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Fluctuations in seismicity in the Dalton area, NSW, Australia, and their relevance to earthquake forecasting

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In the Dalton area, 60 km north of Canberra, Australia, earthquakes are strongly clustered in time, but the presence of multiple events with magnitudes around 2.8 is not a useful criterion for earthquake forecasting. If magnitude ML >2.7 events less than 14 months apart during the period 1960–1993 are grouped together, the magnitude ML(MAX) of the largest event of a group may be forecast from the relationship: ML(MAX) = 0.097 + 2.296 log t, where t months is the quiescent interval preceding the group in question and 2.8<ML(MAX)<4.2.

Introduction

The Dalton area, 60 km north of Canberra (Fig. 1), is one of several seismically active regions of eastern Australia. Several earthquakes have caused damage near the epicentre and been felt in Canberra. A magnitude ML 5.5 in 1949 also produced minor cracking in some Canberra buildings. The largest recorded earthquake had magnitude ML 5.6 and occurred in 1934 (McCue et al. 1989). It was the same size as the destructive December 1989 Newcastle earthquake. Michael-Leiba et al. (1988) discussed earthquake swarms as short-term precursors. The aim here is to investigate other fluctuations in seismicity and their usefulness for earthquake forecasting.

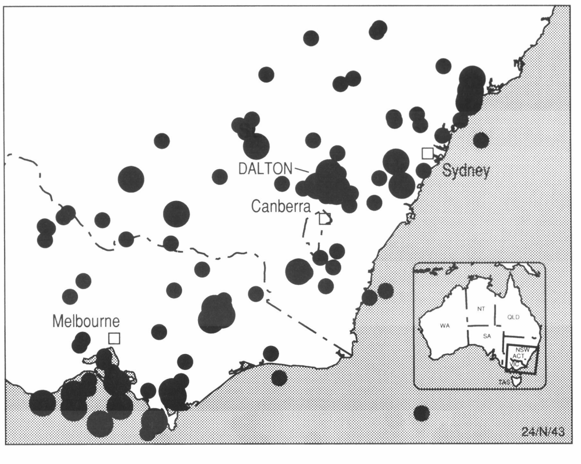

Figure 1. Locality map. Dalton is in the middle of the cluster of earthquakes indicated by the arrow. The black dots are epicentres of earthquakes with magnitudes ML 4.0 or greater.

Fluctuations in seismicity

The ten magnitude ML >3.9 events known to have occurred within 15 km of Dalton are shown in Table 1. When foreshocks and aftershocks within nine months of each other or of a main shock are removed, the number of events decreases to seven, three of which happened during the years 1949–1954. The seismicity during this short interval may have been anomalously high, but the data are too few to investigate statistically and may not be complete to magnitude ML 4.0 prior to 1960: much of the Australian National University (ANU) seismic net was established in 1958–59, and the seismograph coverage before then was very limited.

Table 1. Magnitude ML >3.9 earthquakes at distances of 15 km or less from the Dalton seismograph.

Date (UTC) Dy–Mo–Year	*Latitude °S*	*Longitude °E*	*Magnitude ML*
05–07–1888	34.8	149.1	5.3
18–11–1934	34.8	149.2	5.6
10–03–1949	34.74	149.2	5.5
07–09–1952	34.8	149.3	4.7
18–11–1952	34.8	149.3	4.4
19–11–1952	34.8	149.25	4.9
22–11–1952	34.8	149.3	4.6
09–06–1954	34.75	149.2	4.5
03–11–1971	34.777	149.166	4.0
09–08–1984	34.803	149.170	4.1

A seismograph was installed by ANU at Dalton in 1961, so events with magnitudes as small as ML 2.0 should be complete from 1962. They may well be complete from 1960, as there were ten ANU stations in New South Wales by then, but the accuracy of location would have been poorer than when the Dalton seismograph was in operation. Magnitude ML >2.7 earthquakes should be complete from 1960.

During the period 1960–1993, lower magnitude events are strongly clustered in time (Fig. 2). The events in Figure 2 are from the AGSO earthquake data-base: magnitudes have been converted for consistency with those determined using the attenuation in southeastern Australia derived by Michael-Leiba & Malafant (1992). For magnitude ML >2.5 earthquakes, this meant subtracting 0.2 from pre-1990 magnitudes. When foreshocks and aftershocks of magnitude ML >2.7 events within one month of each other or of a main shock are removed (as suggested by Michael-Leiba 1987 and followed by Gaull et al. 1990), the annual number of residual main shocks (Fig. 2, bottom histogram) fluctuates between zero and two—except for 1984, when there were five. As a magnitude ML 4.1 earthquake occurred in 1984, the elevated residual seismicity may be related to this. However, if the main shocks follow a Poisson distribution, then the five events in one year would be the result of the Poisson process. In this case, the time intervals between events would follow a negative exponential distribution (Lomnitz 1974). The Kolmogorov–Smirnov test (Siegel 1956) of goodness of fit to a negative exponential distribution with mean time interval 13.6 months is shown in Table 2. The greatest divergence, D, between the two distributions is 0.104. The critical value of D at the 0.05 level of significance is 0.24, so the null hypothesis of a negative exponential distribution cannot be rejected at the 0.05 level of significance. Consequently, there is insufficient

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evidence to regard the occurrence of five events in 1984 as other than the result of a Poisson process.

The presence of multiple events with magnitudes around 2.8 is not a useful criterion for earthquake forecasting in the Dalton area. The magnitude ML 4.0 earthquake in November 1971 had no ML >2.7 foreshocks in 1971, whereas the ML 4.1 event in August 1984 had three foreshocks in the preceding seven months. Also, seismicity was elevated in 1965, 1979 and 1987, with multiple events of magnitude around 2.8, without being precursory to ML >3.9 earthquakes.

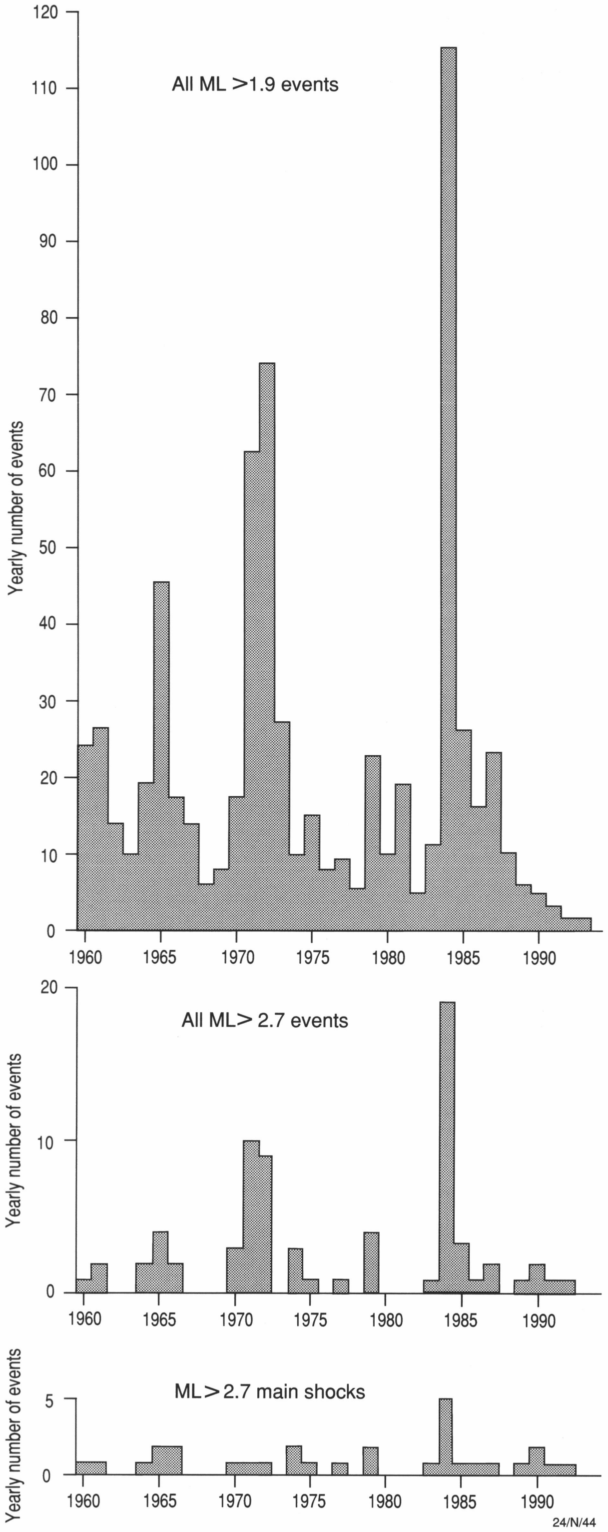

Figure 2. Yearly numbers of earthquakes at a distance of 15 km or less from the Dalton seismograph.

Table 2. Kolmogorov–Smirnov test on goodness of fit of time intervals between magnitude ML >2.7 main shocks at distances of 15 km or less from the Dalton seismograph (1960–1993) to a negative exponential distribution.

Interval (months)	*No. observations*	*Cumulative theoretical*	*Cumulative observed*	*D*
1	2	0.071	0.069	0.002
2	3	0.137	0.172	0.035
3	2	0.198	0.241	0.043
4	3	0.255	0.345	0.090
5	1	0.308	0.379	0.071
6	1	0.357	0.414	0.057
7	1	0.402	0.448	0.046
9	1	0.484	0.483	0.001
10	2	0.521	0.552	0.031
11	1	0.555	0.586	0.031
12	3	0.586	0.690	0.104
18	1	0.734	0.724	0.010
19	2	0.753	0.793	0.040
20	1	0.770	0.828	0.058
21	1	0.786	0.862	0.076
29	1	0.881	0.897	0.016
34	1	0.918	0.931	0.013
44	1	0.961	0.966	0.005
56	1	0.984	1.000	0.016

Forecasting from quiescent periods

Forecasting magnitude from quiescent interval

The magnitude ML 4.0 and 4.1 earthquakes in 1971 and 1984 were each preceded by a quiescent period of more than three years eight months with respect to magnitude ML >2.7 events, including foreshocks and aftershocks. During 1960–1993, there was no other three-year interval without an ML >2.7 event (Fig. 2). This suggests a relationship between the magnitude of an event and the length of the quiescent interval preceding it, possibly because of stress build-up during this period.

The quiescent periods before the 1971 and 1984 ML >3.9 events ended, respectively, 12 and 16 months before these earthquakes. During these 12 and 16 month periods leading up to the ML >3.9 events, the longest time between events of ML >2.7 was, respectively, 12 and 7 months. Also, 13.6 months is the mean interval between ML >2.7 main shocks; hence, I define a quiescent period as 14 months or more without an event exceeding magnitude ML 2.7. Then, magnitude ML >2.7 events (including foreshocks and aftershocks) less than 14 months apart constitute groups of one or more earthquakes, separated by the quiescent periods. There are ten such groups during the period 1960–1993 (Table 3). If ML(MAX) is the magnitude of the largest event in a group and t months is the time between the last event in the preceding group and the first event of the group in question, then the least squares line (Fig. 3) for nine pairs of observations (with ± indicating the standard errors of the coefficients, calculated by small-sample statistics) is

$$ML(MAX) = (3.36 \pm 0.06) + (2.296 \pm 0.330)(\log t - 1.421)$$

or

$$ML(MAX) = 0.097 + 2.296 \log t \quad (1)$$

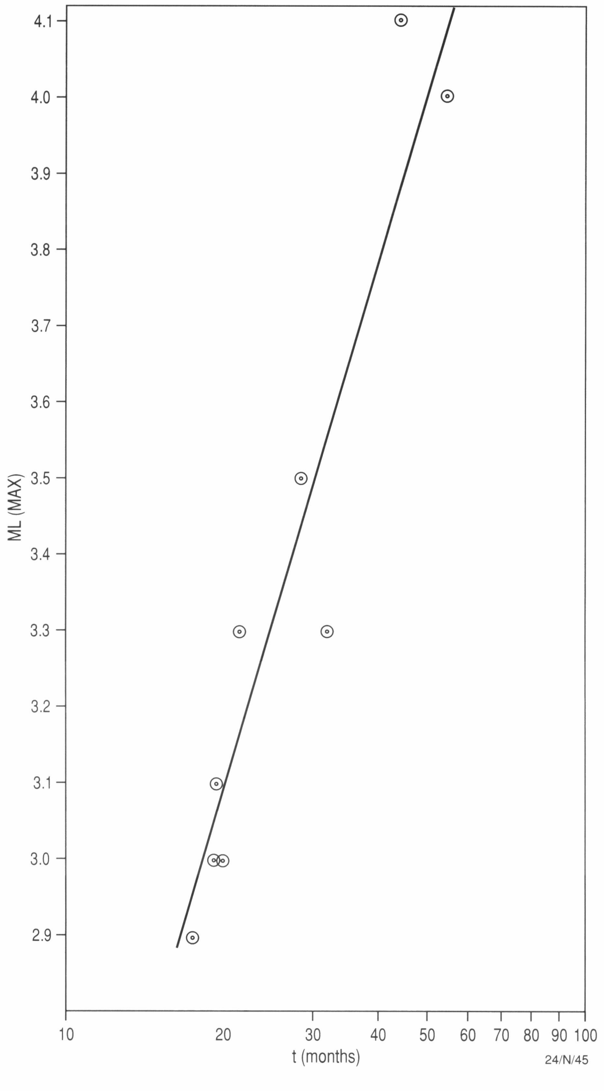

Figure 3. Relationship between magnitude of largest event in group ML(MAX), and length, t months, of quiescent period preceding it.

with a standard error of estimate of ML(MAX) of 0.15. The 95% confidence limits for the slope are 1.589<slope<3.003. Despite the small number of observations, the largest residual was only 0.25 ML (Table 3) and the magnitude range used to derive the relation was ML 2.9–4.1, so (1) may be useful for forecasting the magnitude of an impending event after a quiescent period (in terms of ML >2.7 events). However, it does not indicate if two or more events of equal maximum magnitude will occur in the group. This happened in two instances in Table 3. At the time of writing (2 June 1994), it is 23.0 months since the last ML >2.7 earthquake. If the next group of events were to start now, the 95% prediction interval for ML(MAX) from (1) would be 2.8<ML(MAX)<3.6.

Forecasting date of occurrence from ML(MAX)

If T months is the time interval measured from the start of the preceding quiescent period to the occurrence of the largest event of the group, then the date of this event may be estimated from the least squares relationship (Fig. 4)

$$\log T = (1.472 \pm 0.021) + (0.4295 \pm 0.0591)(ML(MAX) - 3.36)$$

or

$$\log T = 0.029 + 0.4295\, ML(MAX) \quad (2)$$

where ML(MAX) in (2) may be calculated from (1) provided that the largest event in the group is not the first. Three of the ten groups started with the largest earthquake and in this case (2) could not be used as a forecasting tool. The 95% confidence limits for the slope in (2) are 0.3028<slope<0.5562. For the nine pairs of observations (Table 4) used to derive equation (2), the standard error of estimate of the residuals was 5.2 months. Only two residuals exceeded this value, but the greatest was 11.4 months for the ML 4.0 event in 1971. The residual for the ML 4.1 earthquake in 1984 was only –0.8 months, but the 11.4 months residual for the 1971 event suggests that equation (2) may not be accurate enough to use as a short-term warning system for damaging earthquakes in the Dalton area.

Sensitivity of the ML(MAX) – log t relationship to changes in the minimum values of ML and t

Tests were conducted to ascertain how sensitive the relationship between ML(MAX) and the length, t, of the preceding quiescent period is to changes in the minimum

Table 3. Relationship between magnitude of largest event in group, ML(MAX), and length, t months, of quiescent period preceding it.

Date of Group	*t (months)*	*ML(MAX)*	*Least Squares ML*	*Residual*	*Comments*
14.08.1960–21.08.1961	—	2.8	—	—	3 events with ML2.8
18.04.1964–27.03.1966	31.9	3.3	3.55	–0.25	
21.10.1970–16.08.1972	54.8	4.0	4.09	–0.09	
22.03.1974–04.08.1975	19.2	3.0	3.04	–0.04	
05.04.1977	20.0	3.0	3.08	–0.08	
18.01.1979–12.07.1979	21.4	3.3	3.15	0.15	
24.03.1983–07.01.1986	44.4	4.1	3.88	0.22	
20.06.1987–26.06.1987	17.4	2.9	2.95	–0.05	
14.11.1989–15.04.1990	28.6	3.5	3.44	0.06	
24.11.1991–02.07.1992	19.3	3.1	3.05	0.05	2 events with ML3.1

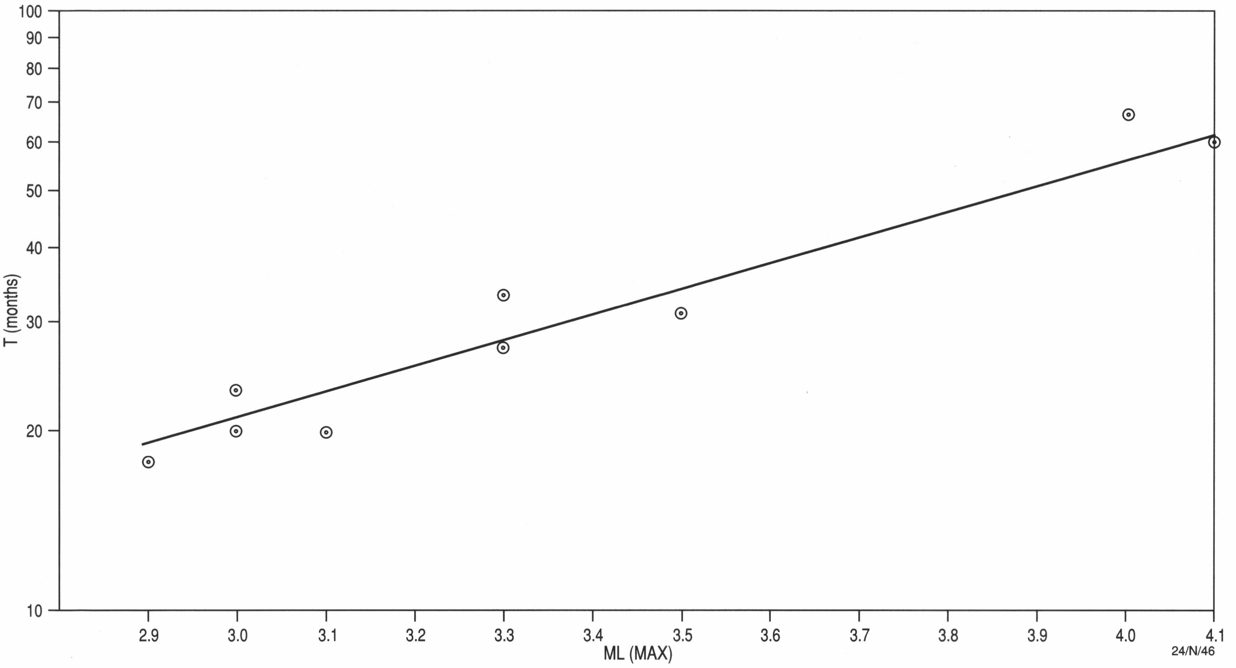

Figure 4. Relationship between time interval, T months, from start of preceding quiescent period to occurrence of largest event of group.

magnitude of the data set. The same 14 month minimum value of t was used.

In the Dalton area, epicentres tend to occur in two distinct zones, one to the north and the other to the south of the township, the southern zone being the more active (McCue et al. 1989). All the events delimiting groups and/or having the maximum magnitude in each group in Table 3 had their epicentres in the southern zone. For this reason, only events in this zone were considered in the sensitivity tests for magnitudes less than 2.8.

Table 4. Relationship between time interval, T months, from start of preceding quiescent period to occurrence of largest event of group. The groups are as in Table 3.

ML(MAX)	*Observed T*	*Estimated T*	*Residual (months)*
2.8	—	—	—
3.3	33.3	27.9	5.4
4.0	67.2	55.8	11.4
3.0	23.1	20.8	2.3
3.0	20.0	20.8	–0.8
3.3	27.2	27.9	–0.7
4.1	60.9	61.7	–0.8
2.9	17.6	18.8	–1.2
3.5	30.6	34.0	–3.4
3.1	19.3	22.9	–3.6

For ML 2.8 and above, the standard error of estimate of ML(MAX) by equation (1) is 0.15. For ML 2.7 and above, using a Microsoft EXCEL linear regression function, the relationship becomes

$$ML(MAX) = 2.14 \log t + 0.37 \quad (3)$$

with a standard error of estimate of ML(MAX) of 0.22 and a correlation coefficient of 0.88. For ML 3.0 and above, using the same package, the relationship is

$$ML(MAX) = 1.86 \log t + 0.54 \quad (4)$$

with a standard error of estimate of ML(MAX) of 0.27 and a correlation coefficient of 0.84. For ML 2.6 and above and ML 3.1 and above, there is no obvious relationship between ML(MAX) and t. Thus, a log-linear relationship holds for cut-off magnitudes in the range ML 2.7–3.0 when the minimum length of a quiescent period is defined as 14 months. For a quiescent period of 23 months, the values of ML(MAX) calculated from equations (3) and (4) are 3.3 and 3.1, respectively, which lie well within the 95% prediction interval, $2.8 < ML(MAX) < 3.6$ of ML(MAX) from equation (1).

If the minimum length, t, of the quiescent period were taken to be less than 12 months, the ML 4.0 earthquake in 1971 would no longer appear to be related to the quiescent period of 54.8 months in Table 3. For minimum values of t in the range 13.0–17.0 months, the pattern of groups would be unchanged from that in Table 3. If the minimum t were chosen to be 24 months, the number of quiescent periods in Table 3 would decrease to four, insufficient data on which to base a useful regression.

Conclusions

The null hypothesis of a Poisson process cannot be rejected at the 0.05 level of significance for describing the occurrence of magnitude ML >2.7 main shocks in the Dalton area. Clustering occurs in the original data containing all ML >2.7 events, but does not appear to be useful for predicting ML >3.9 earthquakes. Quiescent periods may be helpful in forecasting earthquakes with magnitudes up to ML 4.1; however, there are no data at present to ascertain whether they may be useful for higher magnitude events.

The relationship between the magnitude of the largest event of a group of magnitude ML >2.7 earthquakes and the preceding quiescent period (with respect to ML >2.7 events) suggests that this magnitude is a function of stress build-up during the quiescent period. It may be a useful magnitude forecasting tool, but the date of occurrence may not be able to be estimated with sufficient accuracy for short-term warnings of potentially damaging earthquakes.

Acknowledgments

Brian Gaull and I became aware of the quiet periods prior to the magnitude ML >3.9 earthquakes of 1971 and 1984 when working on another project in 1985. I am grateful to Stewart Dennis for performing the regressions for equations (3) and (4). I thank Phil McFadden for useful discussions on statistics and the nature of the earthquake process; Kevin McCue, David Denham, Brian Gaull, Gary Gibson, Phil McFadden and an anonymous referee for critically reading the manuscript and suggesting improvements; Jill Clarke and John Convine for drafting the figures; the staff of Research School of Earth Sciences, Australian National University, particularly Jan Weekes, for their data and cooperation; and the late Vicki Klein for many years of help and support with the Dalton earthquake-monitoring project.

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Editorial note: Some readers may wish to offer comments on both the observational and interpretive information in the above article.

The Editor would welcome discussions for publication in the *AGSO Journal of Australian Geology & Geophysics.*