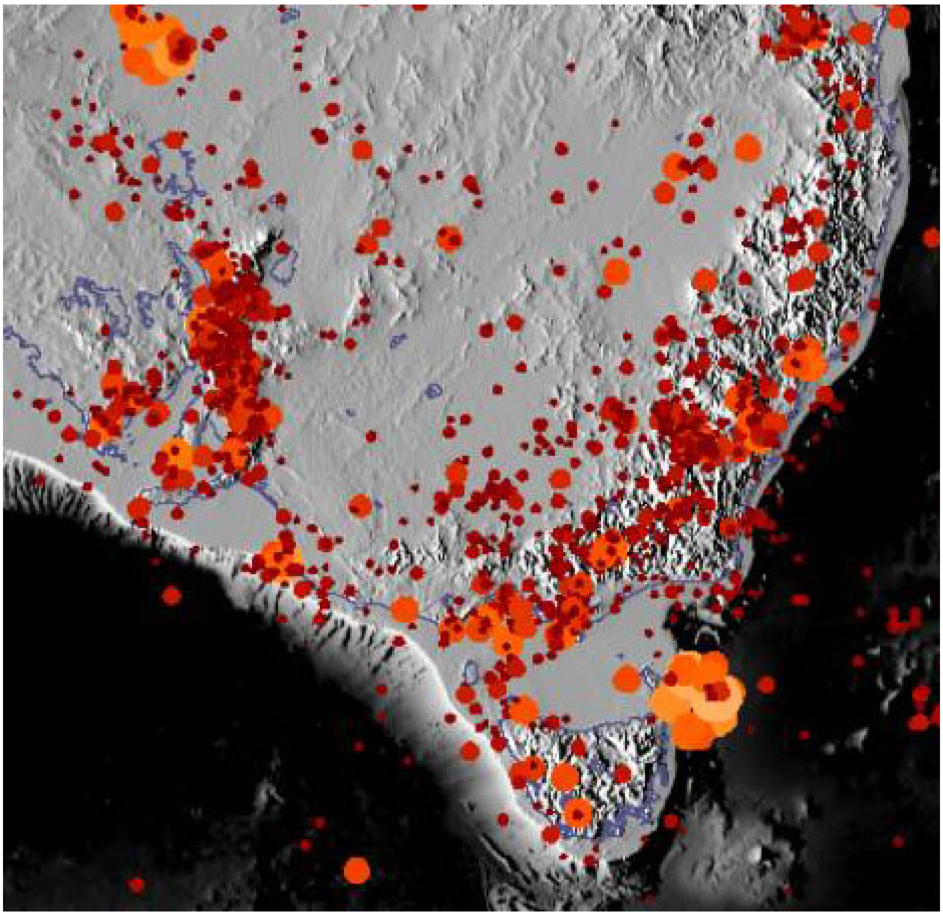

Figure 1: *Distribution of seismicity in southeastern Australia. Earthquakes concentrated in the Mt Lofty-Flinders Ranges-eastern Gawler Craton region and in a belt traversing the west coast of Tasmania through the Eastern Highlands in southeast Victoria and New South Wales.*

recorded in the region from 1958 to 1999 (Spassov and Kennett, 2000). Two distinguishable belts of enhanced seismicity are visible; the first centred within the Mt Lofty-Flinders Ranges-eastern Gawler Craton region and the second continuing from the west coast of Tasmania through the Eastern Highlands in southeast Victoria and New South Wales in the vicinity of the Sydney Basin (Fig. 1). Seismicity is considerably lower in the intervening Murray Basin and cratons to the west. Earthquake focal mechanisms in the Flinders Ranges indicate combinations of compressive strike-slip and reverse faulting along roughly north- to northeast-striking focal planes, from which a principle horizontal compressive stress orientation (S_{hmax}) of ~ 83^o was inferred (Greenhalgh et al., 1994; Hillis and Reynolds, 2000; Clark and Leonard, 2003). Reverse fault mechanisms and borehole breakouts define a roughly southeast-northwest oriented S_{hmax} azimuth (~130^o) throughout the eastern highlands in Victoria (Gibson et al., 1981; Hillis and Reynolds, 2000). The bulk of focal-mechanism data from the Sydney Basin seem to indicate a roughly northeast-southwest oriented S_{hmax} (Clark and Leonard, 2003). In summary, when historical earthquake and *in situ* stress data is considered at the scale of southeastern Australia, there seems to be a general pattern of roughly east-west oriented compression, with superimposed S_{hmax} variability a possible artefact of either seismic sampling (Clark and Leonard, 2003) and/or local geologic conditions such as topography or basin structure (Zhang et al., 1996; Hillis and Reynolds, 2000).

Quaternary faulting

Geologic studies have identified as many as 100 faults with demonstrable Quaternary displacements across southeastern Australia (Fig. 2). Recent studies have integrated ASTER and SRTM high resolution satellite imagery (Sandiford, 2003; Quigley et al., 2006), structural geology and geomorphology (Clark et al. in press), optically stimulated luminescence (OSL) dating (Quigley et al., 2006; Clark et al. in press), ^{10}Be cosmogenic nuclide dating (Quigley et al., 2007) and other techniques to provide quantitative constraints on paleoseismicity, fault slip rates, recurrence intervals, and related sedimentary and landscape responses to faulting. Several important conclusions and implications have come from this work: (1) All documented Quaternary faults involve either purely dip-slip reverse movement or oblique-reverse movement; no Quaternary strike-slip or normal faults have been found. Fault kinematic data derived from fault plane and slickenline orientations indicate a roughly east-west oriented palaeo-S_{hmax}, consistent with the S_{hmax} azimuth derived from historical seismicity (Sandiford, 2003; Quigley et al., 2006); (2) Quaternary faults commonly occur along geologic boundaries such as inherited lithotectonic boundaries (e.g., Wilkatana and Roopena / Ash Reef Faults within Lake Torrens Rift Zone) and range fronts (Flinders and Mt. Lofty Ranges) and commonly reactivate ancient fault zones (e.g., Mundi Mundi Fault, Lake Edgar Fault) (3) Estimates of prehistoric southeastern Australian earthquake magnitudes (M), based on fault rupture lengths, single-event displacements and inferred ranges of hypocentral rupture depth, range from M = 5.8 to 7.2 (Clark and McCue, 2003; Quigley et al., 2006). The data is consistent with M estimates for the largest recorded Australian earthquakes (Meeberiee, WA 1941, M=7.3; Meckering, WA 1968, M=6.8; Tennant Creek, NT 1988; M=6.7); (4) Plio-Quaternary fault slip rates derived from cumulative displacements of Pliocene and Quaternary sediments range from 20-150 m Myr^{-1} (Sandiford, 2003; Quigley et al., 2006). Fault slip rates determined from individual fault exposures are difficult to assess because of the tendency of intracontinental faulting to cluster in time and space (Crone et al., 1997, 2003). For example, faults in the Wilkatana area of the central Flinders Ranges may have incurred upwards of 15 m of cumulative slip since ~ 67 000 years ago (Quigley et al., 2006), equating to Quaternary rates of ~225 m Myr^{-1}, whereas the Lady Buxton segment of the Paralana Fault in the northern Flinders Ranges may not have moved since the Pliocene; (5) Estimates of surface-rupturing earthquake recurrence interval from Quaternary faults range from 1: 22,000 years to ≥ 1: 83,000 years and are also severely hampered by the sporadic nature of intracontinental faulting (Quigley et al., 2006); (6) Earthquake activity may have resulted in upwards of several 100’s of meters of cumulative surface uplift in some parts of southeast Australia, such as the Flinders, Mt Lofty, and Otway Ranges (Sandiford, 2003; Tokarev et al., 1999; Bourman and Lindsay, 1989) and Eastern Highlands (e.g. Khancoban-Yellow Bog Fault, Sharp, 2004; Lake George Fault, Abel, 1985). Quaternary faulting also appears to have defeated and diverted the Murray and Goulburn River systems near Echuca in northern Victoria (Clark, 2007) and diverted the Murray River again near Morgan in South Australia. This suggests that major landscape changes have occurred in response to large earthquakes generated within the modern tectonic regime.

Modes and mechanisms of crustal deformation

Insights into the mode of active crustal deformation in southeastern Australia may be obtained by combining historical seismicity with neotectonic studies and geological and geophysical datasets. Celerier et al. (2005) suggest that two modes of active deformation have been in operation in the Flinders Ranges region over the last several million years: (1) low-amplitude (~200-500 m), long-wavelength (~200 km) elastic lithospheric flexure, as indicated by long-wavelength correlations between surface topography and gravity, and (2) active range front reverse faulting. Seismicity has been focused in the Flinders Ranges because of older (Neoproterozoic and Cambrian) tectonic structuring and thermal weakening, generated by high concentrations of heat producing elements within granite bodies that compose the regional basement (Celerier et al., 2005). Older tectonic structuring is also likely to have played a part in localizing seismicity in the Eastern Highlands, where Miocene to Quaternary reverse faulting has in places reactivated normal faults formed during

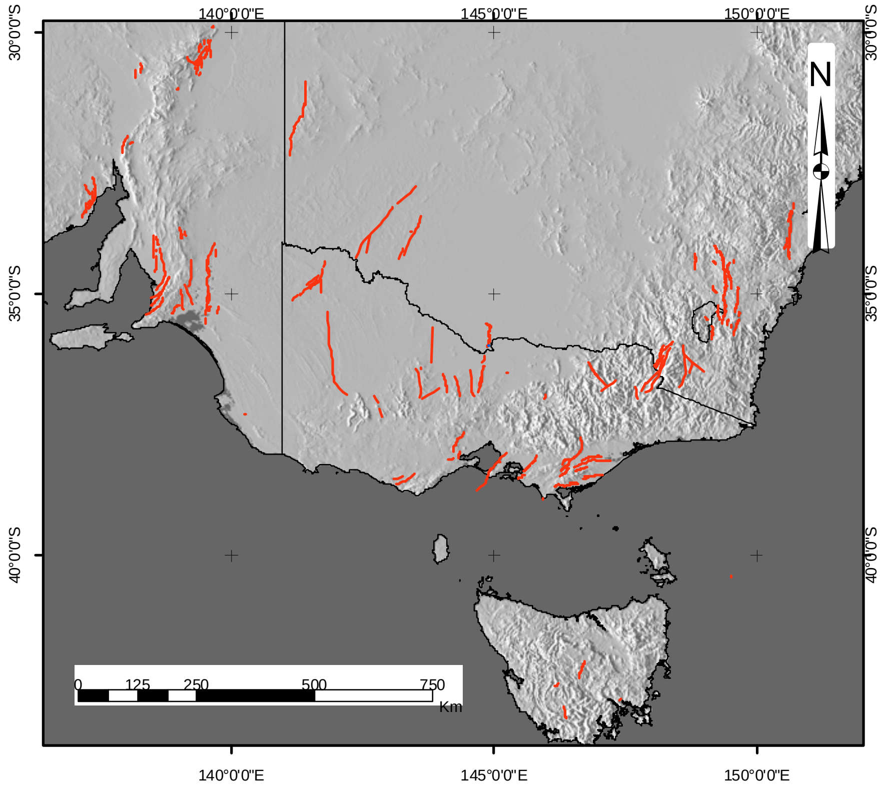

Figure 2: *Distribution of faults in southeastern Australia suspected of hosting Quaternary seismogenic displacement (from the Geoscience Australia neotectonics database).*

Mesozoic rifting. However, thermal weakening appears less relevant to the seismicity of this region, as basement rocks are characterised by significantly lower heat flows than those composing the Flinders Ranges (Cull, 1982).

The origin of the east-west compressional *in situ* stress field in southeastern Australia is controversial and attributed either to variations in density structure associated with the formation of the eastern Australian margin (Zhang et al., 1996) or interactions along the Pacific-Australian plate boundary associated with the generation of the Southern Alps of New Zealand (Coblentz et al., 1995, 1998; Sandiford, 2003; Sandiford et al., 2004). While crustal density structure must undoubtedly influence the local stress regime beneath the Eastern Highlands, it is unlikely to account for S_{hmax} trends across Victoria and in the Flinders Ranges, where there is no prominent coastal escarpment (Sandiford et al., 2004). Alternatively, the shift from a predominately strike-slip to highly transpressional regime along the Pacific-Australian plate boundary, initiating as early as 12 Ma (Sutherland 1995, 1996) but firmly entrenched by 6.4 Ma (Walcott, 1998) is thought to have progressively built the Southern Alps and consequently increased plate boundary resisting forces (Sandiford et al., 2004). Sandiford and co-workers (Sandiford, 2003; Sandiford et al., 2005; Celerier et al., 2005; Quigley et al., 2006) suggest that a small component of this stress is transferred back into the Australian plate, where it is manifested as compressional intraplate earthquakes in southeast Australia.

The geological record of southeastern Australia tentatively attests to the establishment of the modern tectonic regime during the terminal Miocene. For instance, a number of basins in southeastern Australia were inverted and eroded by up to 1 km on structurally controlled highs during the interval 8-6 Ma (Dickinson et al., 2001). Further constraints on the timing at which compressional faulting began in southeastern Australia are urgently required to better constrain temporal-spatial links between changing plate-boundary kinematics and intraplate deformation. Continued research into the evolution of Plio-Quaternary fault systems will contribute to play a vital role in developing a better understanding of contemporary seismicity in southeastern Australia.

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