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Temporal variation in seismicity of the Southwest Seismic Zone, Western Australia: implications for earthquake risk assessment

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In the area 30-33°S, 116-118°E of the Southwest Seismic Zone of Western Australia, ML $\geq$ 4.0 earthquakes for the period 1960-1983 do not fit a Poisson model. However, when foreshocks and aftershocks are excluded, the hypothesis of a Poisson distribution cannot be rejected for the resulting series of main shocks. A similar result holds for the subset of ML $\geq$ 5.0 events for the period 1949-1983. Consequently, when earthquake risk is being assessed by methods that assume a Poisson distribution, foreshocks and aftershocks should be excluded. However, the consequent apparent reduction of risk caused by removing these potentially damaging earthquakes should be pointed out. Although records of seismicity are probably incomplete for the early part of this century, there appears to have been an increase in numbers of ML $\geq$ 4.0 events, starting around 1949. Although, the data are too uncertain to test the increase in the ML $\geq$ 4.0 main shocks statistically, there has been an approximate five-fold increase in the mean yearly number of ML $\geq$ 4.5 main shocks during the period 1949 to 1983, compared with the period 1923 to 1948. This is clearly larger than would be expected from a Poisson process. Consequently, the apparent increase in the number of ML $\geq$ 4.0 events is probably also real and not an artefact of a Poisson process. Also, there were no ML $\geq$ 5.0 events during the period 1923 to 1948, and the only two ML $\geq$ 6.0 earthquakes this century took place in 1968 and 1979. This increase in seismicity since the late 1940s should be taken into account in the interpretation of earthquake risk calculations.

Introduction

That part of Western Australia's Southwest Seismic Zone which lies in the area 30 to 33°S, 116 to 118°E is one of the most seismically active regions of Australia and the largest contributor to the earthquake risk at Perth (Fig. 1). If one assumes that seismic events are independent and the earthquake process is stationary, then the process will probably be a Poisson process. Many computations of earthquake risk assume this to be true (Lomnitz, 1974).

The Mundaring Geophysical Observatory was established in 1959, so it is assumed that data on ML $\geq$ 4.0 earthquakes are complete from 1960. Consequently, detailed investigation of the occurrence in time of these events has been carried out only for the period 1960-1983. However, Everingham (1968) has tabulated Western Australian earthquake reports back to 1904, and Everingham & Tilbury (1971) examined the Milne-Shaw seismograph records and intensity data from the Perth Observatory for the period 1923-1961 and determined some epicentres and magnitudes. The earliest event they located occurred in 1940. Everingham & Tilbury (1972) noted that seismic activity in the Southwest Seismic Zone appeared to have increased markedly since about 1940. From their examination of Perth seismograms, they stated that there were no earthquakes in that area with ML $\geq$ 4.5 during the period 1923-1939, and that felt reports suggested that there were probably none during 1900-1922. (By contrast, there were 12 events with ML $\geq$ 4.5 during the period 1940-1967.) Because of this, I assume that the data on ML $\geq$ 5.0 earthquakes are probably complete back to 1923, and possibly even to 1904.

By examining the reports in Everingham (1968) I have tabulated main shocks that may have had ML $\geq$ 4.0 during 1904-1939 (Table 1). I assumed that reports of Modified Mercalli intensity IV or greater in Everingham (1968) indicated an event with ML $\geq$ 4.0. There were none in Everingham (1968) to add to the post 1939 data from the BMR Earthquake Data File and Everingham & Tilbury (1971) (Tables 1 & 2). This is a very rough method and probably results in the inclusion of smaller magnitude events, but it should give some indication of whether the level of seismicity has changed appreciably with time. I have excluded ML $\geq$ 4.0 foreshocks and aftershocks for the earlier period, as information on the numbers of these is too vague. There was one ML $\geq$ 5.0 aftershock prior to 1960. It occurred on 29 August 1955 at 06hr 09min GMT. Its epicentre was at 30.7°S, 116.4°E and its Richter magnitude was 5.3.

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Earthquakes with ML $\geq$ 4.0, 1960–1983

The yearly number of events is plotted in Figure 2. With foreshocks and aftershocks included, the events appear to be strongly clustered, particularly in 1968 and 1979, the years of the ML 6.9 Meckering and ML 6.2 Cadoux earthquakes respectively.

For a pure Poisson process, the ratio of the variance to the mean is unity. (Variance/mean) xdf has a χ^2 distribution with df degrees of freedom, where df = N-2, and N is the number of observations. ($\chi^2 = \Sigma[(O-E)^2/E]$, where O is the observed value and E is the expected value). I used the variance/mean test because it is a very quick easy test to apply. If $\chi^2 >$ 95th percentile, the null hypothesis of a Poisson distribution may be rejected. If not, then it is worth doing a more sophisticated test.

For the ML $\geq$ 4.0 earthquake data, the variance is 11.77 and the mean 1.875, giving a ratio of the variance to the mean of 6.275 and (variance/mean) xdf of 138.05. For a χ^2 distribution with 22 degrees of freedom, the 99.95 percentile is 42.80, so the null hypothesis of a Poisson distribution can be rejected at the 0.0005 level of significance. Consequently, the ML $\geq$ 4.0 earthquake data with foreshocks and aftershocks included cannot possibly be described by a Poisson distribution. This is not surprising, because foreshocks and aftershocks are not independent events, so their inclusion contravenes one of the basic assumptions of a Poisson process. Therefore, earthquake risk analyses that include foreshocks and aftershocks, but assume a Poisson distribution, should be regarded with reservation.

Figure 2 also shows the yearly number of ML $\geq$ 4.0 main shocks only. Foreshocks and aftershocks occurring within 30 km of a main shock and within one month of each other or of a main shock have been excluded. The data from 1960 to 1983 have a ratio of variance to mean of 1.124 or (variance/mean) xdf of 24.73. The 95th percentile of the χ^2 distribution is 33.92, and the possibility of a Poisson distribution cannot be rejected. It requires further investigation.

For a Poisson process, the time intervals, T, between events follow a negative exponential distribution: $f(T) = \lambda e^{-\lambda T}$, where the mean of T is λ^{-1} (Lomnitz, 1974). From Table 3,

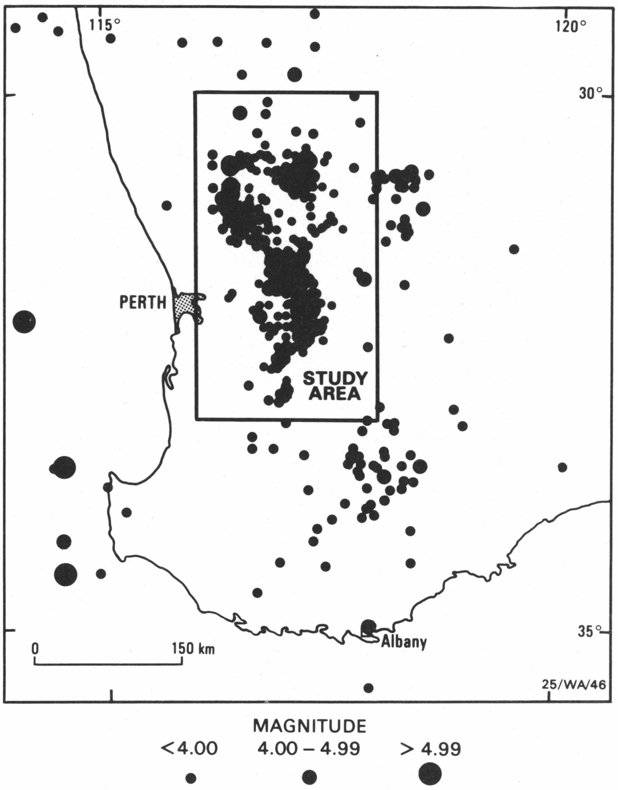

Figure 1. The Southwest Seismic Zone of Western Australia.
The rectangle shows the area 30–33°S, 116–118°E, which is the subject of this study.

the maximum likelihood estimate for λ is 394 (days). Table 4 shows the observed and expected distribution of time intervals using λ = 394. The negative exponential distribution provides a good fit to the observed data. Consequently, for the occurrence of ML ≥ 4.0 main shocks from 1960–1983, we are not in a position to reject the null hypothesis of a Poisson distribution.

Earthquakes with ML ≥ 5.0, 1949–1983

The yearly number of ML ≥ 5.0 earthquakes is plotted in Figure 2. As there were no events prior to 1949, I decided initially to see whether the earthquakes from 1949 to 1983 fitted a Poisson distribution.

For the data with foreshocks and aftershocks included, df is 33, the ratio of the variance to the mean is 2.088 and (variance/mean) xdf is 68.90. The 99.95 percentile of the χ^2 distribution for 33 degrees of freedom is 66.66, and the hypothesis of a Poisson distribution can be rejected at the 0.0005 level. Consequently, there is no way in which the data with foreshocks and aftershocks included can be described by a Poisson distribution.

For the same period, with foreshocks and aftershocks excluded, the ratio of variance to mean becomes 0.994, and (variance/mean) xdf is 32.80. The 95th percentile of the χ^2 distribution is 47.52, and the probability of a Poisson distribution requires further investigation.

The time intervals between the main shocks are shown in Table 5. As there are only eight of them, there are insufficient data to test for a negative exponential distribution and, hence, for the fit of the earthquake process to a Poisson distribution. However, the variance/mean test gives no reason to reject the null hypothesis of a Poisson process. Also, the ML ≥ 5.0 main shocks are a subset of the ML ≥ 4.0 main shocks, for which the hypothesis of a Poisson distribution was not able to be rejected.

Possible increase in seismicity

ML ≥ 5.0 earthquakes

The occurrence of main shocks of ML ≥ 5.0 during the period 1904–1983 is shown in Figure 2. The data may be complete back to 1904, but, to be conservative, I assume that they are complete back to 1923.

There appears to have been an increase in seismicity starting in 1949, but, with only nine main shocks, the data are too few to test this.

However, for ML ≥ 4.5 main shocks (Tables 1 and 2) there are more data, complete back to 1923 (Everingham & Tilbury, 1972). It appears that the Perth seismograph would have covered about 50 per cent of the study area. There was only one ML ≥ 4.5 main shock during the period 1923–1948, a

Table 1. Probable ML ≥ 4.0 earthquakes, 1904–1959, excluding foreshocks and aftershocks

ID no.	*Date* *y*	*m*	*d*	*Origin time* *h*	*m*	*Locality*	*Richter magnitude*	*Richter magnitude from intensity data (Everingham & Tilbury, 1971)*
	11	08	19			Quellington & York		
	16	06	02			Quellington		
	16	12	01			Meckering		
	17	06	03			York & surrounding districts		
	32	03	15			Muresk		
	32	11	02			Northam		
	36	08	18			48 km ENE of Katanning, & Brookton		
	37	03–05				48 km NE of Katanning		
	40	12	18	21	45	32.2°S, 117.2°E	4.2	
	41	04	15			Northam		
	46	05	07			Yallingup		
	46	09	17	15	12	32.5°S, 116.9°E	4.5	
(−4)	49	05	02	10	00	30.9°S, 116.4°E	5.1	
(−3)	52	03	11	06	09	31.3°S, 116.5°E	5.1	4.6
(−2)	55	04	29	09	14	30.9°S, 116.4°E	4.7	5.1
(−1)	55	08	30	13	52	30.7°S, 116.4°E	5.8	5.5
	56	02	24	06	27	30.9°S, 116.4°E	4.5	
	56	04	05	23	13	30.9°S, 116.4°E	4.5	
(0)	58	03	20	03	03	32.3°S, 117.2°E	4.8	5.2

Table 2. ML ≥ 4.0 earthquakes, 1960–1983

ID no.	*Classification*	*Date* *y*	*m*	*d*	*Origin time* *h*	*m*	*s*	*Latitude* °*S*	*Longitude* °*E*	*Richter magnitude*
(1)	M	61	06	25	17	59	18.1	32.200	117.200	4.4
(2)	M	63	01	18	05	49	16.8	32.250	117.170	4.9
(3)	M	63	11	19	17	52	05.1	31.000	116.300	4.2
(4)	M	68	02	22	04	40	10.5	30.800	117.300	4.0
(5)	M	68	04	08	01	44	53.8	30.800	117.250	4.4
	F	68	10	03	03	55	33.4	31.590	116.980	4.2
(6)	M	68	10	14	02	58	50.6	31.620	116.980	6.9
	A	68	10	14	03	15	21.4	31.600	117.000	4.0
	A	68	10	14	03	57	47.7	31.660	116.990	4.0
	A	68	10	14	04	09	07.5	31.600	117.010	4.6
	A	68	10	14	06	47	50.4	31.690	116.980	4.2
	A	68	10	15	03	30	07.0	31.680	117.030	5.7
	A	68	10	16	00	55	10.2	31.660	117.020	4.2
	A	68	10	18	10	31	47.9	31.760	117.070	4.1
	A	68	10	21	15	32	59.2	31.610	117.090	4.6
	A	68	10	22	01	04	04.9	31.580	117.010	4.1
	A	68	10	31	00	58	48.9	31.780	116.980	4.1
	A	68	11	28	14	17	31.5	31.640	117.000	4.0
(7)	M	69	02	01	03	29	57.7	31.960	117.150	4.0
(8)	M	69	07	27	09	20	47.3	30.950	117.100	4.2
(9)	M	70	03	10	17	15	11.2	31.110	116.470	5.9
(10)	M	70	12	26	18	25	51.0	31.080	116.310	4.0
(11)	M	71	07	16	12	32	24.4	31.640	117.080	4.0
(12)	M	74	07	09	10	46	47.4	31.650	117.000	4.3
(13)	M	74	09	04	23	17	42.4	30.790	116.970	4.5
(14)	M	74	11	19	09	30	22.6	31.630	117.030	4.0
(15)	M	76	10	29	06	04	48.2	31.640	117.000	4.7
	F	79	06	01	21	54	02.9	30.830	117.170	5.2
(16)	M	79	06	02	09	48	01.0	30.830	117.150	6.2
	A	79	06	02	11	04	57.2	30.800	117.210	4.1
	A	79	06	03	07	45	34.5	30.770	117.170	5.3
	A	79	06	07	06	45	16.1	30.810	117.160	5.5
	A	79	06	07	22	33	30.4	30.730	117.160	4.0
	A	79	06	10	18	24	52.6	30.780	117.190	4.3
(17)	M	79	10	11	04	04	11.7	30.790	117.150	4.8
(18)	M	80	12	10	04	35	05.6	30.730	117.150	5.0
(19)	M	81	04	07	20	15	55.8	30.744	117.164	4.5
	F	82	01	24	04	06	20.0	30.900	117.120	4.3
	F	82	01	25	23	26	58.7	30.910	117.130	4.4
(20)	M	82	02	06	15	24	39.5	30.880	117.150	4.9
	A	82	02	06	15	30	36.7	30.870	117.100	4.6
	A	82	02	07	13	07	31.4	30.890	117.090	4.1
	A	82	02	08	04	39	34.5	30.890	117.100	4.1
(21)	M	83	01	26	06	16	15.4	30.730	117.130	4.8

F—foreshock; M—main shock; A—aftershock.

mean of 0.04 events per year. During the period 1948–1983, there were 18 such events, a mean of 0.51 events per year. Therefore, there appears to have been a more than ten-fold increase in the mean yearly number of ML ≥ 4.5 main shocks during the period 1949–1983. Even if one assumes that some of the increase was because only about 50 per cent of the study area was covered in the earlier period, there would still be approximately a five-fold increase in seismicity if ML ≥ 4.5 main shocks are considered. This is clearly larger than would be expected from a Poisson process. Consequently, it is highly likely that the increase in the subset of ML ≥ 5.0 main shocks is also real and not an artefact of a Poisson process.

ML ≥ 4.0 earthquakes

The number of ML ≥ 4.0 main shocks also appears to have increased at around the same time, although not as obviously as for the ML ≥ 5.0 subset (Fig. 2). The mean annual number of events during the period 1904–1948 is 0.27. However, Table 6 shows that the mean number per year drops for the period before 1929, suggesting less complete reporting before then. This is probably because the wheat belt expanded geographically (Encyclopaedia Britannica, 1963) between 1905 and 1930, so that by the late 1920s the population in the area was enough for reasonably complete reporting. The mean annual number for the period 1929–1948 is 0.40, compared with 0.67 for the period 1949–1957. This indicates a 167 per cent increase in seismicity. These two periods are comparable, as both are earlier than the operation of a short-period vertical seismograph at Watheroo (31 March 1958 to 12 January 1959), which was superseded by the establishment of Mundaring Geophysical Observatory in 1959 (Everingham, 1968). The mean annual number of ML ≥ 4.0 main shocks during the period 1949–1983 is 0.80, compared with 0.40 for the period 1929–1948. This appears

Table 3. ML ≥ 4.0 main shocks: time intervals between events

Earthquake ID nos.	*Interval between earthquakes (d)*
1,2	571
2,3	306
3,4	1555
4,5	45.9
5,6	189
6,7	110
7,8	176
8,9	226
9,10	291
10,11	202
11,12	1089
12,13	57.5
13,14	75.4
14,15	710
15,16	946
16,17	131
17,18	426
18,19	119
19,20	305
20,21	354
	Mean = 394 days

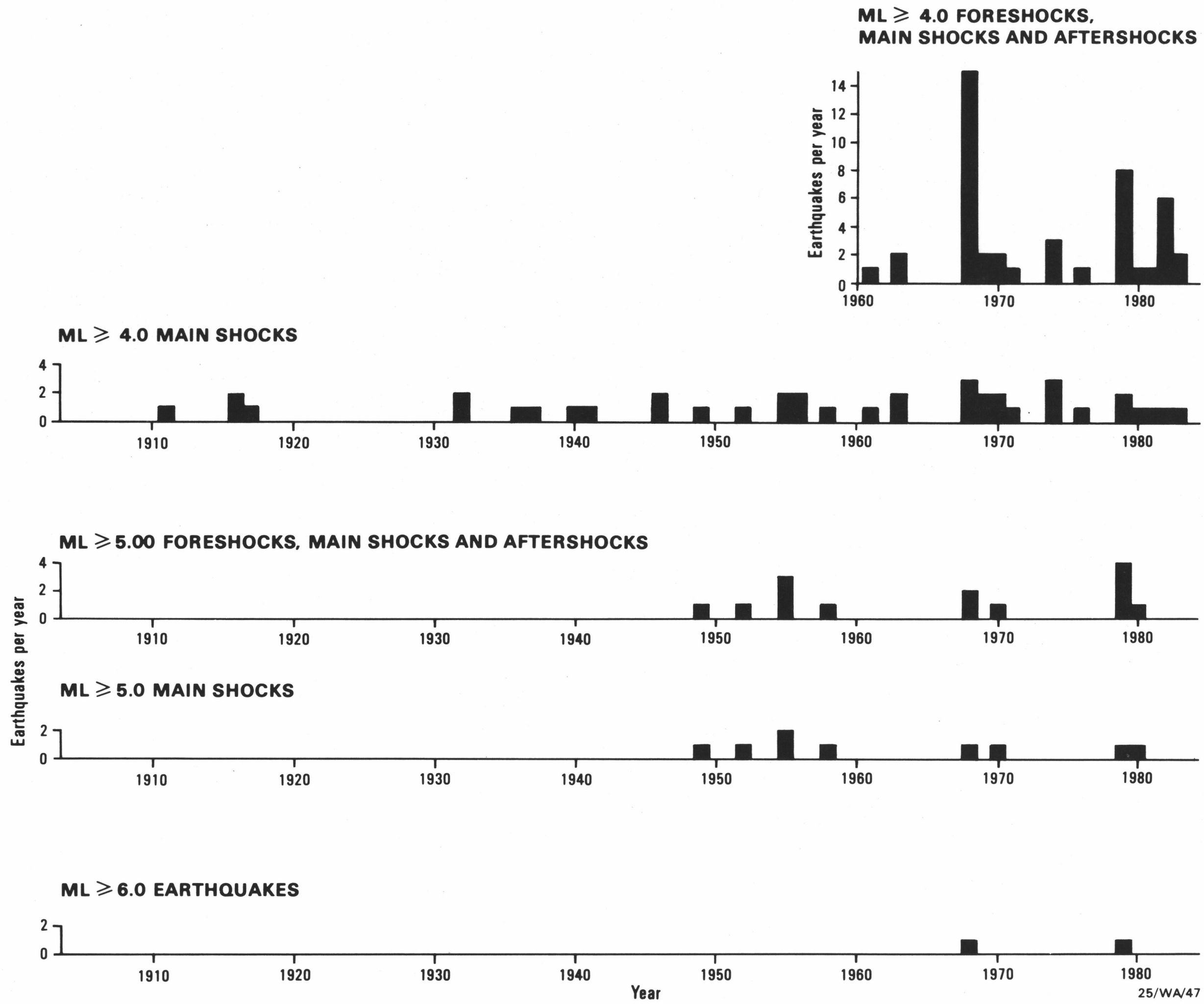

Figure 2. Variations in the yearly numbers of earthquakes in the area 30–33°S, 116–118°E.

Table 4. ML ≥ 4.0 main shocks, 1960–1983: test of fit of time intervals between events to a negative exponential distribution

Time interval (d)	*Observed no. of intervals*	*Expected no. of intervals*
0-113.5	4	5
113.6-273	6	5
273.1-545.9	5	5
546 +	5	5

df = 4.2 = 2, χ^2 = 0.4
The 10th and 25th percentiles are 0.21 and 0.58 respectively.
Therefore, χ^2 lies between the 10th and 25th percentiles.

Table 5. ML ≥ 5.0 main shocks: time intervals between events.

Earthquake ID nos.	*Interval between earthquakes (d)*
- 4, - 3	1044
- 3, - 2	1144
- 2, - 1	123
- 1,0	933
0,6	3861
6,9	512
9,16	3371
16,18	557
	Mean = 1443 days

to be a doubling of seismicity since 1949, but the data prior to 1958 are too uncertain to test this. However, the very large increase in the number of ML ≥ 4.5 main shocks (mentioned in the previous section) strongly suggests that the increase in ML ≥ 4.0 main shocks is also real.

ML ≥ 6.0 earthquakes

Data on these are complete probably from 1849 to 1984. There have been only two events during this period (Fig. 2). Although they occurred 10.7 years apart in 1968 and 1979, it is impossible to test with two events whether this represents an increase in seismicity or an artefact of a Poisson process.

Conclusions and implications for earthquake risk assessment

ML ≥ 4.0 earthquake data for the period 1960–1983, and ML ≥ 5.0 data for the period 1949--1983, do not fit a Poisson distribution if foreshocks and aftershocks are included.

However, if foreshocks and aftershocks occurring within one month of each other or of a main shock are excluded, there is no reason to reject the null hypothesis that the remaining sequence of main shocks can be represented by a Poisson distribution. Consequently, methods of earthquake risk assessment that rely on the assumption of a Poisson distribution should *not* be applied to the raw data.

The sequence of ML ≥ 5.0 main shocks from 1949 to 1983 and ML ≥ 4.0 main shocks from 1960 to 1983 appears to fulfil the criteria of completeness and having a Poisson distribution, necessary for most earthquake risk computations. However, it must be remembered that ML ≥ 4.0 foreshocks and aftershocks are potentially damaging

Table 6. Check on relative completeness of ML ≥ 4.0 earthquake data, 1904–1948.

Period	*No. of years*	*No. of events*	*Mean no. of events/year*
1944–1948	5	2	0.400
1939–1948	10	4	0.400
1934–1948	15	6	0.400
1929–1948	20	8	0.400
1924–1948	25	8	0.320
1919–1948	30	8	0.267
1914–1948	35	11	0.314
1909–1948	40	12	0.300
1904–1948	45	12	0.267

earthquakes that will have been omitted from the analysis. This should be clearly pointed out to users of the earthquake risk assessment (B.A. Gaull, BMR, personal communication).

Another property of the earthquake process that may not fulfil assumptions for earthquake risk calculations is that it does not appear to be stationary. Drawing conclusions from few data and probably incomplete historic reports for main shocks of ML ≥ 4.0 is risky, but the evidence for an increase in the numbers from about 1949 onwards merits serious consideration. It should be tested when more and better data become available. The increase in numbers of ML ≥ 4.5 and ML ≥ 5.0 main shocks during this period appears to be real.

If there has been an increase in seismicity, but only short-term, then using earthquake data from 1949 onwards will give conservative estimates of earthquake risk. However, if the increase is long-term, then assuming only two ML ≥ 6.0 events are likely to occur in 136 years or more may well underestimate the risk of these earthquakes.

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