Bulletin of the Seismological Society of America, Vol. 98, No. 3, pp. 1458–1470, June 2008, doi: 10.1785/0120050193

One Hundred Years of Earthquake Recording in Australia

by Mark Leonard

Abstract A comprehensive new catalog of Australian earthquakes has been compiled and used to review the seismicity of Australia. The catalog contains 27,000 events, of which 17,000 are considered to be mainshocks. The catalog is complete for all Australian events with a magnitude greater than M_L 5.5 since 1910, M_L 5 since 1960, M_L 4 since 1970, and M_L 3.5 since 1980. It is complete for events in southern Australia above M_L 3.5 since 1965 and M_L 2 since 1980. Before the development of local magnitude scales for Australia, around 1990, the Richter magnitude scale was generally used. At 600 km (a typical hypocentral distance for much of Australia) the Richter formula overestimates magnitude by around 0.5 units. Thus, the results in the catalogs before and after the early 1990s are potentially discrepant.

Most well-located Australian earthquakes are in the southern areas of the continent, where the seismometer density is greatest. In general, the location uncertainty of Australian earthquakes is high. Only 60% of events are located with an uncertainty of 10 km or less. This percentage is smaller for earthquakes before 1980, and before 1960 very few events were located to within 10 km. The hypocentral depths of Australian earthquakes range mostly between 8 and 18 km, except for the southwest corner of the continent where they are typically shallower than 5 km.

The seismicity in some areas of Australia has been steady for at least 100 yr (including the southeast corner, the Flinders Ranges, and the northwest corner). In contrast, seismicity in the southwest corner jumped by at least a factor of 6 in the 1940s and has been steady since then. Much of the rest of Australia is characterized by episodic seismicity. These episodes begin with a period of high activity lasting 1–10 yr and they are normally associated with a large ($M > 6$) earthquake. Following the large earthquake, there is often a period of moderate activity lasting from a few years to several decades. Before and after each episode is a quiescent period of low activity lasting 0.1–10 ka, during which the seismicity is more than an order of magnitude lower than during the period of high activity.

Frequency-magnitude relations were calculated using events since 1970 from the new catalog. Gutenberg–Richter a- and b-values were calculated on an 85-km grid, and maps of the probability of an earthquake of $M \geq 4.9$ occurring per year were derived. These results are very similar to the Global Seismic Hazard Assessment Program (GSHAP) map for Australia. The results were used to define four large ($> 20,000$ km^2) seismogenic zones (Fig. 1). There are also several other small zones, some of which appear to reflect recent episodes, while others appear to be long-lived. The expected number of earthquakes $M \geq 5$ and $M \geq 6$, strain rate, and deformation rate is given for the four large zones, the remainder of Australia, and the whole Australian continent. The combined estimates of strain using seismic Global Positioning System (GPS) and Satellite Laser Ranging (SLR) data suggest east–west compressive deformation across southern Australia of 0.65 ± 2.0 mm per year, likely to be in the 0.5–1.0-mm-per-year range.

Introduction

The first part of this article gives an overview of the history of Australian seismic networks, magnitude scales, and earthquake catalogs. The second part presents results on the distribution and depth of Australian earthquakes, recurrence

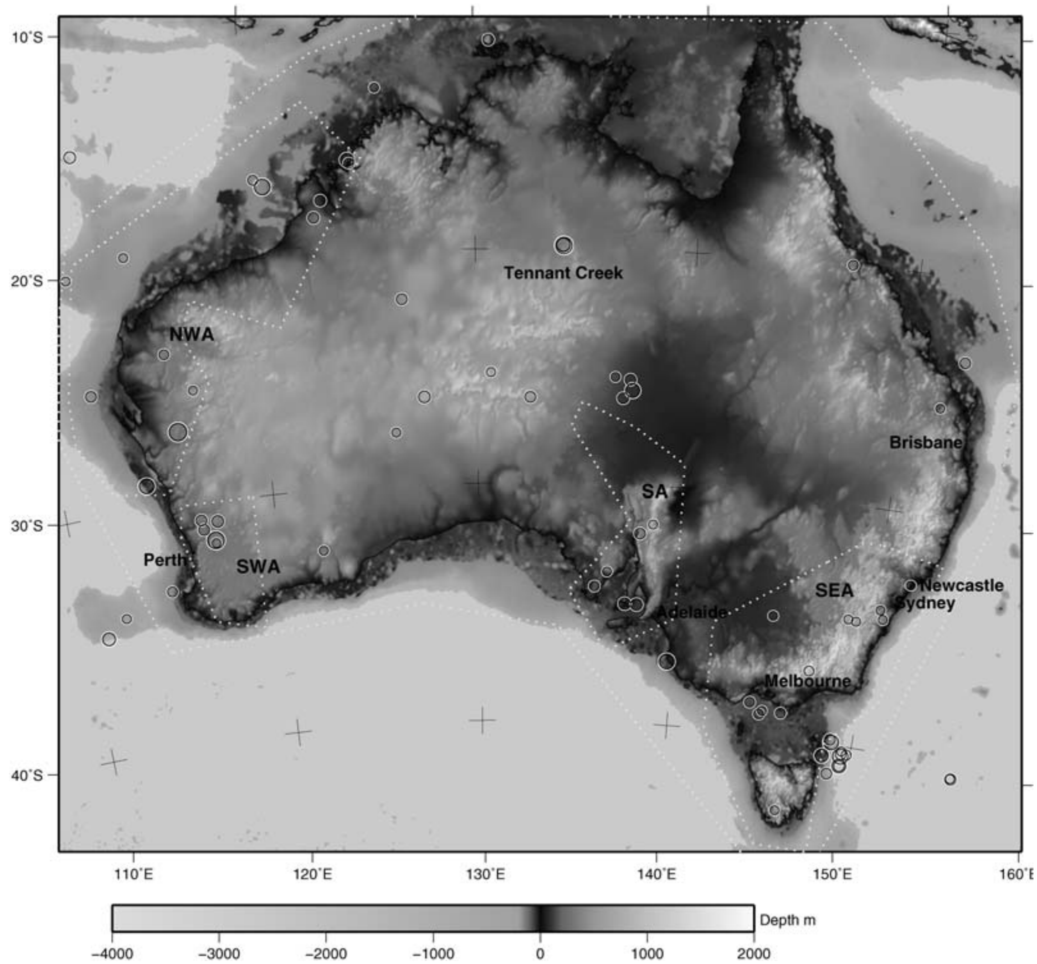

Figure 1. Map of Australia. The circles are the 75 earthquakes of $M \geq 5.5$. The four regions, northwest Australia (NWA), southwest Australia (SWA), South Australia (SA), and southeast Australia (SEA), are marked by dashed lines. The outer dashed line is the area considered continental Australia. Northern Australia (NA) is all of Australia excluding the four regions. These areas are discussed throughout the text.

relations for several regions, and strain rates. The idea that much of Australia's seismicity is episodic, not stationary, is discussed. The results are based upon a new comprehensive catalog of Australian earthquakes compiled for this study.

Australia resides entirely within the Australian Plate and is drifting north at around 7 cm per year (Tregoning, 2002). The northern margin of the Australian continental crust, in the island of New Guinea, is a complex convergent plate boundary that significantly evolved during the Cenozoic Period (0–45 Ma) (Hill and Hall, 2003). In contrast, Australia underwent no significant deformation during this period, with low seismicity when compared to areas of active tectonics. Tectonically, Australia is similar to North America east of the Rocky Mountains. Australia is under compressive stress, which, uniquely, is not parallel to plate motion. In the southern half of Australia, the direction is east–west (Clark and Leonard, 2003; Hillis and Reynolds, 2003). This is generally considered to be due to the complex margin of the Indo-Australian plate, with the collisional boundaries of Himalaya and New Zealand controlling the east–west stress (Reynolds *et al.*, 2003). On average, Australia experiences two earthquakes $M \geq 5$ per year (Fig. 1), a high level of seismicity compared to areas of stable continental crust around the world (Johnston, 1994b). In the past century, about 27,000 earthquakes have been recorded in Australia. Research into the seismicity of Australia dates back more than a century.

Seismic Networks in Australia

Doyle and Underwood (1965) and Denham (1988) comprehensively reviewed the development of seismic stations in Australia up to 1965. The recording of earthquakes in Australia began in 1883, when the first seismoscope was built in Australia (Biggs, 1885). The first permanent Australian seismic station was installed at the Perth Observatory in 1901. Subsequent stations were installed in observatories in Melbourne, Sydney, and Adelaide by 1910 (Doyle and Underwood, 1965) (Fig. 1). These all used underdamped Milne seismometers with a gain of only six. In 1909, a seismic observatory, using a Wiechert recorder, was established at Riverview College in Sydney. All of these instruments were low gain and long period and were not suitable for recording local earthquakes.

After around 1910, the instrumental recording of Australian earthquakes can be divided into two instrumental periods: the low gain period (1910–1959) and the high gain period (1960–present). The low gain period began with the installation of a Mainka recorder at Riverview in Sydney in 1910 (upgraded to a Galitzin recorder in 1948) (Drake, 1984). In the early 1920s, the Perth, Adelaide, and Melbourne Milne seismometers were replaced by the superior Milne-Shaw seismometer, which was damped and had a gain of 150–250. A Milne-Shaw seismograph also began operating in Brisbane in 1937. By 1955, these were still the only five seismographs in Australia and all were low gain instruments. Around this time coverage of Australia for all earthquakes $M > 5$ became possible (in practice closer to M 5.5). Records from these seismographs were sent to John Milne, and results were published in a report of the Seismological Committee of the British Association for the Advancement of Science (later the International Seismology Survey) (Bath, 1973). Stations were also established in other areas in the Asia-Pacific region in this period, including India in 1910, Hawaii in 1912, Wellington in 1915, and Hong Kong in 1921.

The 1950s and 1960s saw a rapid expansion of seismic networks in Australia (Fig. 2 illustrates the development of seismic networks in Australia). Local networks were set up by universities in Tasmania and New South Wales (NSW) (Doyle and Underwood, 1965), South Australia (Sutton, 1968), and nationally by the Bureau of Mineral Resources (Denham *et al.*, 1975). Five of these stations, provided by the U.S. Coast and Geodetic Survey, were part of the World Wide Standard Seismographic Network and included long-period instruments. These stations set new standards of data quality and high gain levels. During the 1970s, a network was also established in Victoria (Gibson *et al.*, 1981). By 1980, there were about 70 permanent seismic stations operating in Australia. Between the late 1970s and early 1990s, several temporary networks were established to monitor the aftershocks of large earthquakes. The 1990s saw some consolidation of seismic networks. Most of Australia's seismic stations were also converted from analog to digital. The deployment of strong-motion instruments was in its infancy when the city of Newcastle (Fig. 1) was hit by an M 5.6 earthquake in 1989 (Table 1), resulting in 12 deaths (McCue *et al.*, 1990). The 1990s saw a rapid increase in the number of strong-motion instruments in Australia.

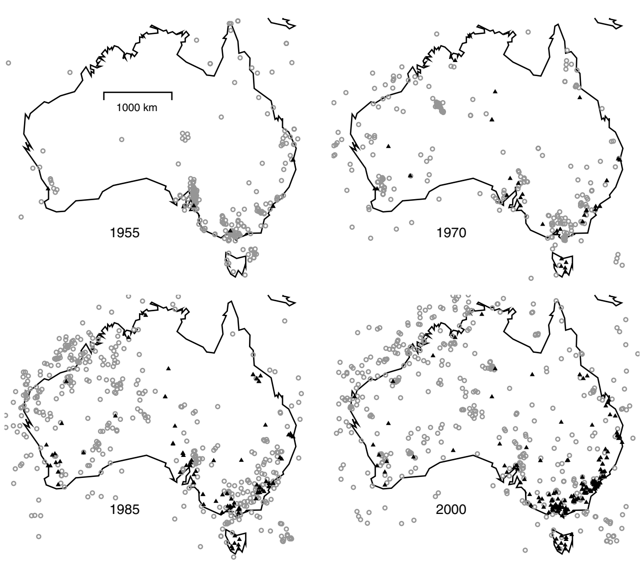

Figure 2. Development of seismic stations in Australia and the earthquakes of $M \geq 3.5$ recorded during the periods 1880–1955, 1956–1970, 1971–1985, and 1986–2000. Seismic stations are plotted as triangles.

The Catalog

The catalog referred to in this article is a compilation of catalogs from eight Australian organizations. The combined catalog has 27,793 events. It is estimated that 1%–2% are duplicates, with around 27,000 unique earthquakes in the catalog. The earliest event in the catalog occurred at Sydney in June 1788, only months after European settlement of Australia (Hunter, 1991). The catalog contains 131 events $M > 5$ since 1910 (Fig. 1). The locations of these epicenters define regions of enhanced seismicity in southwest Australia (SWA), northwest Australia (NWA), southern Australia (SA), and southeast Australia (SEA) (Fig. 1). The seismicity of these areas and how they were defined is discussed in a following section. Table 1 lists all of the earthquakes $M > 5.9$ and some notable M 5–6 earthquakes.

Since the late 1980s most observatories in Australia have used a location program, Eqlocl (developed by the Seismological Research Center [SRC] in Victoria). It uses a similar approach to the Hypoellipse program and uses Geiger's method (Lee and Lahr, 1975) to minimize travel-time residuals. Its reported errors are the maximum deviations of the 95% error ellipse in the north–south and east–south direction, whereas Hypoellipse reports the zero crossing of the smaller 68% confidence limit. Local velocity models (mostly derived from refraction surveys) were developed around the same time and are incorporated into Eqlocl.

Declustering

Large Australian earthquakes often have significant aftershock sequences. Details of notable examples are listed in Table 1. For applications such as hazard analysis and other statistical analyses, removal of aftershocks is required.

Data from the Tennant Creek, Meckering, Cadoux, and Burakin earthquakes (Table 1) were used to develop an aftershock removal, or declustering algorithm. The approach used assumes that the background seismicity rate is approximately constant for a region not experiencing an aftershock se-

Table 1

Australian Earthquakes with an $M \geq 6.0$ and Some of the Notable $M > 5.0$ Earthquakes

Year	Magnitude	Latitude	Longitude	Name and Information
1892	6.9	39.5° S	148.0° E	Flinders Island
				1884 *M* 6.4, 1884 *M* 6.4, 1885 *M* 6.5, 1885 *M* 6.8
				Michael-Leiba (1989)
1897	6.5	37.5° S	140.0° E	Beachport
				Greenhalgh *et al.* (1986)
1902	6.0	34.5° S	137.0° E	Warooka
				Greenhalgh *et al.* (1986)
1929	6.6	17.5° S	122.0° E	Broome
1937	5.0	25.0° S	127.0° E	Simpson Desert
				1937 *M* 5.0, 1938 *M* 5.3, 1941 *M* 5.0 and *M* 5.6
				Sutton and White (1968)
1970	6.7	22.5° S	129.0° E	Lake Mackay
				1978 *M* 6.2, and 1970–1982 nine several earthquakes $M > 5$
1968	6.8	31.5° S	117.0° E	Meckering earthquake in 1968
				Everingham and Gregson (1970), Gordon and Lewis (1980)
1970	5.9	31.0° S	116.5° E	Calingri
				Gordon and Lewis (1980)
1972	6.2	25.0° S	127.0° E	Simpson Desert
				Stewart and Denham (1974)
1979	6.0	31.0° S	117.0° E	Cadoux
				Lewis *et al.* (1981)
1986	5.8	26.0° S	133.0° E	Marryat Creek
				Bowman and Barlow (1991)
1988	6.7	19.5° S	134.0° E	Tennant Creek
				All on January 22 1988 *M* 6.3, *M* 6.4, and *M* 6.7
				Bowman (1992)
1989	5.6	32.5° S	151.5° E	Newcastle
				12 deaths, McCue *et al.* (1990)
1997	6.3	16.0° S	124.5° E	Collier Bay
2001	5.1	30.5° S	117.0° E	Burakin
				Leonard (2002)

quence. When many aftershocks are present, a plot of the cumulative number of small earthquakes in time will have big steps during the months to years following a large earthquake. Once the aftershock sequence has died off, the cumulative number of earthquakes for the region resumes a steady linear increase. In developing a declustering tool, the aim was to remove sufficient earthquakes to remove these steps but not affect the steady linear increase. The resulting relations are given as

$$\text{Distance(km)} = 7 + 2 \times \sqrt{10^{(M-4)}}, \tag{1}$$

$$\text{Period(days)} = \exp(M\ 1.6\text{–}3). \tag{2}$$

McCue (1990) developed a magnitude-fault length relation for Australian earthquakes that gives fault lengths slightly larger than Wells and Coppersmith (1994). The distance given by equation (1) is approximately twice the fault length estimate from the McCue (1990) relation. The equation (1) distances are comparable with those of Reasenberg (1982) and Molchan *et al.* (1999), who developed declustering algorithms for plate boundary seismic zones, but the periods from equation (2) are significantly longer. Table 2 gives the resulting values for various magnitudes. Overall, 39% of events were removed from the catalog. The effect of declustering varied across Australia: in SWA 63% of events were removed, in SA 23% were removed, and in SEA 41% were removed. After declustering, the earthquake catalog of Australian mainshocks contained 16,880 of the original 27,790 events.

Magnitude Scales in Australia

The history of use of various magnitude scales for Australian earthquakes is complicated. Until the late 1980s, Richter's formula was generally used to calculate local magnitude (M_L) at all Australian observatories. In the late 1980s and early 1990s, most observatories moved to a M_L scale. To the present day, magnitudes calculated by different observa-

Table 2

Magnitude Dependent Distance and Period Values Used to Remove Aftershocks from the Australian Earthquake Catalog

Magnitude	4.0	4.5	5.0	5.5	6.0	6.5	7.0
Distance (km)	9	11	13	18	27	43	70
Period (days)	30	67	148	330	735	1636	3641

tories for the same earthquake regularly vary by 0.3 units. The major cause is the variation in attenuation functions used across Australia and the effect this has on M_L calculation. Duration magnitudes (M_D) have also been used in several Australian observatories, particularly in South Australia (Greenhalgh *et al.*, 1994) and Victoria (Gibson *et al.*, 1981). Until the adoption of the M_L formula, around 1990, duration magnitudes were often the preferred magnitudes. The teleseismicly calculated M_S (surface wave) scale has normally been used for events larger than M 6.0. For magnitudes between 5.0 and 6.0, M_L is commonly used, but M_S and M_b scales are also used. These scales should all merge smoothly with M_L at M 5–6. Whether this is actually the case for Australia, particularly before the adoption of Australian M_L scales, is not certain. Only 10 events in the catalog have an M_w.

During the late 1980s and early 1990s, local magnitude scales were developed and implemented for most regions of Australia including South Australia (Greenhalgh and Parham, 1986; Greenhalgh and Singh, 1986), Western Australia (Gaul and Gregson, 1991), and southeast Australia (Michael-Leiba and Malafant, 1992; Wilkie *et al.*, 1993).

Local magnitude (M_L) as defined by Richter (1935) is given by $M_L = \log A - \log A_0$, where $A_0 = C_0 \log R + C_1 R + C_2$; A is the amplitude, R is the hypocentral distance in kilometers, C_0 and C_1 are attenuation constants, and C_2 is a station correction. Developing a local magnitude scale essentially involves determining an A_0 that reflects local geometric and inelastic attenuation. Values for regions of Australia and the United States of America are given in Table 3.

The $\log A_0$ curves derived for Australia, together with Richter's 1958 M_L curve, are shown in Figure 3. The results imply that WA and SEA have very similar far-field (>250 km) attenuation (with near-field attenuation in WA being slightly lower) and that SA has a higher attenuation than most of the other Australian regions. Southern California (CR) appears to have a higher far-field attenuation rate than Australian regions, but in the near-field (5–30 km) the situation reverses. The EAW model (Wilkie *et al.*, 1993) was derived using data from a small area east of Melbourne (Fig. 1) mostly with source-receiver distances of <200 km. Whether this model is applicable outside this region is uncertain. The use of both the EAW and EA models (Michael-Leiba and Malafant, 1992) in southeast Australia since 1992 has resulted in the different agencies allocating differing magnitudes to the same earthquake.

Because of the sparse Australian network, few earthquakes have had their magnitudes determined from stations within 30 km, so discrepancies in the near field have little effect on catalog magnitudes. As most Australian earthquake magnitudes are calculated at average hypocentral distances of 300–600 km, variations between the Richter A_0 and the A_0 derived for Australia imply that magnitudes calculated for a given event using relations before and after ~1990 will be discrepant in the Australian catalog.

Despite the Richter scale being the most widely used earthquake magnitude scale, it is not without its problems. Uhrhammer and Collins (1990) concluded that the original assumption that a Wood-Anderson seismometer has a gain of 2800 was incorrect. The actual gain is 2080 and as a result, the M_L scale consistently underestimates the size of events by 0.13 magnitude units. While noted by Australian seismologists (McGregor and Ripper, 1976; Gaul and Gregson, 1991), it was assumed that instruments in Australia were nonstandard so they compensated for the difference. Another complication is that a WA is a displacement seismometer while most other seismometers in Australia are velocity seismometers, resulting in higher frequencies. Conversion to a pseudo-WA record has not been routine at any Australian observatory. An overview of problems with magnitude scales and their usage have been given by Bormann (2002). Hutton and Jones (1993) concluded that the apparent variations in seismicity rates in southern California were not real but caused by changes in magnitude scale. Given the issues discussed previously, the Australian earthquake catalog is also likely to be characterized by this problem.

The Seismicity of Australia

Epicentral Accuracy of Australian Earthquakes

As the distribution of seismic stations in Australia is sparse (Fig. 2), the location accuracy is generally poor. The Australian catalog contains 750 mainshocks between March 2000 and March 2004. Of these, 0.4% are located to within 1 km (2σ error), 4% within 2 km, 14% within 3 km, 32%

Table 3
M_L Formula Parameters for Australian Regions

Model	C_0	C_1	C_2
WA (Gaul and Gregson, 1991)	1.136	0.000645	0.7
SA (Greenhalgh and Singh, 1986)	1	0.0013	0.67
SEA (Michael-Leiba and Malafant, 1992)	1.34	0.00055	0.27
Victoria (Wilkie *et al.*, 1993)	1.0	0.0049*	0.55
Southern California (Hutton and Boore, 1987)	1.11	0.00189	0.61
Central California (Bakun and Joyner, 1984)	1.0	0.00301	0.7

*C_1 of Wilkie *et al.* (1993) is $0.0056R \exp(-0.0013R)$ and the value given is calculated at 100 km.

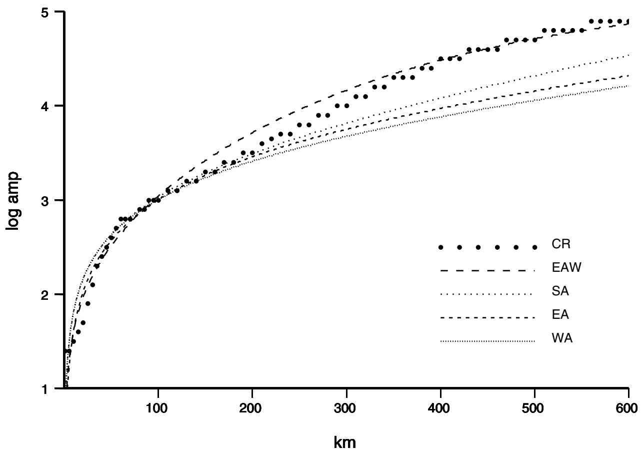

Figure 3. The log A_0 curves derived for Australia, together with Richter's (1958) M_L curve for southern California. CR: Richter (1958). EAW: Wilkie *et al.* (1993). SA: Greenhalgh and Singh (1986). EA: Michael-Leiba and Malafant (1992). WA: Gaul and Gregson (1991). CR is stepped because Richter defined it at discrete distances, not as a function.

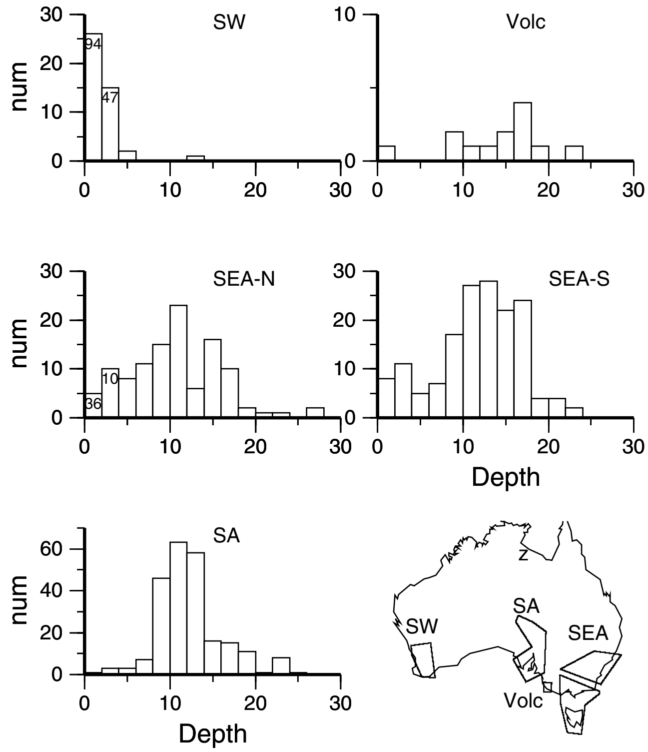

Figure 4. Histograms of the depth of earthquakes in various regions of Australia. The numbers inside some of the bars are the number of earthquakes before aftershocks were removed. The earthquakes are a subset of the catalog where the 95% depth uncertainty was either smaller than the depth itself or was <5 km.

within 5 km, 62% within 10 km, and 85% within 20 km. All events that are located to within 3 km are in the SWA, SA, and SEA regions, as are 95% of events within 5 km. Outside these three regions, most events have location uncertainties of at least 5 km and typically more than 10 km. Before 1980, few events were located to within 10 km.

Depth

A subset of the earthquake catalog was selected in which the depth uncertainty was either smaller than the depth itself or was <5 km. Only areas in southern Australia produced sufficient numbers of earthquakes to allow detailed analysis. The data for southern Australia have been divided into five zones (Fig. 4). These zones correlate with the areas of highest network density (Fig. 2, 1985). The small zone, labeled Volc in Figure 4, is an area of isolated seismicity and includes the *M* 6.5 earthquake in 1897. This region is of interest, since as recently as 4500 yr B.P. there was volcanic activity immediately to the northeast of this area and the age of the volcanic activity increases with distance to the northeast (Johnson, 1989).

Earthquakes in SWA are typically very shallow. 95% of earthquakes are shallower than 5 km. This region has produced three surface faulting earthquakes in the last four decades (Gordon and Lewis, 1980). In the Volc region, 95% of earthquakes are relatively deep at 9–17 km. In SEA–S and SEA–N earthquakes range between very shallow (<4 km) and 17-km deep. Aftershocks in SEA–N tend to be very shallow and numerous. Using a catalog containing aftershocks, Gibson *et al.* (1981) obtained a similar distribution for Victoria, except they had a greater proportion of very shallow earthquakes, reflecting the shallower depth of aftershocks. Earthquakes in SA tend to be relatively deep with 75% of earthquakes between 8 and 14 km deep.

Magnitude Completeness Periods: Instrumental Catalog

Statistical analysis of the earthquake catalog requires knowledge of the completeness of the catalog at various magnitudes. Tests for catalog completeness are generally based on the Gutenberg–Richter relation ($\log N = a - bM$) (e.g., Wiemer and Wyss, 2000). This implies that above the magnitude completeness threshold, there is a log-linear increase in the number of earthquakes with decreasing magnitude. Because of uncertainties in earthquake catalogs (previously discussed) and the low numbers of events in each region, the method used in this article is less refined than some methods. After declustering, the method involved calculating the logarithm of the number of earthquakes in 0.5 magnitude unit bins, at 5-yr increments, for 10-yr periods. Within each period tested, the magnitude below which the log-linear increase no longer applies is considered the completeness cutoff for this period. For example, in SWA (Fig. 5) the catalog is complete above *M* 4.5–5.0 since 1940, above 3.0 since 1960, above 2.0 since 1980, and above 1.5 since 1990. This analysis has been used to determine dates for catalog completeness at different magnitudes for the Australian regions (Table 4). In SEA the earthquake catalog is complete above *M* 1.5 between 1975 and 1995. Since 1995, the completeness threshold has increased to *M* 2.0–2.5 (Fig. 5).

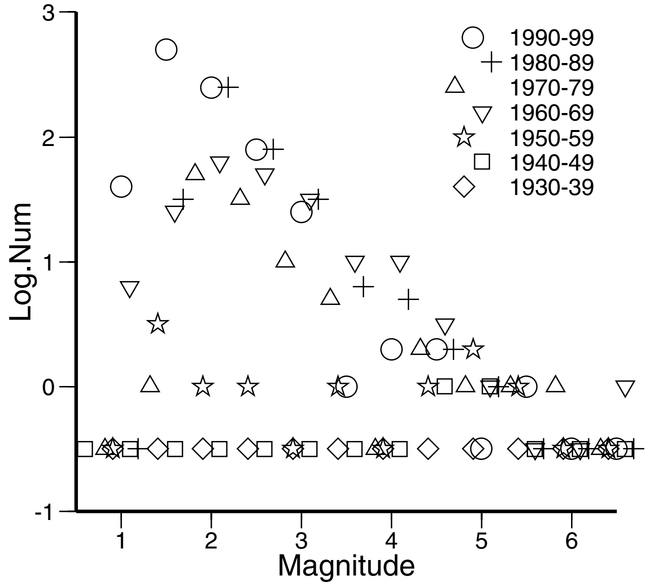

Figure 5. The number of earthquakes per decade in SWA are plotted in 0.5 magnitude bins. To simplify the figure, only the 10-yr increments are shown, not the 5-yr increments. The symbol for each data period has been offset to aid viewing. Plots of this type were used to determine catalog completeness at different magnitudes. Where there is no data it has been allocated −0.5.

Magnitude Completeness Periods: Historical Catalog

Before instrumental recording began, the earthquake catalog was limited to felt reports, which in parts of Australia is surprisingly comprehensive. Malpas (1991) added 21 new or revised events to existing historical earthquake lists for South Australia principally by examining newspaper archives from 1840–1962. In this period, the catalog has 90 earthquakes in South Australia for which approximate locations and magnitudes have been determined using intensity data. Within the SA region historical records are reliable between 1880 and 1920 and the catalog is probably complete above M 4.5. However, between 1920 and 1932 it is incomplete, as local newspapers closed and the Adelaide Observatory discontinued collecting felt reports. After 1932, the University of Adelaide began collecting felt reports (Malpas, 1991). From 1962, the network was expanded and instrumental records replaced felt reports.

McCue (1978, 1980) undertook a similar study for parts of southeastern Australia and concluded the catalog is likely to be complete above M 5.0 since the 1880s. Everingham (1968) and Everingham and Tilbury (1972) undertook a similar analysis for southwestern Australia and concluded that the catalog is complete above M 4.5 since 1900 and probably since 1878. In other areas of Australia, the historic record is less complete.

Because of the small number of events, the method used to test the completeness of the instrumental catalog was not suitable for the historical catalog. Instead, three time periods were used to predict the number of earthquakes above M 5 per century: 1960–2003, using the high gain instrumental catalog, 1910–1959, using the low gain instrumental catalogue, and 1880–1910, using the historical record. The results are summarized in Table 5. In SA and SEA, the number of expected earthquakes is similar for all three estimates, indicating that the catalog is most likely complete above M 5 since 1880. The low variance ($\pm 10\%$) indicates approximately constant activity for at least the last century. In NA and NWA, the catalog is complete above M 5 only since 1960. The results for SWA indicate completeness since 1960; however, the catalog is considered to be complete above M 5 since 1900. This is consistent with the hypothesis that there was a jump in activity in the 1940s—this is discussed later. On average, Table 5 suggests that the SA region has an earthquake M 5 or larger every 10 yr, SEA every 4 yr, and SWA every 5 yr. On average, Australia has two earthquakes above M 5 per year.

Recurrence Relations for Australia

Gutenberg and Richter (1942, 1947) introduced the now-famous equation for the exponential distribution of earthquake magnitude:

$$\log 10(N) = a{-}bM, \qquad 3$$

where N is the number of earthquakes of magnitude M, and a and b are constants. In this article, I consider the cumulative

Table 4

Dates for the Completeness of the Australian Earthquake Catalog for Various Regions of Australia (See Fig. 1 for a Description of These Regions)

Region	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0	5.5
SWA	1990	1980	1965	1960			1880[*]		
SA	1980	1970			1965	1960	1880[*]		
SEA	1975[†]	1970		1960		1955		1880[*]	
NWA				1980	1970	1965	1960	1960	1910
NA[‡]					1980	1970	1965	1960	1910

[*]These dates are from estimates of the historical record.
[†]In SEA completeness cutoff, it has increased to 2.0–2.5 since 1995.
[‡]NA is all of Australia excluding the four regions analyzed in detail.

Table 5

Number of Earthquakes above M 5.5 Expected Per Century

Region	1960–2000	1910–1959	1880–1909
SA	10	10	13
SEA	30	24	27
SWA	22	8	0
NWA	79	6	3
NA	95	30	20

The data in this table are based on the number of earthquakes recorded during the high and low gain instrumental periods (1960–2000 and 1910–1959, respectively) and the historical period (1880–1909). These results indicate that the SA and SEA catalogs are complete back to 1880.

version as it gives smoother curves when data are sparse. Given the catalog limitations, this analysis uses a simple least-squares fit to equation (3). In the text following this paragraph, $A5$ means $\log_{10}(N)$ at M 5, $A6$ at M 6, and a could be considered $A0$.

To date, the work on a- and b-values in Australia has been for earthquake hazard assessment and focused on the division of Australia into source regions based primarily on seismicity, which is then analyzed independently within those source regions (Everingham and Gregson, 1970; Doyle, 1971; McEwin *et al.*, 1976; Denham, 1979; Stewart, 1984; Gaul *et al.*, 1990; Michael-Leiba *et al.*, 1993). Brown and Gibson (2004) divided Australia into more than 100 zones based on geological and geophysical data. They derived a for each zone, but used regionally determined b. Williams and Leonard (2001) demonstrated that even with the relatively sparse data available, statistically significant estimates of a and b on a 1° grid was possible for much of Australia.

In this study, a method similar to Williams and Leonard (2001) was used, where a region is divided into cells and each cell was a weighted average of the earthquakes in its cell and its eight neighbors. The weights are $1/4$ for the center cell, $1/8$ for the side cells, and $1/16$ for the corner cells. Cells of 85 by 85 km were found to give a good balance between resolution and maximizing the area for which the cells have an $R > 0.7$ (R is the least-squares correlation coefficient). The results for a and recurrence intervals ($A5$ and $A6$) are normalized to $10{,}000$ km^2.

The results of the recurrence analysis are shown in Figures 6 and 7. There is a clear relationship between the seismicity of Australia (Figs. 1 and 2) and areas of high a and b (Fig. 6). The relationship is not so clear for earthquakes M 5 and higher. There is strong correlation between the seismicity of Australia and R (Fig. 7a), with almost all cells with more than 40 earthquakes in the tile having an $R > 0.9$. High R was one of the three criteria used to select the four regions of Australia discussed throughout this article. The areas where $A5$ is greater than 0.4 are comparable to the areas in the GSHAP map (Giardini, 1999) for Australia, with a 10% probability in 50 yr of exceeding 0.8 m/sec.

The effect of a large earthquake within a cell is to decrease b for all cells that include that earthquake. This, combined with a steady or even increased a, results in $A5$ being increased, often excessively so. When using recurrence relations to forecast future patterns in seismicity, there is an implicit assumption that future events will follow the calculated distribution. However, as discussed in the following section, seismicity in Australia can be episodic so any hot spot that is active during the period of the catalog used will bias the long term recurrence rate, perhaps unjustifiably. Research that uses recurrence relations, such as hazard or strain modeling, needs to take care to not overemphasize those areas where recent large earthquakes have biased the moment release rate.

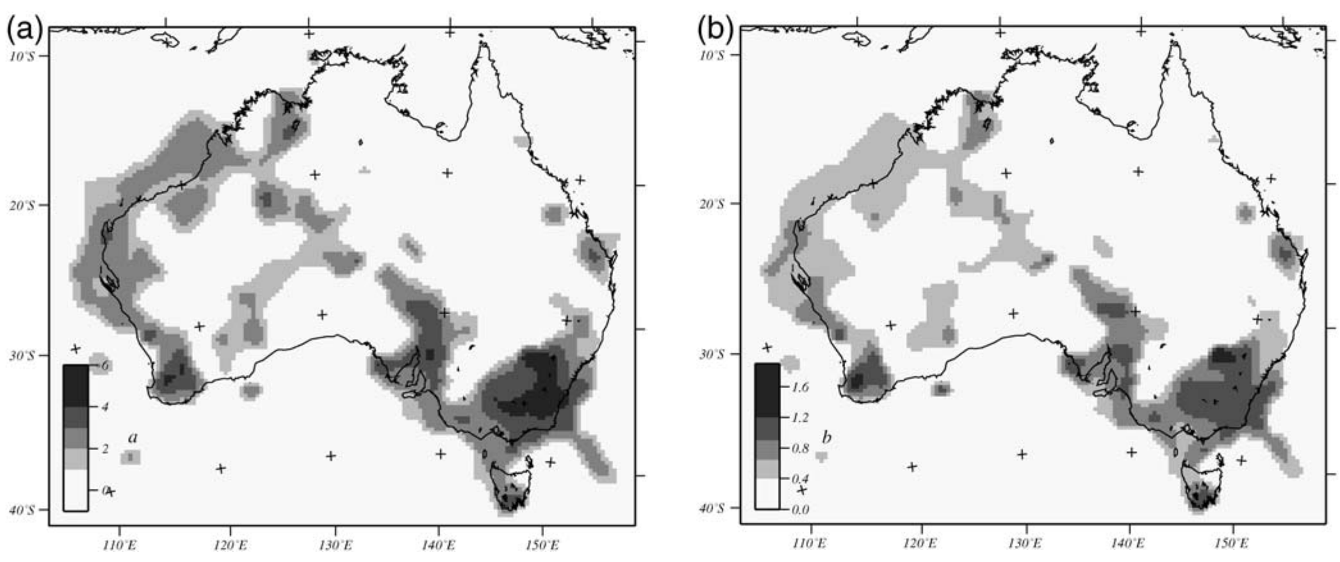

Figure 6. Recurrence relations for 84- by 84-km cells: (a) a-values normalized to $10{,}000$ km^2 and 100 yr and (b) b-values. The cells are left blank when the least-squares coherence $R \leq 0.7$.

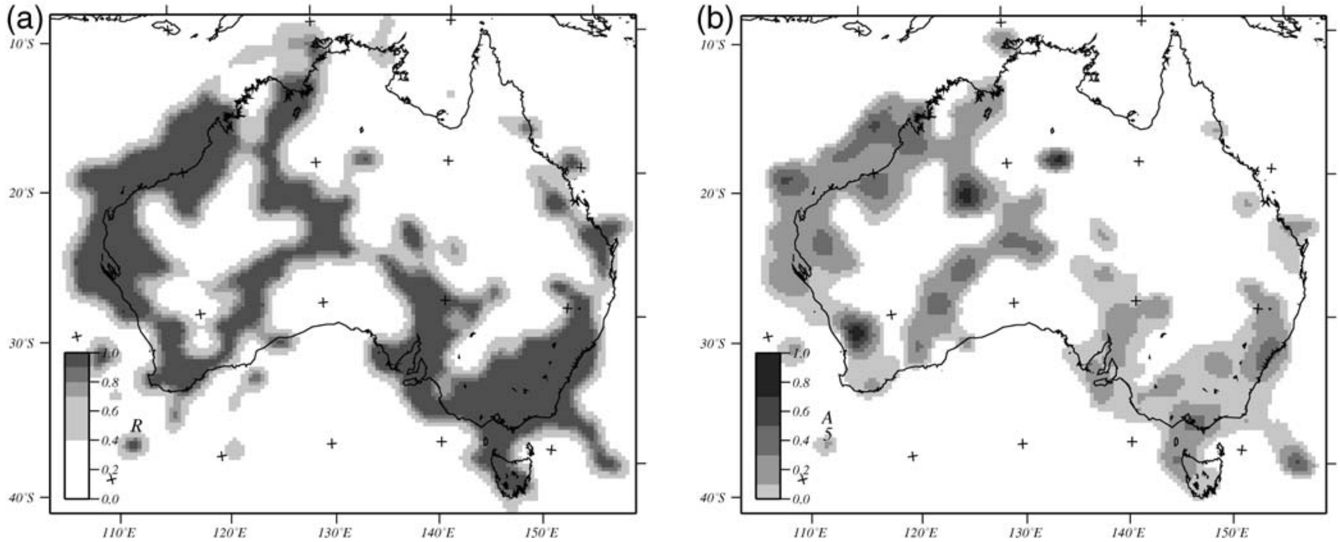

Figure 7. Recurrence relations of Australia: (a) is the least-squares coherence (R) and (b) is the probability of an earthquake $M > 4.9$ occurring in 100 yr for each cell, referred to as $A5$ in text.

Regional Recurrence Relations

The Australian continent is defined here as the area south of 10° S and above the 2500-m isobath (Fig. 1). This differs from Johnston (1994a) who used a deeper isobath, which included rifted continental crust.

The seismic regions NWA, SWA, SA, and SEA (Fig. 1) are used throughout this article. The three criteria for choosing these four regions were enhanced ongoing seismicity for at least 50 yr, a least-squares coherence (R) > 0.9 (Fig. 7) when recurrence relations are determined on a 55 by 55-km grid of Australia, and an area of at least $100,000$ km^2 in size. The three southern regions closely match the regions for which the earthquake catalog is most complete. The SWA zone approximates the Everingham and Gregson (1970) zone A and was referred to by Doyle (1971) as the southwest seismic zone (SWSZ) (a term now in common usage). The fifth region (NA) is the entire Australian continent. Hot spots, such as in the Kimberly (17° S, 127° E), Peterman Ranges (25° S, 131° E), and Bundaberg (25° S, 152° E) appear to have a long history but are not large enough to warrant separate analysis here. Other hot spots (Fig. 7b) have not been long-lived.

Recurrence relations were calculated for the five regions. The results for NWA, SA, and SEA are consistent with the number of large earthquakes over the last century, as is SWA since 1960. Other areas of Australia have less consistent results. Areas such as the northeast part of the continent, which had several earthquakes $M > 5.4$ between 1910 and 1960, have very low values of $A5$, due to the sparsity of moderate earthquakes since 1970. Other apparent hot spots, around Lake Mackay (23° S, 127° E), Marrayat Creek (27° S, 130° E), Simpson Desert (20° S, 134° E), and Tennant Creek (19° S, 134° E) have a high to very high $A5$ (see Table 1 for details of these earthquakes). However, these results are based on high levels of activity for a period of only a decade or less, consistent with the idea, discussed later in the article, that much of Australia's seismicity is episodic, not spatially or temporally stationary.

Estimates of a, b, $A5$, $A6$, and R^2 (least-squares R^2 value) were made for the NWA, SA, SEA, SWA, and NA regions, and the results are summarized in Table 6. The results for NWA, SA, and SEA are robust with R^2 of 0.98–0.99, and they have similar values for a (5.2–5.4) and b (0.85–0.98). NWA has a higher $A5$ than SA and SEA, which is consistent with the number of earthquakes larger than M 5 since 1960 (Table 5).

For the rest of Australia (NA) b is 0.83, a typical value for intracratonic regions (Frohlich *et al.*, 1993), and R is 0.98. The $A5$ is 0.088. However, while 968 earthquakes are used to calculate a and b, $A5$ is sensitive to the three Tennant Creek earthquakes (M 6.7, 6.4, and 6.3), which are the only earthquakes above M 5.9. Treating Tennant Creek as one M 6.9 earthquake, based on energy release during the 9 hr in which the three earthquakes occurred, $A5$ is reduced by 20% to 0.07. Also, the distribution of earthquakes is not as log-linear as the other regions with more earthquakes between M 4.0 and 5.0, and fewer earthquakes below M 3.9 and above M 5.8 in this region, than expected. Given the problems with the catalog, discussed previously, the source of these problems is not easily determined. For catalogs that include these larger earthquakes, regression techniques that include maximum magnitude (Weichert, 1980) might be preferred to simple least-squares analysis.

For SWA, a is high at 3.7 and b is low at 0.58, which results in the highest $A5$ in Australia. The b is very low by world standards and why this is the case is yet to be explained. It could be that the episodic nature of seismicity in this area (see later discussions in the article) results in low values of low b. It could be that the declustering algo-

Table 6

Summary of Recurrence Relations and Strain Rates for Australia and Australian regions

	Area	a	b	R^2	$A5$	$A6$	ε (sec^{-1})	v (mm/yr)
SWA	23.0	3.7	0.58	0.98	0.72	0.191	46×10^{-18}	0.48 (0.15–1.6)
NWA*	92.0	3.9	0.85	0.97	0.46	0.066	16×10^{-18}	0.38 (0.11–1.3)
NWA†	92.0	3.9	0.85	0.97	0.46	0.066	16×10^{-18}	0.75 (0.22–2.5)
SEA	90.5	3.7	0.90	0.99	0.16	0.021	5.9×10^{-18}	0.10 (0.02–0.22)
SA	36.5	4.2	0.99	0.99	0.195	0.020	4.9×10^{-18}	0.07 (0.02–0.22)
NA	720	3.2	0.86	0.99	0.07	0.010	2.3×10^{-18}	0.22 (0.07–0.73)
Australia*	940	3.6	0.92	0.99	0.095	0.012	2.8×10^{-18}	0.39 (0.12–1.3)
Australia†		4.5	0.90				2.2×10^{-18}	0.31 (0.13–0.76)
Australia‡							30×10^{-18}	3 ± 2
Australia§							6.4×10^{-18}	0.65 ± 2

a and b are the usual Gutenberg–Richter constants—a is per century per 10,000 km^2. $A5$ and $A6$ are the expected number of events per century above magnitude 5 and 6 in an area of 10,000 km^2, respectively. All velocities are derived from the strain rate in the direction of the stress field of Australia (Clark and Leonard, 2003). For NWA, two velocities are determined: one northeast–southwest (A) and the other east–west (B).

*This study.

†Johnston (1994a).

‡Satellite laser ranging measurements (Smith *et al.*, 1990).

§Geodetic GPS analysis (Tregoning, 2003); see text for details.

rithm used in the SWSZ catalog, which removed 63% of earthquakes, has removed mainshocks. However, as previously mentioned, by other criteria the declustering algorithm was not excessive, so this is not considered the cause of the low b. Another possibility is that it is an area of high stress which can result in low values of b (Urbancic *et al.*, 1992). Whilst the orientation of the stress field in Australia is well understood (Hillis and Reynolds, 2003 and Clark and Leonard, 2003) the magnitude is not. Modeling of the stress field (Reynolds *et al.*, 2003; Zhao and Muller, 2003; Burbidge, 2004) does not suggest that the SWSZ/SWA is a region of particularly high stress compared to NWA, SA, and SEA. However, the major principal stress at 1000-m depth in the Yilgarn Craton, in which SWA lies, is 2–4 times higher than Canadian or South African mining areas, and 1.6 higher than the rest of Australia (Lee *et al.*, 2001). Table 6 summarizes recurrence relations and strain rates for Australia and regions within Australia.

Moment Release and Strain

The rate of moment release can be determined (equation 4) from the Gutenberg–Richter relation (equation 3) and the definition of moment magnitude (Hanks and Kanamori, 1979) (equation 5).

Rate of moment release M_0 can be determined as

$$\sum M_0 = \frac{1}{T}\left(\frac{b(10^{a+d})}{c-b}\right)\left(10^{(c-d)M_{\max}} - 10^{(c-d)M_{\min}}\right) \approx \frac{1}{T}\left(\frac{b(10^{a+d})}{c-b}\right)(10^{(c-d)M_{\max}}), \tag{4}$$

where

$$\log_{10}(M_0) = cM + d. \tag{5}$$

From Hanks and Kanamori (1979) $\log M_0 = 1.5M_w + 16.1$ dyne cm; thus $c = 1.5$ and $d = 9.1$ N m. In these calculations M will be assumed to be equivalent to M_w even though, as discussed previously, a number of M_L formulas have been used and most of the larger events are M_S. The use of a number of magnitude types, for which the conversion to M_w is not known, affects the values of a, b, c, and d and introduces potentially large unknown errors to the calculation of $\sum M_0$. The strain rate per unit time, ε, is given by equation (6) (Kostrov, 1974),

$$\varepsilon = \frac{1}{2\mu V}\sum M_0, \tag{6}$$

where rigidity $\mu = 3.3 \times 10^{10}$ Pa, and V is volume of the seismogenic crust. The thickness of the seismogenic crust is taken to be 20 km.

Table 6 summarizes the strain and implied deformation velocity for various regions of Australia using a variety of methods. The moment release is sensitive to the value of a, b, c, d, and $M_{\max}$, each of which are not well constrained. Based on modifying a, b, c, and d through reasonable values, the errors to the strain rate and deformation velocities are taken to be -60% and $+250\%$, which spans an order of magnitude. As the problems with estimating a, b, c, and d are similar for all regions of Australia, the precision within Australia is better than these absolute errors, and so comparing different regions of Australia will generally be valid. The poor accuracy of these estimates will have the most impact when comparing the Australian regions with areas outside

Australia. The velocities in Table 6 are estimated from the strain rate in the direction of maximum compressive stress given by Hillis and Reynolds (2003). Adding together the results for SWA, SA, and SEA to approximate the strain across southern Australia gives 0.65 mm per year.

The five strain rate estimates for the whole of Australia are derived from several sources. The first two, labeled Australia* and Australia† in Table 6, are determined using equations (4) and (6). The Australia* results are from this study. Australia* strain rates are from Johnston (1994a), who used a database that included large earthquakes from 1875–1989 and the instrumental catalog for earthquakes $M \geq 4.5$. Australia‡ strain rates are derived from satellite laser ranging data from 1979–1987 (Smith *et al.*, 1990). Johnston (1994a) concluded that the geodetic monitoring tended to overestimate the strain rate and the lower rate, within the confidence interval, is probably closer to the actual rate. Tregoning (2003) concluded that, within the ~2-mm-per-year 95% confidence level, there was no internal deformation of the Australian continent. However, using results for stations near Perth, on the western edge of SWA, and near Sydney, on the eastern edge of SEA, indicate compression across southern Australia of 0.65 ± 2 mm per year (Australia in Table 6). This sets the limits for compression over southern Australia of 0–2.65 mm per year, with the number most likely to be in the 0.5–1.0-mm-per-year range.

Temporal and Spatial Stationarity of Australian Earthquakes

Most Australian earthquakes of $M \geq 5.5$ appear to be spatially and temporally clustered. Examples of this episodic behavior include the Flinders Island earthquakes in the 1880s, Robe in the 1890s, Warooka in the 1900s, Simpson Desert in the 1930s and 1940s, SWA since the 1960s, Lake Mackay in the 1970s, and Tennant Creek in the 1980s (see Table 1). All of these areas are characterized by low seismic activity punctuated by a period of enhanced seismic activity associated with one or more large earthquakes. In SWA the catalog is complete above M 4.5–5.0 since 1880 and the seismological record demonstrates a jump in activity by a factor of least 5 since 1949 (Everingham and Tilbury, 1972; Michael-Leiba, 1987). In the Tennant Creek area, the detection threshold has been ~M 2 since 1965, when the Warramunga seismic array was installed. In the 23 yr prior to the foreshocks in 1987, no earthquakes had been recorded. Since the three scarp-forming earthquakes (M 6.3, 6.4, and 6.7), there have been thousands of aftershocks that are still ongoing. Except for Tennant Creek and SWA, the seismic activity in all of the areas associated with the large events mentioned previously has been low over the last decade.

A few generalizations can be made about each seismic episode. These regions have all had periods of high activity associated with at least one $M > 6$ earthquake, which was preceded by a period of very low seismicity and/or followed by a period of very low seismicity. The period of high activity is typically 1–10 yr and is considered a typical aftershock sequence. A period of moderate activity follows, typically lasting from a few years to several decades. The seismicity rates during the periods of high and low seismicity differ by least one and often two orders of magnitude. Some episodes (e.g., SWA and Tennant Creek) had a period of moderate foreshock activity a few years before the very large earthquakes.

Palaeoseismic investigations have been undertaken on a limited number of surface ruptures associated with large earthquakes in several areas of Australia including Tasmania, Tennant Creek, Marryat Creek, and southwest Australia (Hyden and Lort River). Clark and McCue (2003) summarize the studies in Australia. Although no well-constrained recurrence intervals are yet available for active faults in Australia, estimates for the recurrence of large scarp-forming earthquakes ($M \geq 6.0$) are between 10 and 100 ka. Based on palaeoseismic studies in Australia and intracratonic northeast America, Crone *et al.* (1997, 2003) suggest that earthquakes in stable continental regions are episodic. An episodic seismicity model, where an area undergoes an episode of high activity associated with at least one large earthquake followed by a long period of quiescence, is consistent with the seismological, palaeoseismic, and strain rate data for much of Australia.

Conclusion

The seismic network in Australia is generally sparse with no more than 70 seismic stations suitable for general earthquake monitoring in a continent of a similar size to continental United States of America or western Europe. This results in generally poor constraints being placed on the location of earthquakes in Australia. Local magnitude scales have been used since around 1990. Before 1990, the Richter scale was used. Australia regularly has large, potentially damaging earthquakes, with an earthquake $M > 6$ every 3–5 yr and two earthquakes $M > 5$ per year. The seismicity varies significantly across Australia; however, it appears that large earthquakes can occur anywhere in Australia. The quality of current earthquake catalogs means that, outside SEA and SA, defining seismogenic zones smaller than $50,000$ km^2 is difficult to justify. The NW, SA, and SEA regions have been active at a steady rate of seismicity for over 100 yr. In contrast, the SWA region appears to have been highly active only since the 1940s. The seismicity of the rest of Australia is episodic and substantially lower than these four regions. Episodic seismicity is characterized by a period of high activity, usually associated with at least one $M > 6$ earthquake, which lasts up to a decade. Following the large earthquakes, a period of moderate activity, which might be considered an extended aftershock sequence, typically lasts from a few years to a few decades. This is thought to be followed by a long period (1–100 ka) of low seismicity. The effects of the episodic nature of much of the seismicity of Australia need to be taken into account when calculating recurrence relations, particularly when used to calculate hazard maps and strain rates. Strain rates derived independently from seismic and geodetic data are consistent and suggest compressive deformation across Australia of 0.65 ± 2.0 mm per year.

Acknowledgments

I would like to thank David Burbidge for the compiling the catalog used in this study, Phil Cummins and Dan Clark for their valuable comments, and Angela Bullock and Paula Boldra for their contributions to the bibliography and building a database of Australian seismic stations. I am thankful to the referees who provided helpful suggestions and helped to improve the manuscript.

By early 2008, the Geoscience Australia online catalog will include all of the earthquakes in the catalog used in this study. In the meantime, the earthquake catalog is available from the author (mark.leonard@ga.gov.au).

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Manuscript received 12 June 2007