GEOLOGICAL CONSTRAINTS ON ACTIVE SEISMICITY IN SOUTHEAST AUSTRALIA

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1. INTRODUCTION

The occurrence of widespread, low-level seismicity in stable continental regions (SCR) raises important questions concerning the nature of the intraplate stress field, earthquake mechanisms and seismic hazard within continental interiors (Johnston & Kanter, 1990). Although accounting for less than one percent of the Earth's total seismic energy release, SCR seismicity presents substantial risk because earthquake rupture is general shallow and seismic attenuation is low. The most dramatic historical example of SCR seismicity was the 1811-1812 New Madrid sequence of M_w 7-8 quakes (Johnston & Kanter, 1990). Because repeat times for the largest SCR earthquakes such as the New Madrid sequence are likely to be many thousands of years or more, historical seismic records are likely to be incomplete. This is especially the case in Australia, where the records extend back only ~150 years. Therefore, it is pertinent to ask whether geological observations might provide additional constraints useful for seismic risk assessment.

This paper focuses on active tectonic deformation in southeastern Australia, a SCR region of moderate, but spatially variable seismicity. The main objective is to provide constraints on neotectonic deformation rates, and compare them to estimates of strain rates based on the seismic record. We begin with a brief summary of modelling studies that inform the origin of the *in situ* stress regime and provide a temporal framework for understanding the ongoing deformation.

2. *IN SITU* STRESS IN SOUTHEAST AUSTRALIA

The first order pattern of the Indo-Australian stress field has been explained in terms of the interaction between plate driving forces acting along the southern mid-ocean ridge segment and the northern plate boundary forces (Cloetingh & Wortel, 1986; Coblentz et al., 1995, 1998). The intraplate stress field is characterized by a broad arcuate trend in S_{Hmax} from N-S in India through E-W in the central Indian Ocean to western margin of the continent to NE-SW in northern Australia (Coblentz et al., 1998; Hillis & Reynolds, 2000). This trend implicates the importance of the Himalaya and New Guinea in balancing the driving torques associated with subduction and ocean lithosphere cooling (Coblentz et al., 1995, 1998; Sandiford et al., 1995). The intraplate stress field in several subregions of the plate appears to be influenced by boundary forces other than the ones acting along the northern plate margin. This is particularly true for southeastern continental Australia (Figure 1), which forms a unique and distinctive stress province.
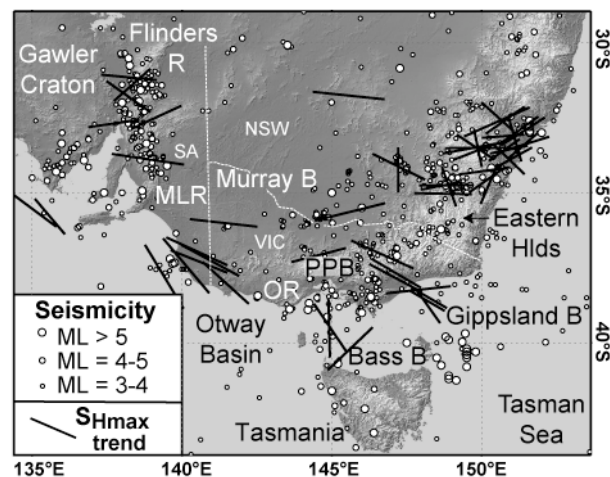
Figure 1,. Distribution of seismicity (Geoscience Australia earthquake database), topography and S_{Hmax} trends (after Hillis and Reynolds, 2000) in southeast Australia. OR = Otway Range; PPB = Port Phillip Bay, MLR= Mount Lofty Range.

As is true throughout most of continental Australia, the S_{Hmax} orientation in this region shows considerable scatter, particularly in comparison to other stable intraplate regions (Zoback, 1992). Information about *in situ* stress field in southeast Australia (Figure 1) is constrained by both earthquake focal mechanisms and borehole breakouts (Denham & Windsor, 1991; Hillis & Reynolds, 2000). Strike-slip and reverse focal mechanisms for earthquakes in the Flinders Ranges yield a principal horizontal compression (S_{Hmax}) of 83±30° (Greenhalgh et al., 1994; Hillis & Reynolds, 2000). In the Eastern Highlands of Victoria, reverse focal mechanisms define a SE-NW azimuth for S_{Hmax} (Gibson et al., 1981). Hillis & Reynolds (2000) summarise borehole breakout data from two basins along the southeast margin where the data are considered sufficient to define a significant trend. In the Otway Basin, the azimuth of S_{Hmax} derived from breakouts is 136°±15°, while in the Gippsland Basin, near the southeast corner of the continent, breakouts yields a S_{Hmax} of 130°±20°.

The tectonic forces controlling the present day regional intraplate stress field in continental Australia have been evaluated through a finite element analysis of the intraplate stresses. Modelling studies show that the stress field in southeast Australia relates to the convergence between the Pacific and Australian plates that have built the Southern Alps of New Zealand (Coblentz et al, 1995, 1998; Reynolds et al, 2002). Figure 2 shows the impact of New Zealand collisional forces on the stress field of southeast Australia. Figure 2a shows the stress field with an effective collisional force acting along the southern part of New Zealand of 3 x 10^{12} Nm^{-1}. As discussed in Reynolds et al., (2002) a force of this magnitude forms part an ensemble of plate boundary forces that minimizes the misfit with the *in situ* stress indicators throughout the Indo-Australian plate. Variations in the magnitude of the force acting along the New Zealand boundary force have a profound influence on the intraplate stress field in southeastern Australia. Figure 2b and 2c show the modelled stress field at 50% and 0% of the Reynolds et al. (2002) best-fit New Zealand boundary force, respectively. Reduction in the boundary force magnitude acting across the New Zealand boundary segment produces a substantial rotation in the S_{Hmax} azimuth (from a dominant NW-SE

to a NE-SW orientation), and a slight reduction in the stress magnitudes (from ~ 25 MPa to ~ 20 MPa, averaged over a 100 km thick lithosphere).
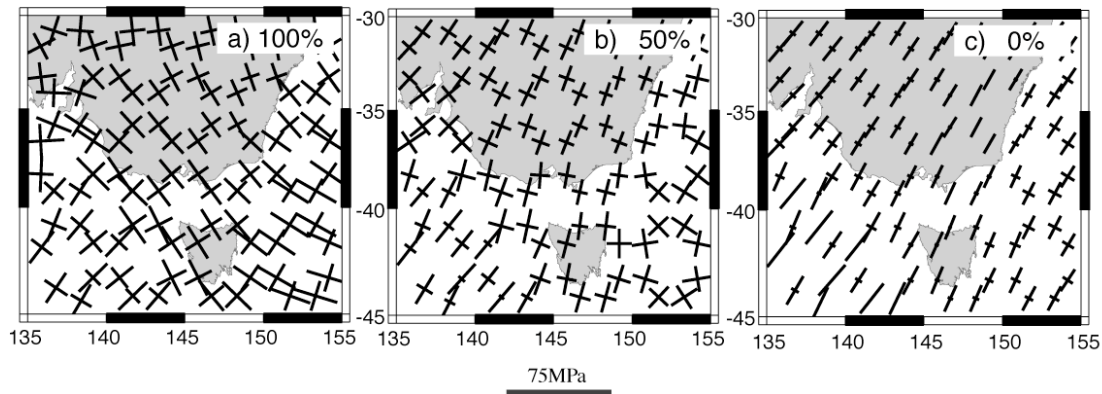

Figure 2. Details of modelled stress in the southeast Australian region. The individual panels show the impact of reducing the magnitude of the New Zealand compressional force from 125% of the Reynolds et al. (2002) present-day "best fit" model (a) to 0% of the "best-fit model" in f). The best-fit solution is shown in panel b). A stress scale of 75 MPa is shown at the bottom centre.

The timing of this change in the New Zealand boundary force is constrained by formation of the Southern Alps of New Zealand (the most obvious geological manifestation of this compression). The southern Alps have been constructed since the late Miocene (about 6 million years ago) due to a change in the relative velocities of the Pacific and Indo-Australian plates (e.g., Walcott, 1998). This places an important temporal constraint on the change in the southeast Australian stress field that is critical for understanding the time frame relevant to neotectonic activity in southeast Australia.

3. NEOTECTONIC FAULTING RECORD IN SOUTHEAST AUSTRALIA

The late Neogene record of southeast Australia contains abundant evidence for faulting. The intensity of this faulting shows marked spatial variation correlating, to a large extent, with the distribution and intensity of seismicity (Sandiford, 2003a). The most extensive faulting record occurs in the Flinders and Mount Lofty Ranges of South Australia, and in southern Victoria, in upland systems such as the Otway and Strezlecki Ranges (in Gippsland) bordering the southern coastline.

The Flinders and Mount Lofty Ranges in South Australia are bounded by N-S to NE-SW trending fault scarps, with morphology of the Mount Lofty Ranges in particular providing dramatic testimony to the role of active faulting and formation of tilt blocks in shaping the landscape (Figure 3a). Exposures of the main range-bounding faults characteristically reflect steep reverse motion with a hanging-wall of ancient (> 500 million year old) rock above a footwall comprising conglomerates shed from the developing upland systems in the last one-two million years (Figure 3b). Fault-slip kinematics are consistent with structures having formed in response to reverse stress regime with S_{Hmax} trending between N080°E and N125°E (Figure 3a) more or less identical to the *in situ* stress field. Slip rates on the major range-bounding faults have been estimated at between 20-100 m/million years. The cumulative vertical displacement on the fault network that forms the western front of the Mount Lofty Ranges is estimated to be ~ 240 m (Sandiford, 2003), with ~80 m offset of early

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Quaternary (~1.6 million year old) strata. Assuming that this displacement has accumulated in the last 5-6 million years then the time averaged displacement is ~ 40-50 m/million years.
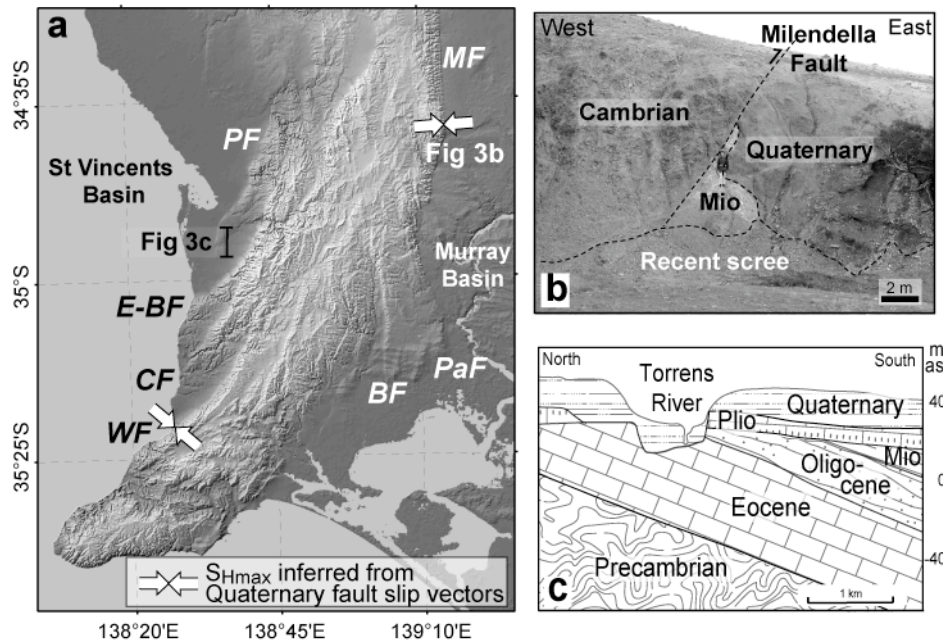

Figure 3. (a) Shaded topography of the Mount Lofty Ranges highlighting the youthful, fault bounded nature of this landscape. The main range bounding faults are the : Para (PF), Eden-Burnside (E-BF), Clarendon (CF), Willunga (WF), Bremer (BF), Palmer (PaF) and Milendella (MF) faults. (b) Outcrop of the Milendella Fault (location as shown in Fig. 3a). Reverse fault movement has thrust Cambrian metasedimentary sequences above Quaternary outwash gravels (~780 ka) and deformed and overturned early Miocene limestone (~ 20 milllion years old, Bourman and Lindsay, 1988). (c) N-S cross section through township of Adelaide modified (location as shown in Fig. 3a). The angular nature of the Miocene(Mio)-Pliocene(Plio) unconformity, implicates significant titling of the Para Fault block at around 6 million years ago.

On the northern flanks of the Otway Range, the remnants of 3-5 million year old beach deposits rise ~120 metres over a series of ENE trending faults and monoclines to elevations of ~ 250 metres. These ancient beach deposits were developed during falling sea levels following a 6 million year old sea stand high approximately 65 m above present day sea level (Brown & Stephenson, 1991) and thus imply almost 200 m of tectonic uplift in the last 3-5 million years due to contemporaneous faulting.

These observations are consistent with slip rates approaching ~ 40-60 m/million years on faults bounding the Flinders Ranges and southern Victorian uplands. This can be contrasted with the intervening Murray Basin, where comparative (but not complete) tectonic stability is demonstrated by preservation of 0-5 million year old shorelines (Sandiford, 2003a).

4. SEISMICITY IN SOUTHEAST AUSTRALIA

The southeast is one of the most seismically active parts of the Australian continent (Figure 1) with a broad distribution of earthquakes up to local magnitude (M_L) 6.4 across a zone ~ 1000 km in width from the eastern seaboard to the Eyre Peninsula in the

west. Distinct concentrations in seismic activity occur in the Mount Lofty-Flinders Ranges-eastern Eyre Peninsula of South Australia, and in the belt trending from the west coast of Tasmania, through south-central Victoria, northeast through the Eastern Highlands to southern New South Wales (Figure 2). The intensity of seismic activity in these zones contrasts the intervening Murray Basin and the regions further west.

The intensity of seismic activity for any region can be quantified using Gutenberg-Richter relations (Gutenberg & Richter , 1944, 1949):

$$\text{Log}_{10}(N) = a - bM$$

where N is the number earthquakes of magnitude M, and a and b are constants. The a-value indicates the background level of seismicity (or activity rate), and the b-value characterises the ratio of small magnitude events to large events. In order to evaluate the a and b-values, the method used here defines N as the number of events of magnitude M or greater (after Gaull et al., 1990).

The nature of observed variability in b-values is debated. Some researchers suggest it approaches a global value of 1 (Suzuki, 1959) with departures from unity due to incomplete catalogues. Other researchers suggest b varies spatially and temporally (e.g., Utsu, 1999). It is important to note that a and b-values deduced form historical records depend on the magnitude scale, the magnitude range, and data completeness, with accurate estimates of a and b-values requiring relatively large sample sizes. As a guide, a magnitude range of at least 2 and a sample size of 200 events is desirable. For Australia, the earthquake catalogues are complete above magnitude 3 for 25-40 years at best (Gaull et al 1990). The low activity rate of most of Australia means obtaining the necessary numbers of earthquakes can be challenging.

In order to ensure statistically significant sample sizes, we have used relatively large regions. In addition, we have employed a composite approach. The historical record of 100 - 150 years is used for characterising the larger events, while the 25 - 40 year instrumental record is used for the smaller events, enabling us to extend the range of magnitudes to greater than 3 units (Figure 3). Results for three regions, normalised to an area of 10,000 km^2 and one year, are summarised in Table 1 and Table 2.

The Flinders Ranges dataset yields an a-value of 3 implying a magnitude 5+ earthquake every 100 years per 10000 km^2. Extrapolating this to the entire Flinders Ranges suggests a recurrence interval for magnitude 5+ events of 12 - 15 years. The Murray Basin has an a-value of 2, suggesting it has one-tenth the number of earthquakes of the Flinders Ranges. However, the area used to extract the Murray Basin data reflects the most active part of the basin (in order to obtain the requisite number of events), and doubling the area results yields an a-value of 1.7, or ~3% of the activity rate of the Flinders ranges.

For Gippsland the a and b-values calculated for all available data are 1.95 and 0.79, respectively, with the low b-value reflecting an anomalously high proportion of magnitude 4.5+ earthquakes in the dataset. These values suggest that the Gippsland region has a higher moment release rate than the Flinders Ranges. However, it is probable that the low b-value results from a spurious over representation of large events

in the historical time window (see Discussion below). Using only the last 27 years of instrumental data, excluding magnitude 4.5+ events, and assuming a *b*-value of 1, yields activity rate intermediate between the Flinders Ranges and Murray Basin (see Gippsland #1 in Table 2).

Region	Min Mag.	Max Mag	Number of Earthquakes	Number of Years
Flinders Ranges 1	5.6	6.0	1	153
Flinders Ranges 2	4.0	5.5	74	115
Flinders Ranges 3	3.1	3.9	138	40
Murray Basin 1	4.0	5.5	14	104
Murray Basin 2	2.3	3.9	179	29
Gippsland 1	4.5	5.7	19	123
Gippsland 2	2.5	4.4	167	27

Table 1 Completeness intervals adopted for the three seismogenic zones of interest.

Region	a	B	R^2	5.5+/500yr
Flinders Ranges	3	1.0	0.99	1.6
Murray Basin	2	1.0	0.98	0.16
Gippsland #1	2.6	1.0	0.99	0.6
Gippsland	1.95	0.79	0.98	2.0

Table 2 *a, b* and number of earthquakes (per year) M5.5 or larger per 500 years for the 3 regions, normalised to 10,000 km². The method of analysis for Gippsland #1 is discussed in the text.

5. SEISMOGENIC STRAIN RATES

Following Johnstone (1994b), we can derive an estimate for notional seismic strain rate, in terms of the total seismic moment:

$$M_O \approx \frac{1}{t}\left(\frac{b\left(10^{(a+d)}\right)}{c-b}\right)\left(10^{(c-b))}M_{max}\right)$$

where *t* is the timespan of the seismic record, M_{max} is the maximum expected magnitude for earthquakes in the region of interest, and *c* and *d* are factors that relate to the conversion of magnitude scale to seismic moment (Hanks & Kanamori, 1979) :

$$\log(M_O) = c\,M + d$$

In terms of the seismic moment, the seismic strain rate is (Kostrov, 1974) :

$$\dot{\varepsilon}_{xx} = \frac{1}{2\mu\,v}\,M_O$$

where μ is the Young's modulus (8 x10¹⁰ Pa) and *v* is the volume of crust in which the seismicity occurs (here we assume the seismogenic zone is 15 km thick, based on the

knowledge that the great majority of Australian earthquakes have epicentral depths less than ~15 kms, e.g., Gaul et al., 1990).
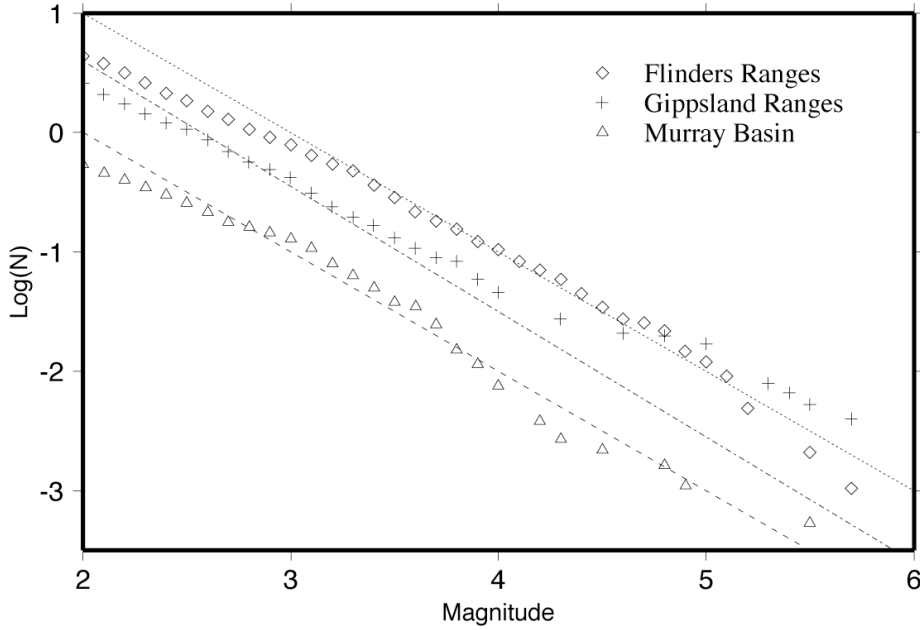

Figure 4. The data used to calculate the *a* and *b*-values for the three regions across southeast Australia.

Since the majority of the moment is carried by the most infrequent, largest earthquakes, the main uncertainty in the calculation of the seismic strain rates is the value of M_{max} (Figure 5). As noted earlier, the historical record can only provide a lower bound on M_{max}. The largest estimated earthquake (pre-instrumentation) in southeast Australia is $M_L \sim 6.4$. Elsewhere in Australia $M_L > 6.5$ quakes have occurred at a number of widely distributed localities, with the largest earthquake of magnitude $M_L = 6.8$ (in 1941, near Mereebie in Western Australia). On longer timescales we would expect somewhat larger earthquakes, and thus the maximum earthquake expected on geological timescales could conceivably be as high as $M_L \sim 7.5$. Assuming $M_{max} = 7$, the calculated seismic strain rate for Flinders Ranges is $\sim 1 \times 10^{-16}$ s^{-1} (Figure 5), with uncertainties in both the M_{max} and the thickness of the seismogenic zone ($\pm$ 5kms) yielding an uncertainty of at least a factor of 2. The seismic data suggest the Murray Basin is deforming at an order of magnitude lower strain rates, while the preferred value for Gippsland (Gippsland#1) yields a seismic strain rate of about 4×10^{-17} s^{-1} (which is an order of magnitude lower than the rate using the parameter set including all Gippsland seismic data). These estimates are compatible with Johnstone's (1994b) estimate of $\sim 2 \times 10^{-17}$ s^{-1} for bulk Australian seismic strain rates.
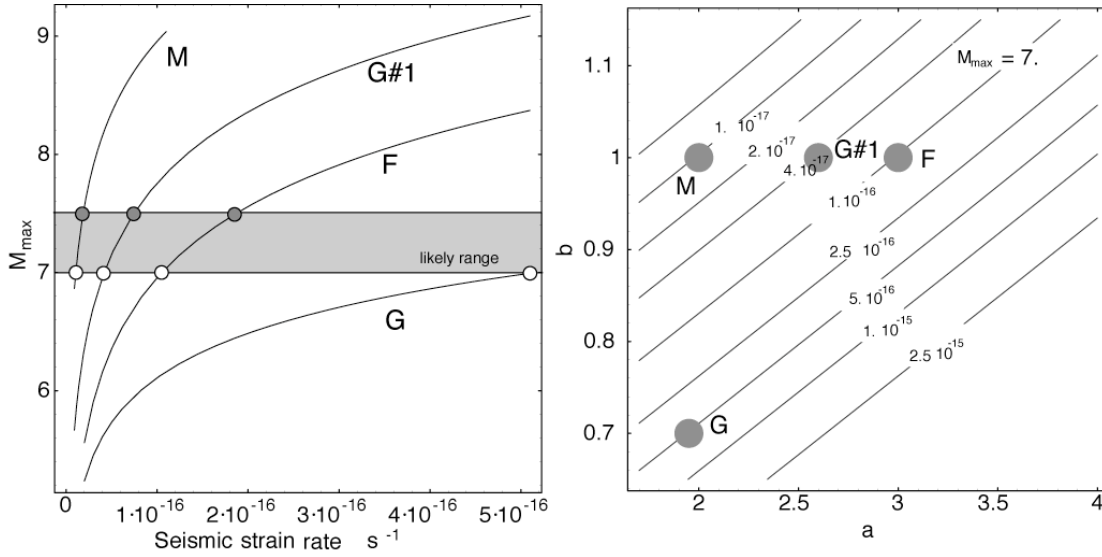
Figure 5. Relationship between, (a) M_{max} and seismic strain rate for the seismic zones listed in Table 2, (b) strain rate as a function of a-b values for $M_{max}= 7$. Grey shaded region in (a) the preferred range in M_{max}. F : Flinders seismic zone, M: Murray Basin, G: Gippsland, G#1: Gippsland, with analysis as described in text.

Our incomplete knowledge of seismic efficiency (i.e., the relative accommodation of strain by seismic and aseismic mechanisms) imply further uncertainty in translating seismically determined strain rates to bulk crustal strain rates. Nevertheless, these calculations provide a basis for comparison with the fault-slip rates determined from geological observations (see Discussion).

6. DISCUSSION

The geological observations summarised here highlight a spatial correspondence between the young faulting record and the distribution of seismicity (see Sandiford 2003a for further elaboration). Our understanding of the origin of stress field responsible for both the contemporary earthquakes and for the young faulting record suggests that the present tectonic regime developed around 6 million years ago. In the Flinders Ranges and southern Victorian uplands, such as Gippsland, faulting has been responsible for several hundred metres of relief generation in this time, with cumulative vertical slip component on the range-bounding faults systems estimated at about 50 m/million years. For comparison, the seismic strain rates equate to a cumulative vertical slip component on range bounding faults (assuming reverse fault motion on 45° surfaces) of ~95 m/million years for the Flinders Ranges (where the width of the deforming zone is about 100 km wide). A zone of comparable with in Gippsland would be slipping at ~ 35 m/million (Gippsland #1), while in the Murray Basin the cumulative slip rates would be no more than 10 m/million years across a 100 km wide zone. Uncertainties in the thickness of the seismogenic zone or the Young's modulus suggest that these estimates have uncertainties of at least a factor of 2, without considering the uncertainty in the *a* and *b*-values.

While the seismic strain rates should be expected to be lower than geological strain rates, because seismic efficiency is likely to be less than 100%, these estimates are

surprisingly close to those deduced from the geological observations (especially in view of the uncertainties). In turn, this correspondence suggests that the historical seismicity is not particularly anomalous in terms of its geological context, at least for the Flinders Ranges and Murray Basin, providing that the maximum expected earthquake magnitude is not much greater than $\sim M_w\, 7$. Because seismic moment release is dominated by the largest earthquakes, the calculations summarised here suggest that if $M_w > 7$ earthquakes do occur in southeast Australia, then they must occur much less frequently than expected on the basis of linear extrapolation of historical earthquake statistics (ie., $M < 6.4$).

In Gippsland, the seismic strain inferred from the a and *b*-values derived from all available events ("Gippsland" in Table 2) is an order of magnitude higher than allowed by geological observations, and suggest either (1) an over-representation of larger events in the existing database for Gippsland, or (2) strain rates have increased markedly over the last one million years or so.

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