COMMONWEALTH OF AUSTRALIA

DEPARTMENT OF NATIONAL DEVELOPMENT

BUREAU OF MINERAL RESOURCES, GEOLOGY AND GEOPHYSICS

REPORT No. 132

SEISMICITY OF WESTERN AUSTRALIA

BY

I. B. EVERINGHAM

Issued under the Authority of the Hon. David Fairbairn
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ILLUSTRATIONS

SUMMARY

The epicentres of 238 earthquakes that occurred in the Western Australian region during the period from August 1959 to the end of June 1965 have been determined. Most of these shocks were of a magnitude (M_L) less than 3.5 and occurred along a region of minor seismicity 500 kilometres long and 50 kilometres wide, which is located on the south-western part of the shield and which may be correlated with changes in geology, geomorphology, and gravity anomalies. It is suggested that this active zone where the changes occur be named the 'Yandanooka/Cape Riche Lineament'.

Instrumental and observational data collected since 1904 suggest that the most seismically active regions in Western Australia have probably been in the north-western part of the State (the Marble Bar area), the area along the Yandanooka/Cape Riche Lineament, and an area centred about 300 kilometres south-east of Carnarvon. Each of these areas is relatively close to the margin of the Precambrian shield, and earthquakes are scarce on the central part of the shield. Shocks have also occurred off the coastlines of the State on and beyond the continental shelf.

Isoseismals for an earthquake that occurred on the shield near Mundaring are shown; these may be used to estimate shaking effects of other shocks similarly situated.

1. INTRODUCTION

Before the installation of Benioff seismographs at Mundaring Geophysical Observatory in July 1959, only three earthquake epicentres in the region of Western Australia had been determined from instrumental data. Two of these earthquakes occurred in the Indian Ocean close to the continental slope. The other, which occurred at Meeberrie (about 350 kilometres south-east of Carnarvon) on 29 April 1941, ranks as the largest known Australian earthquake to date. Epicentres were listed by Gutenberg and Richter (1954, p. 225) and two of these were revised by Bolt (1959). Details of these earthquakes, plus two others that occurred to the west of the continent beneath the Indian Ocean, are given in Table 1; the epicentres are shown in Plate 1.

This laok of recorded seismic activity is not surprising in view of the lack of suitably equipped seismic stations and the fact that Western Australia forms the major part of one of the Earth's stable crustal masses, which are typically aseismic.

Macroseismic data on Western Australian seismicity are also rare. Clarke, Prider, and Teichert (1955, p. 171) published an isoseismal map of the 1941 earthquake (see Plate 5B), and Jaeger and Browne (1958) indicated places in the south-west of the State at which minor earth-movements were reported. The latter authors used unpublished data of Carrigy and Main, gathered to a large extent from files of the Perth Observatory, which had received numerous reports of minor earthquakes since 1904 (Table 5). Several earthquakes were recorded by the long-period instruments in use at Perth Observatory; by plotting isoseismals, Carrigy and Main located epicentres of three of these near Bolgart (March 1952), Calingiri (April 1955), and Yericoin (August 1955) respectively.

Since routine seismological recordings have been made at Mundaring much more information has become available, and it is now possible to locate the epicentres and estimate the magnitudes of earthquakes. For convenience, these earthquake data are divided into two groups depending on the magnitude of the earthquake.

Details of all the larger recorded shocks with magnitude 3.5 or greater are given in Table 2. Epicentres, where determined, are plotted in Plate 1. These shocks could be damaging and would probably be felt in populated areas; many of them were recorded at several Australian seismological stations.

Table 3 lists all shocks with magnitude less than 3.5 for which an epicentre was determined. Plates 2A and 2B show the positions of these smaller shocks. Most of these shocks had no effects that could be observed without instrumental aid and would be recorded only locally, by seismographs within about 300 kilometres of their epicentres.

In this report the principal facts known about the seismicity of Western Australia prior to 1965.5 are discussed and their derivations presented.

Thanks are due to the Directors of the Perth Observatory for supplying all their available data and for helpful discussions on the subject of this report.

2. MUNDARING DATA

General remarks

With a three-component instrument at Mundaring (details have been given by McGregor, 1966) it was possible to obtain the bearings of epicentres of local earthquakes by measuring two horizontal components of ground motion of the P-phase, the sense being given by the vertical movement. Epicentral distances were calculated by measuring arrival time differences between easily identifiable phases such as Pn, Sn, P1 (or Pg), S1 (or Sg), Lg, and LR. Recordings of typical near-earthquake phases are shown in Plate 4. When employing bearing and epicentral distance measurements to locate epicentres, inaccuracies may result from the assumption of the depth to the hypocentre, the assumption of travel-time curves, and errors in the measurement of the bearing. Data recorded at only one station are not generally relied on. However, for many of the shocks recorded at Mundaring such data had to be used, and, for reasons given later, the accuracy was better than would normally be expected.

Most of the local tremors shown in Plates 2A and 2B were located from single-station data. The more accurately located epicentres have an estimated accuracy of better than about ten percent of the distance from Mundaring; the less accurate epicentres have an estimated accuracy of better than about twenty percent of the distance from Mundaring. Results obtained from a tripartite network operated during the latter half of 1963 were also employed to determine epicentres, and helped to confirm the accuracies quoted above.

For larger shocks recorded at other Australian seismological stations, results from all stations were used to locate the epicentres. The phases Pn, Sn, and Lg were generally well recorded and, by successive approximations, epicentres and origin times were found to fit all recorded phases. Positions located in this manner were, in every case, in reasonable agreement with the result obtained using the Mundaring data alone. About half the shocks shown in Plate 1 were located by these single-station data.

During the period from August 1959 to the end of June 1965, larger shocks occurred on 18 June 1961, 18 January 1963, 23 March 1964, and 19 May 1965. These were recorded at a sufficient number of stations for preliminary epicentres to be determined by the United States Coast and Geodetic Survey (USCGS). The listed epicentre of the 23 March 1964 shock was redetermined by USCGS using 15 stations with epicentral distances in the range 25^{o} to 85^{o}. Results from closer stations were neglected to avoid the effects due to the J-B travel times for Pn waves being incorrect for Australian conditions. PKP residuals indicated a shallow depth for this shock. Using tentatively revised travel times Sutton and White (1966) subsequently computed an epicentre for this shock 30 miles west of the USCGS epicentre.

In addition to the larger shocks referred to above, another (34B) was large enough to be recorded at most Australian stations but no preliminary epicentre was determined by USCGS. However, D.J. Sutton and R.E. White of Adelaide University kindly computed a provisional epicentre and origin time which are listed in Table 2.

Epicentres shown as having higher accuracy in Plate 1 are probably situated within one hundred kilometres of their indicated position, and those with lesser accuracy within two hundred kilometres. Errors were mainly due to the measurement of bearings, and epicentres are most accurate for shocks close to Mundaring or where several stations were used in their determination; for example, the accuracy of epicentres determined by the USCGS is about 30 kilometres and of those nearest Mundaring about 10 kilometres. Although the overall accuracy of epicentre locations is not great it is sufficient for a reconnaissance of seismic activity in Western Australia.

Depth of focus

A surface focus was assumed for the minor shocks listed in Table 3. When the P1-S1 travel-time differences are used to calculate the epicentral distance, its error due to the assumption of a surface focus is less than two kilometres if the hypocentre is at a depth less than 15 kilometres.

That the shocks were probably shallow is indicated by:
(a) the similarity between the character of the waves generated by them and by quarry blasts (see Plate 4); (b) the fact that many of the smallest tremors were heard or felt over a very limited area; and (c) the P1-Pn and S1-Sn travel-time differences, i.e. the Pn-P1 and Sn-S1 cross-over distances, decrease with focal depth. With a surface focus, the cross-over point beyond which the upper-mantle waves arrive first is approximately 250 kilometres.

In calculating the origin times and epicentral distances for shocks with magnitudes 3.5 or greater, where a depth is not listed in Table 2, an 18-kilometre focal depth was assumed because small earthquakes in other stable continental areas most commonly occur within the crust at depths of this order (see e.g. Cleary & Doyle, 1962).

Travel-time curves

Travel times employed in the epicentre determinations were based on a crustal thickness of 36 kilometres and the following velocities:

Phase	P1	S1	Pn	Sn	Lg
Velocity	6.25	3.6	8.23	4.75	3.50 km/s

The selection of the above P and S travel times was based on measurements of P1, S1, Pn, and Sn velocities made on the south-eastern parts of the Australian Shield by Bolt, Doyle, and Sutton (1958) and Doyle and Everingham (1964). The velocity of the Lg phase was determined by Bolt (1959) and by Cleary and Doyle (1962). Preliminary investigations of crustal and upper mantle velocities around Mundaring (Everingham, 1965a) indicate that errors involved in using the values selected above are small.

Earthquake records were examined for the phases from intermediate crustal layers (P2 and S2) with velocities between those of the upper crustal layer and Pn or Sn. Phases that could be interpreted as P2 or S2 were recorded from shocks in the extreme south-west of the State and from a rock-burst at Kalgoorlie, but generally they are not apparent on recordings from earthquakes on the shield.

A short-period LR phase was frequently well recorded, particularly from distances less than 200 kilometres (see Plate 4). Dispersion was noticeable and velocities ranged from about 3.0 km/s at a period of 0.8 second to 3.2 km/s at a period of 2.5 seconds. This phase was very useful for interpretation of records from shocks with epicentral distances less than 300 kilometres.

Measurement of brearings

Considerable errors may occur in the bearing of an epicentre measured from seismograms if the seismograph is uncalibrated or if there are appreciable velocity changes in the rocks between the epicentre and the seismograph. However, the latter effects are thought to be small in the case of the Mundaring data because the seismograph is situated in an area of outcropping granite and gneiss, whose velocities would not differ greatly, and the earthquakes presumably occur in similar basement rock. Also, the instruments were calibrated and the accuracy of the bearings is believed to be almost entirely limited by the accuracy of reading the amplitude of the P-phase impulses. This conclusion was reached because, when clear impulsive P-phases were used, accuracy was proved for measurements of azimuth to (a) distant, known earthquake epicentres, (b) local shocks located by a temporary network of stations, i.e. Mundaring, Grass Valley, and Narrogin, and (c) local quarry blasts.

Inability to locate epicentres was most often caused by inability to measure the bearing because the initial P-phase impulses were too small to measure.

It may be seen from Table 3 that for epicentral distances of 70 to 100 kilometres, the minimum magnitude (M_L) for which bearings could be ascertained is about 2.0. Numerous tremors with smaller magnitude (as low as about 0.5) were noted on the seismograms, but only their epicentral distance could be measured.

Magnitude determinations

The methods of determining the magnitude of an earthquake are well known and have been described by Gutenberg and Richter (1956). The original Richter magnitude, M_L, was given by maximum trace deflections of standard Wood-Anderson seismographs and could be used for epicentral distances (Δ) up to 600 kilometres. To apply this scale to distances greater than 600 kilometres, a new magnitude, M_S, was defined by comparison of earthquakes recorded on the Wood-Anderson and long-period seismographs. M_S can be determined from the maximum amplitude of horizontal components of ground motion of surface waves with a period of 20 seconds, and is useful in the range 20° to 180°. For less than 20°, 20-second surface waves are seldom observed, so that M_S is not defined and a gap is left for magnitude determination between 6° and 20°. An extrapolated curve to cover this gap was published in the form of a nomogram by Gutenberg and Richter (1942) and is used extensively for magnitude determinations at present.

The next step was to use P waves for magnitude determinations. Gutenberg and Richter (1956) found the relation

$$m_B = 0.63\ M_S + 2.5 \qquad \text{..........}\ (1)$$

where

$m_B = A_2 + \log (A/T)$

$A_2 = f\ (h, \Delta)$, an empirical attenuation function

A = amplitude of P wave in microns

T = period of the motion in seconds

h = depth of hypocentre

The term A represented the maximum ground motion. The function A_2 could be replaced by other functions when A refers to phases S or PP.

The unified magnitude, m, was than defined as a weighted mean taken between m_B as determined directly from body waves and from M_S via Equation (1). Alternatively, the unified magnitude M is often used, it being related to m by analogy with Equation (1).

During 1963 the USCGS commenced routine magnitude determinations with their preliminary epicentre determinations. They determined m_b, which differed from m_B in that

(a) The trace motion is always measured from seismograms of short-period instruments

(b) Measurements are restricted to P waves only

(c) For practical purposes the USCGS required measurements of the first few cycles of P or Pn, whereas for Gutenberg and Richter's unified magnitude the maximum amplitudes are measured.

At shorter distances, where Pn is the first arriving phase, attenuation curves for m or m_b determinations vary because crustal and upper-mantle variations affect attenuation properties. Thus Gutenberg and Richter's curves for A_2 can be applied to California shocks but not necessarily to those in Western Australia. Accordingly, for epicentral distances less than 25^o a provisional curve for A_2 was assumed for shocks that occurred in Western Australia.

Limited evidence derived from several shocks recorded at other Australian stations, as well as at Mundaring, indicated that for shallow Western Australian earthquakes the attenuation effects due to an upper-mantle low-velocity zone found by Gutenberg and Richter were too large; therefore the tentative curve for A_2 adopted for the Western Australian shocks is a smoothed version of their curve. The values for A_2 used for magnitude determinations in this report and Gutenberg and Richter's figures are as follows:

Δ (km)	Phase	A2 Mundaring	A2 Gutenberg and Richter
50	P1	0.7	
100	"	1.3	
200	"	1.9	
250	Pn	2.5	
500	"	3.2	(2.6)
750	"	3.6	4.0
1000	"	3.9	4.3
1250	"	3.9	4.3
1500	"	3.6	3.9
1750	"	3.3	2.9
2000	Pn?	3.3	2.9
2500	P?	3.6	3.3
3000	P	3.6	3.6

For values of Δ>3000, Mundaring A_2 values are the same as those of Gutenberg and Richter.

For an epicentral distance of 100 kilometres, A_2 was determined firstly by equating M as derived from m_b with M as derived from M_L (see below for M versus M_L values), and secondly, by equating m_b (MUN) with m_b (distant stations).

At very short distances, the slope of the A_2 (P1) curve was drawn for attenuation varying as the square of the epicentral distance. Near the point where Pn becomes a first arrival it has been found that this phase usually has about half the amplitude of the Pg phase. Accordingly, the curve for A_2 (Pn) was commenced at a point 0.3 above the curve for A_2 (P1) at an epicentral distance of 250 kilometres, and was interpolated over the range 250 to 700 kilometres, where it continued into the smoothed version of the Gutenberg and Richter curve.

It is emphasised that the A_2 curves used at Mundaring are provisional curves employed as a starting point for magnitude determinations using Pn waves and will need future revision when more Australian earthquake data are available. Results to date indicate that for epicentral distances less than 2000 kilometres the values of A_2 used are too high by about 0.4.

The arithmetic mean maximum amplitude of the horizontal components of the S-phase was the basis for the determination of M_L. At epicentral distances greater than about 250 kilometres, the S1 and Lg phases were prominent with amplitude generally about three times that of the earlier S-phases. The latter were measured to obtain the magnitude.

For larger shocks, M (derived from the unified magnitude m) and M_L are approximately equal, but for shocks with M_L less than 6 they differ substantially. Gutenberg and Richter (1956, p. 4) found the following relation:

M_L	3	4	5	6
M	(2.4)	(3.6)	4.7	5.8
m	(4.0)	(4.7)	5.4	6.1

(Values in brackets are outside observable ranges)

From a comparison of M_L and M_S (using limited data), it appears that, when M_L is calculated using epicentral distances less than about 800 kilometres, the two magnitudes are related in a similar manner to M_L and M, whereas for epicentral distances greater than 1300 kilometres, there is a discrepancy of approximately 1.3 units, with M_L too great. Thus values of m include values derived from M_L only for epicentral distances less than 800 kilometres. (The M_L referred to was obtained from the maximum amplitude measurements of S-waves arriving prior to Lg and by using the nomogram of Gutenberg and Richter, 1942).

As far as magnitude determinations are concerned, earthquakes that have occurred in Western Australia fall into three main categories: (a) those which occur within 600 kilometres of Mundaring and for which M_L may most reliably be determined; (b) those which are recorded at Mundaring only, occur at distances greater than about 600 kilometres, and for which m_b may be determined from assumed values of A_2 and M_L from Gutenberg and Richter's (1942) extrapolated curve; and (c) larger shocks which are recorded at other stations and for which m_b, M_S, and M_L are possibly measurable. The majority of shocks are in the first two categories and rely on estimates of magnitude made from Mundaring seismograms.

The epicentres of shocks with $M_L \geqslant 3.5$ are listed in Table 2 together with the magnitudes of M_L, m_b, and M_S. Also listed is m, the unified magnitude. Values of m_b for all stations were derived from the assumed Mundaring A_2 curve for epicentral distances up to 3000 kilometres. The values of magnitude will need revision, and the recently installed, carefully calibrated stations included in the World-wide Standardised Seismographs network (W.W.S.S.) should provide such data with high quality.

Epicentres of smaller shocks having $M_L < 3.5$ are listed in Table 3. The unified magnitude was not calculated as these shocks are all in the distance range where M_L is most accurately determinable.

When considering Plate 1 it should be noted that epicentres of shocks with $m < 5.0$ would probably not be determined for the northern half of Western Australia (epicentral distances greater than 1000 kilometres) because of P-wave attenuation. On the other hand, shocks with $m > 5.3$ would almost certainly be locatable wherever they occurred in the State. For smaller local shocks such as those presented in Plate 2, epicentres could be determined when the epicentral distance is 100, 200, and 400 kilometres if the magnitude M_L were at least 2.0, 3.0, or 4.0 respectively.

Isoseismal map

On 18 January 1963 an earthquake was felt over an area centred about one hundred kilometres east-south-east of Mundaring. Subsequently macroseismic data were collected. The shock was recorded by other Australian stations and a preliminary epicentre was determined by the USCGS.

Information about the shock is of particular interest because it may be used to estimate the shaking effects of other shocks in this area and because it bears on the assumptions and accuracy of the Mundaring methods. It was possible (a) to estimate the focal depth, (b) to check by macroseismic data the epicentre derived from Mundaring seismograms, and (c) to compare preliminary routine USCGS results with Mundaring results. Details of the shock determined by Mundaring and the USCGS are:

	Origin time (GMT)			Depth (km)	Epicentre Lat. (S)	Epicentre Long. (E)
USCGS	05	49	18.4	35 ± 25	32.0°	117.1°
Mundaring	05	49	16.8	18	32°15'	117°10'

In order to study the macroseismic effects, two hundred questionnaires on earthquake intensity were distributed from Mundaring; replies were received from about three-quarters of these. Plate 5 shows the isoseismal map based on these data. The region of maximum intensity (MM 7) at a farm at Nourning Spring was coincident with the epicentre determined from Mundaring instrumental data and was approximately 28 kilometres south-east of the USCGS epicentre.

Using the macroseismic data, a depth was estimated from the empirical formula of Blake (1941):

$$J - j = -s \log_{10} \cos \Theta \; ; \; \Theta = \tan^{-1} (Rj/h),$$

in which J is the maximum intensity, Rj is the radius of the area enclosed within isoseismal J, h is the depth of focus, and s is an empirical constant (5.35). Using six different radii, the mean determined depth was 17 kilometres. Also, very clear pP phases were recorded at Charters Towers (pP-P = 4.0 seconds) and Adelaide (pP-P = 5.0 seconds). These phases indicate a focal depth of about 19 kilometres, which is in excellent agreement with the other results.

3. MISCELLANEOUS DATA

Watheroo recordings

During the period 31 March 1958 to 12 January 1959 a vertical component short-period seismograph was operated at BMR's Watheroo Magnetic Observatory (Everingham, 1958), now closed down and replaced by Mundaring Geophysical Observatory.

Loval earthquakes recorded at the station are listed in Table 4. Because Watheroo was a single-component station, and on no occasion did other stations simultaneously record the local shocks, it was not possible to determine epicentres of earthquakes. Therefore only distances from the station are shown. Magnitudes, although determined from vertical ground movements, are approximately equivalent to those determined at Mundaring using horizontal motions because it has been found that the vertical motion usually about equals the mean horizontal movement.

Earthquakes were most frequently recorded at an epicentral distance of 240 to 250 kilometres, and the epicentres of these are probably in the active Beverley/ Brookton region. The two shocks with epicentral distance 1150 kilometres possibly occurred in the Marble Bar/Port Hedland area, and the remainder in the active zone south-east of Watheroo.

Perth Observatory files

Table 5, 'Western Australian earthquake record and damage from 1904', is based on a list compiled by Perth Observatory. Several minor modifications were made to the original list as a result of close examination of their newspaper cuttings and files of reports from people who felt earthquake effects. A few remarks about recent shocks have also been added. Some of the Perth Observatory data had been collected from files of the Commonwealth Bureau of Meteorology, which often received reports of earthquakes. Included in this table is the description of the greatest recorded damage for a Western Australian shock, namely that suffered by Meeberrie Station during the April 1941 earthquake. The station is situated 10 kilometres south-west of the position of the epicentre calculated by Bolt (1959).

Because it is the only existing list of effects that were possibly due to earthquakes in Western Australia prior to the installation of high-gain short-period seismographs, Table 5 is of historical as well as scientific interest.

It is recognised that reports collected from an area of unevenly distributed, sparse population, such as Western Australia, can be misleading. However, much information can be gained by an overall appreciation of the data. For example, the single report of 31 May 1913 'Perth - a Mr X at Mrs Y's house, St George's Terrace, felt shaking of house at 4.10a.m. again at 5.30 a.m.' is meaningless in the seismic sense, whereas the frequent reports from the Marble Bar region describe typical earthquake effects and indicate that the region has been seismically active since the early 1900s.

The towns from which possible earthquake effects were reported are shown in Plate 3. In cases where several districts reported earthquake effects at the same time, the most central township is plotted.

Also included in the Perth Observatory files was an isoseismal map of the April 1941 shock, which was drawn by the Dominion Observatory, Wellington. Although this map has been published previously, first by Clarke, Prider and Teichert (1955) and subsequently by Bolt (1959), it is reproduced here, in Plate 5B, so that all the available data on Western Australian seismicity may be found in a single publication.

4. REGIONS OF SEISMIC ACTIVITY

General remarks

Reliable accounts of earthquake effects have consistently come from several regions since 1904, and it is apparent (compare Plates 1 and 3) that recently recorded earthquakes have for the most part occurred in these regions of past activity.

Inhabitants of the Marble Bar area and the Brookton/Walebing area have been the most frequent reporters of earth tremors during this period, and in view of the fact that the Marble Bar area has a very low population density it is probably the most seismically active area in the State. This active zone is not well defined but apparently has a north-westerly trend roughly parallel to the southern margin of the Canning Basin.

The activity of the Brookton/Walebing area, relative to other regions, is exaggerated because of the higher population density, and a shock is far more likely to be noticed and commented on here than in more eastern and northern areas. Moreover, more shocks have been instrumentally recorded from this area because of its proximity to Mundaring Observatory, with the result that in both Plates 1 and 3 the seismic activity is accentuated.

Other fairly well defined regions of activity occur in an area near Broome, in the region of Meeberrie, and on the south-western continental slope and shelf near Cape Leeuwin.

Shocks distributed along the western continental margin, such as the May 1965 earthquake west of Carnarvon (Table 2, No. 46), may have been more common prior to 1959 to account for the previous observations at Onslow and Geraldton.

The earthquake numbered 34B evidences an active area in the Wyndham/Turkey Creek area. Reports from this area describe effects lasting for several seconds only, and indicate that minor tremors have often occurred there. Further evidence of activity in this region became available early in 1967 when a seismograph at Kununurra recorded several shocks within 100 km of that township.

Two earthquakes recorded at Mundaring (Table 2, Nos. 9 and 22) were possibly located east of Kalgoorlie near the margin of the Eucla Basin, and although it was not possible to determine with certainty whether the epicentres were east or west of Mundaring, the presence of the Lg phase indicated a continental path from the east.

Credible reports of earthquakes have originated from the Ravensthorpe/Balladonia area, but the effects have been felt over a wide area and the shocks may have occurred off the south coast. Shocks felt at Northcliffe, Albany, and other places in the south also may have occurred beneath the ocean to the south.

Tremors that have been reported at major mining towns (e.g. Cue and Kalgoorlie) may have been sudden earth movements (commonly referred to as rock-bursts) caused by the release of accumulated strains resulting from the large-scale mining operations. The shocks in July 1964 and October 1962 (Table 2, Nos. 42, 26, and 27) were probably due to such movements at the Wittenoom Gorge asbestos mine, and on 22 October considerable damage to the mine occurred. The first suspected rock-bursts to be recorded at Mundaring from the Kalgoorlie region occurred in February to March

ERRATUM

On page 13, Equation (2) should read:

$$\log N = (3.9 \pm 0.1) - (1.0 \pm 0.03)M_L$$

1964, the magnitudes (M_L) being in the range 2.5 to 3.9 (e.g. Table 2, No. 38). Subsequent recordings by a seismograph installed at Kalgoorlie (November 1964) and observations within the mines suggest that earth-movements frequently occur in the mined area.

Earthquake frequency

Some idea of the probability of earthquakes within a given magnitude range was ascertained for the active region, about 500 kilometres long and 50 kilometres wide, on the south-western part of the shield closest to Perth. By using the data for the entire active region for the period August 1959 to June 1965 the following relation was determined:

$$\log N = (4.1 \pm 0.1) - (1.0 \pm 0.03)\, M_L \quad \ldots\ldots\ldots\ldots (2)$$

where N is the number of shocks per year with magnitude M_L or greater.

In the above region one earthquake per year could be expected to happen with M_L greater than 4.0 (the smallest likely to cause damage), one every ten years with M_L greater than 5.0, or one every 1000 years with a magnitude greater than about 7.0 (such as the 1941 Meeberrie shock, which would probably have caused extensive damage if it had occurred in a densely populated area). However, earthquakes studied were in the range M_L = 2.3 to 4.9 and there is no evidence to suggest that shocks with M_L much greater than about 5.0 have yet occurred in the area studied.

The approximately linear relation between magnitude and the logarithm of the earthquake frequency holds elsewhere, but the constant term that indicates the degree of activity is considerably lower here than for other regions, e.g. southern California and New Zealand (Richter, 1958, p. 360). Earthquakes are therefore far less frequent in the south-west of Western Australia than in Southern California or New Zealand.

Activity for the entire State is not easy to assess for two main reasons: firstly, smaller shocks are not recorded from larger epicentral distances, which means that smaller shocks from areas such as Broome are not recorded consistently; and secondly magnitude values for shocks from epicentral distances greater than 600 kilometres are difficult to standardise. However, by using only the larger shocks shown in Plate 1, with the exception of the 1906 and 1934 Indian Ocean shocks, a figure of 5.2 was derived for the constant term in Equation 2. This indicates that the total activity in Western Australia is about thirteen times that in the south-western shield zone; hence the level of activity at one or more of the individual regions of seismicity must exceed the level in the south-west region, as there are only about six active zones.

It has been said that a fifty-year period is equivalent to 'a tick of the geological clock', and the above earthquake frequency figures should be considered in this vein. Seismic activity increases and diminishes with periodicities yet to be determined, so values for the constant term in Equation 2 need not be truly representative for very long periods, although historical evidence does suggest that the activity has not changed appreciably in the past sixty years.

Relation to geology

The majority of earthquake epicentres are off the coastlines of Western Australia and in the vicinity of the Western and north-western margins of the Precambrian shield. There appears to be negligible activity on the central shield areas. The South Australian shatter zone, along the eastern margin of the shield near longitude 138°E, is the nearest known seismically active zone to the east.

Of seismicity marginal to stable masses, Gutenberg and Richter (1954, p. 80) state:

> 'Nearly all the stable masses exhibit marginal fractures which are seismically active. Some of these are rift zones, but appear to be different in character from those discussed under that heading. Such are the St Lawrence Valley and the shatter zone of Australia. There are no extended seismic belts in this class, and very irregular minor seismicity. The pattern is that of occasional large shocks, sometimes in groups separated by long intervals of quiet. All these shocks are shallow, though some are deeper than average'.

The majority of inland shocks shown in Plate 1 would fall into this category. Shocks such as those about 150 kilometres east of Perth indicate active fracturing within the stable mass, but none of them was farther than about 150 kilometres from the shield margin and, regionally, they are considered to be associated with the margin.

Epeirogenic uplift of the Western Australian shield occurred in Tertiary time (Jutson, 1934, p. 195) and the marginal activity indicates that adjustment is still taking place despite the fact that the region is very nearly isostatically compensated. It is interesting to note that to the east of the very stable shield the most active regions are associated with the Adelaide and Tasman Geosynclines, where vertical Tertiary movements also occurred.

Earthquakes on and near the continental slope may indicate faulting or slumping at the continental edge whilst others beneath the deep ocean could be associated with uplifted regions of the ocean floor where epeirogenic movements are possibly taking place. Examples of the latter are the shocks on a slight rise of the ocean bottom extending south from Albany (Table 2, Nos. 13 and 20) and shocks on pronounced rises to the north-west of Carnarvon (the 1906 and 1934 shocks, Table 1). The region to the north of Carnarvon, where the continental shelf is narrower than elsewhere in Australia, is considered to have been very unstable during the Tertiary Period (BMR, 1960), and shocks along the north-western continental margin (e.g. Table 2, No. 46) indicate that the instability may still exist.

The epicentres near Broome and 200 kilometres south-east of Carnarvon (Table 2, Nos. 39 and 34) are unusual in that they are located within sedimentary basins. The accurately located shock near Broome is in the Canning Basin on the northern flank of the Broome Swell, which trends west-north-west and lies between the Fitzroy Valley to the north and the Canning Plain to the south (Veevers & Wells, 1961). Earthquakes in the same general area but on the continental shelf west-north-west of Broome could be associated with upwarps trending north-west, such as the Leveque Rise, which extends seawards from the Fitzroy Valley region (Veevers & Wells, 1961, Plate 3).

The pattern of shocks south of the Canning Basin is uncertain owing to the inaccuracy and scarcity of epicentre determinations. The most accurate epicentre, 75 kilometres east-north-east of Port Hedland (Table 2, No. 11), is on the southern margin of the Canning Basin, whereas other epicentres to the south-east of Port Hedland (Table 2, Nos. 29 and 30) are definitely on the shield to the south of the basin.

Because major negative gravity anomalies exist over the Perth Basin area and the region is isostatically unbalanced, the question often arises 'do earthquakes occur along the margins of the basin?' The present answer to this query is that there is no definite evidence that earthquakes have occurred along the faults associated with this structure. Earthquake epicentres to the south-east of Carnarvon are about 50 kilometres east of the northern extremity of the Darling Fault and apparently occur in a north-trending zone near the eastern unconformable margins of the Byro Basin to the north and the Badgeradda Syncline to the south near Meeberrie.

Nothing has been said of the tectonic implications of the seismicity in the region across the south-western corner of the shield, where the epicentres of eight larger shocks have been determined (Table 2, Nos. 12, 17, 28, 31, 36, 41, 43, and 44). Because of its proximity to research facilities in Perth, the area mentioned is better known geologically and geophysically than some other areas, and it is possible to show that the zone of seismicity probably marks a region with a history of recurring tectonic events. The region is discussed below in detail.

5. ZONE OF SEISMICITY ACROSS THE SOUTH-WEST OF WESTERN AUSTRALIA

General remarks

Several hundred local earthquakes were recorded at Mundaring in the period August 1959 to the end of June 1965. Of shocks whose epicentres were located, 210 were of magnitude (M_L) less than 3.5. All but five of the 210 shocks occurred in the active zone that runs in a north-north-westerly direction parallel to geological trends across the south-western part of the State (Plate 2A). For convenience, this active region will be referred to as Zone A. Eight earthquakes of magnitude 3.5 or greater also occurred in the zone during the above period. Activity was spasmodic, with occasional groups of earth tremors followed by periods when no tremors were recorded. Up to 30 earth tremors with magnitude greater than 2.0 have occurred in Zone A on one day (25 June 1961). The overall frequency of the earthquakes is discussed in the previous section.

In the region shown in Plate 2A, seismic activity is almost entirely confined to Zone A, and very few earthquakes have been recorded from other active regions, such as those near Cape Leeuwin and possibly around Perenjori and Mukinbudin (see Plate 3). One unlisted shock (14 May 1962) was weakly recorded at Mundaring and felt at Albany. The calculated epicentral distance indicated that the shock was north of Albany, but whether or not it occurred along the southern projection of Zone A could not be ascertained.

Plate 2B shows the most active region of Zone A, where over eighty percent of the minor tremors have occurred. The tremors happen near the eastern boundary of a tongue of granite, which is part of the eastern margin of an extensive area of granite that crops out as far west as the Darling Fault (Wilson, 1958, geological map). In the area shown in Plate 2B, the general geological trend is roughly north-south although the foliation in the granite is variable. The fact that the trend of the active area as mapped is north-north-east may not be significant because a small decrease in the range of bearings measured would make the active area roughly circular, i.e. errors in the measurement of bearings from Mundaring could give an apparent north-north-east trend. The general coincidence of Zone A with large-scale geological features is discussed below.

The importance of Zone A was previously noticed by Carrigy and Main, who located three epicentres from macroseismic data and plotted towns that had reported earth-movements. On the basis of Perth Observatory data, these authors also postulated other zones of seismicity in the south-west of the State (Jaeger & Browne, 1958); however, there is no instrumental evidence for these zones, and their reality is considered to be doubtful. A paper written by Carrigy and Main remains unpublished.

The coincidence of Zone A with other crustal features suggests that this seismically active zone represents the junction of two geological provinces. These features are demonstrated in Plate 6 and will now be discussed.

Present topography

Zone A lies along the common margin of two natural divisions, namely the South West Division and the Salt Lake Division (Jutson, 1934, pp. 75 and 99). Although both divisions are on the shield plateau, the topography changes in the vicinity of the active zone. To the east is the monotonously flat area of salt lakes, whereas to the west the topography is more rugged, the area being traversed by rivers which are generally mature and which trend in a north-north-west direction at their headwaters in Zone A, but which have more youthful and westerly-trending valleys in their mid-course to the west of Zone A.

Change in grade of matamorphism

The most active region within Zone A is near the margin of a granite body; other active regions are in areas of gneiss outcrop. There appears to be no general distribution of tremors along local geological structures. However, there are regional features of the geology which do coincide with Zone A as a whole.

On Wilson's (1958) tectonic sketch map of the Precambrian area in the south-west of Western Australia, areas of charnockitic rocks are shown. These charnockites indicate regions where a very high grade of metamorphism has taken place, and it is notable that the boundary of one such region roughly coincides with the western edge of Zone A. Wilson (1958, p.81) suggested that a fault possibly separates the granitic rocks of the Darling Range from the high-grade gneisses that are common to the east of a line joining towns in the active zone - namely New Norcia, Bolgart, Northam, York, Brookton, and Wagin.

Whether or not other boundaries of the charnockitic terrains are seismically active is not yet established because shocks with small magnitude could be too distant to be recorded. To date, no larger shocks have been noted from such regions, and activity, if any, must be at a considerably lower level than along Zone A.

Gravity results

In regions around Zone A, gravity observations have been made by Thyer and Everingham (1956) and Everingham (1965b). Plate 7 is a sketch of the Bouguer anomalies over the south-western areas of Western Australia.

Bouguer anomalies east of Zone A range frm -40 to -60 milligals, whereas over the extreme south-west of the shield the anomalies are generally more positive and in the range O to +20 milligals. The general rise in gravity values takes place across Zone A, and the -20 milligal contour, which is the average between the extreme anomalies of +20 and -60 milligals, extends through the whole length of Zone A.

The more positive gravity anomalies to the south-west are believed to be caused by changes in deep crustal structure (Everingham, 1965a and b) and the gravity data suggest that this suspected change is centred along the zone of seismicity.

Regional changes in metamorphism (discussed above, and also by Prider, 1945), in the composition of granites (Wilson, 1958, p. 69), and in mineralisation (Hills, 1953, p. 41) roughly parallel the gravity changes and could also be related to deep crustal structure and the zone of present seismic activity.

Features along the projection of the zone of minor seismicity

Another feature of Zone A is that its projection to the north-west cuts the Darling Fault at a region near Yandanooka where:

(a) Vertical displacement at the Darling Fault since the earlier Palaeozoic is small compared with regions to the north and south.

(b) The Darling Fault has a sudden change in trend from about a northerly to a north-north-westerly direction.

(c) The Urella Fault Zone is parallel to the Darling Fault, and the vertical displacement there since the early Palaeozoic is about equal to that of the Darling Fault farther to the south.

(d) The trend of the Darling and Urella Faults is parallel to the trend of Zone A.

Another interesting area associated with Zone A is in the vicinity of Cape Riche where the southerly projection of Zone A crosses the continental shelf. A zone of negative anomalies trending from this area to the west strongly suggests that an orogeny occurred across the southernmost part of the shield during Precambrian time. In the unsurveyed area off-shore from Cape Riche this orogenic zone may terminate, cross the continental margin, or swing north-east to merge with the Fraser Range structure, which trends north-east. In any event, the region is of particular tectonic importance and its relation with Zone A is notable.

Conclusions

It could be argued that the association of any of the above features with the zone of seismicity is extremely doubtful; e.g. the natural divisions may be purely a function of climates. However, the fact that all these changes should occur in a fairly restricted area of the State seems more than coincidental, and it is most simply explained by a regional crustal change.

In the region of Zone A the change in metamorphic grade, the south coast orogeny, and the cause of the more positive gravity anomalies are features of Precambrian age; the Urella Fault was active at least during the Mesozoic era; the topographical features are possibly caused by comparatively recent tectonic events, and stresses are apparently still present.

Therefore in view of these factors it is reasonable to assume that the zone of seismicity has been a region of tectonic importance throughout geological time and that it delineates two Precambrian provinces with significantly different crustal features.

It is suggested that henceforth the name 'Yandanooka/Cape Riche Lineament' be used for Zone A and its associated features.

6. CONCLUSIONS

A recapitulation of ideas on the seismicity distribution can point to but one conclusion: that knowledge to date is insufficient for specific interpretations of the seismicity pattern, except perhaps along the Yandanooka/Cape Riche Lineament, and even there investigations have barely 'scratched the surface'.

A greater number of more precisely determined epicentres are a prerequisite for a better understanding of the tectonic implications of the seismicity, although such data could still defy confident interpretation. This is perhaps illustrated by Woollard (1958, p. 1139), who studied tectonic activity and earthquake epicentres in the United States of America and concluded that observations tended to support the idea that localised stress and strain relations determined centres of earthquake activity, rather than regional, continent-wide stress conditions.

The value of suitable instrumentation has been demonstrated by the increase in data since the installation of the Mundaring seismograph. Similarly, results from the permanent installation at Kalgoorlie and from installations planned for the north-west of the State should produce a comparable improvement in data by the end of the following decade. In particular, it is desirable to increase the accuracy of epicentre determinations, to measure regional changes in crustal thickness and upper mantle velocity, and to determine empirical curves for magnitude determinations, for a better appreciation of the processes that are causing the earthquakes of Western Australia.

The possibility of earthquake damage in Western Australia is very difficult to assess, because evidence has only been gathered during a fairly short interval and earthquake prediction methods do not generally give clear-cut predictions. However, buildings in the numerous townships along the Yandanooka/Cape Riche Lineament should certainly be built to withstand small shocks (M_L = 4 to 5) as tremors of this magnitude could occur very close to them. It also seems reasonable to expect even larger shocks here, perhaps one in each 50-year or 100-year period; such shocks might even effect some buildings in Perth.

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TABLE 1

Earthquakes in the region of Western Australia recorded prior to August 1959

Date	Origin time, GMT h	m	s	Epicentre Lat. °S	Long. °E	Depth (km)	Magnitude M_S	Reference
1906 19 Nov.	07	18	03	22	109	60	7¾	Gutenberg & Richter (1954)
1920 8 Feb.	05	24	30	35	111		6¼	Gutenberg & Richter (1954)
1929 16 Aug.	21	28	22	17.0	120.9		6¼	Gutenberg & Richter (1954) and Bolt (1959)
1934 12 July	14	24	18	15.0	112.5		6	Gutenberg & Richter (1954)
1941 29 April	01	35	41	26.8	116.1	32	6¾	Gutenberg & Richter (1954) and Bolt (1959)

ADDENDUM

When this Report was ready to go to press, revised values for two of the above earthquakes were discovered. The new data are:

Date	Origin time, GMT h	m	s	Epicentre Lat °S	Long°E	Magnitude M_S	Reference
1906 19 Nov.	07	18	41	19.1	111.8	7¾	Stover (1966)*
1934 12 July	14	24	27.2	14.8	112.3	6	Stover (1966)*

* Stover, C.W. 1966 Seismicity of the Indian Ocean. J. Geophys. Res. 71(10), 2577 et seq.

TABLE 2

Western Australian earthquakes with magnitude $M_L \geqslant 3.5$ recorded at Mundaring August 1959 through June 1965

No.	Date	Origin time (GMT) h	m	s	Epicentre Lat °S	Long °E	Δ (km)	M_L	(m_L)	M_S	(m_S)	m_b	Unified magnitude (m)	Remarks
	1959													
1	3 Oct	12	07	22	34.5	114.5	325	4.2	(4.8)	4.2	(5.1)	5.0	5.0	Felt. Recorded ADE
2	12 Oct	03	46	57			330	3.5	(4.4)			3.7	4.0	
3	27 Nov	06	25	22	25.8	116.2	690	4.8	(5.3)	4.4	(5.2)	5.6	5.4	Recorded ADE
4	27 Nov	06	40	58	(25.8)	(116.2)	690	4.2	(4.8)			4.3	4.6	
	1960													
5	2 Mar	23	45	32	(25.7)	(116.2)	700	4.2	(4.8)			4.4	4.6	
6	4 Jun	18	55	16			1680	4.6				4.3	4.3	
7	7 Jul	03	57	35			840	4.3				5.3	5.3	
8	7 Jul	05	48	11			840	4.6				5.5	5.5	North of MUN
9	2 Oct	21	38	59			660	3.7				-	-	East? of MUN
	1961													
10	12 Jun	18	00	51	34.2	114.5	290	4.1	(4.8)			4.7	4.7	Felt
11	18 Jun	16	13	58*	20.1*	119.3*	1350	6.3		4.5	(5.3)	6.0	5.7	Felt. Recorded ADE, CAN, CTA, DAR
12	25 Jun	17	59	18	32.2	117.2	100	4.4	(5.0)			4.1	4.5	Felt
13	30 Jul	07	28	34	36.9	121.0	700	4.2	(4.8)			4.9	4.9	
14	6 Aug	20	22	18			(500)	3.6	(4.4)			5.2	4.8	
15	23 Aug	18	01	33	18.5	119.0	1520	5.3	(5.6)	4.2	(5.1)	5.2	5.3	Recorded ADE, CTA, DAR.
16	28 Aug	10	29	57	(27.5)	(116.2)	500	3.5	(4.4)			5.4	4.9	
17	31 Aug	21	22	28	32.2	117.1	98	3.6	(4.4)				4.4	

No.	Date	Origin time (GMT) h	m	s	Epicentre Lat °S	Long °E	Δ (km)	M_L	(m_L)	M_S	(m_S)	m_b	Unified magnitude (m)	Remarks
	1961 (Contd.)													
18	13 Sep	15	04	38			840	4.4				4.3	4.3	
19	17 Oct	01	39	06			750	3.9	(4.7)			4.9	4.8	East? of MUN
20	10 Nov	14	59	14	37.5	118.4	650	4.4	(5.0)			5.3	5.2	
	1962													
21	1 Jan	23	29	52	(34.1)	(125.7)	920	4.4		4.6	(5.3)	5.2	5.2	Recorded ADE
22	8 Jan	00	55	35			750	4.6	(5.1)			4.8	4.9	East? of MUN
23	21 Apr	12	34	30			1550	4.6				4.7	4.7	North of MUN
24	16 Jun	21	33	08			1280							
25	3 Sep	19	09	49			760	4.6	(5.1)			5.6	5.4	North of MUN
26	16 Oct	19	08	44			1100	3.7				-	-	
27	22 Oct	05	28	00			1100	4.1				5.5	5.5	Felt 22.3°S 118.3°E Possible rock-burst
	1963													
28	18 Jan	05	49	18	32.2	117.2	98	4.9	(5.4)	4.1	(5.0)	5.8	5.4	Felt. Recorded ADE, CAN, CTA, DAR
					h =	18 km						5.5x		
29	26 Feb	14	10	19	22.2	121.2	1200	4.6				5.5	5.5	Recorded ADE, DAR
30	15 Apr	00	43	54	(21.8)	(120.3)	1200	4.3				5.4	5.4	
31	18 Apr	19	58	10	32.3	117.2	98	3.8	(4.6)			4.8	4.7	Felt
32	15 May	15	03	06			(850)	4.2				5.3	5.3	
33	20 Jun	18	17	07			1180	4.4				5.2	5.2	North of MUN
34	20 Jul	04	21	33	26.3	114.9	650	3.8	(4.6)			4.7	4.7	
34B	27 Aug	19	15	38	16.3	128.8	2170					5.2	5.2	Recorded ADE, BRS, CAN, CTA, DAR, TOO
35	17 Nov	07	55	06	25.0	116.8	780	3.8	(4.6)			-	4.6	
36	19 Nov	17	52	05	31.0	116.3	107	4.2	(4.9)			4.9	4.9	Felt

	1964													
37	6 Jan	15	31	22			1350	4.6				4.6	4.6	
38	9 Mar	11	35	46	30.8	121.5	520	3.9	(4.7)			4.3	4.5	Felt Kalgoorlie Probable rock-burst
39	23 Mar	22	41	10.9*	17.8*	123.1*	1730	6.3		4.7	(5.4)	5.8	5.4	Felt. Recorded Aust.
					h =	0 km*						5.4x		stations and overseas
40	1 May	-	-	-			285	3.8	(4.6)			4.6	4.6	No timing
41	12 Jun	14	08	54	33.6	118.1	240	4.3	(5.0)			4.2	4.6	Felt
42	3 Jul	10	49	28			1100	3.8						Felt 22.3°S 118.3°E possible rock-burst
43	23 Oct	12	52	55	32.2	117.2	95	3.5	(4.4)			4.3	4.3	
44	5 Nov	05	50	55	32.1	116.7	43	3.8	(4.6)			4.3	4.4	Felt
	1965													
45	18 May	10	17	52	17.5	121.0	1690	4.5				4.6	4.6	Recorded DAR, KLG
46	19 May	02	13	47*	25.0*	112.1*	900	6.1		5.0	(5.6)	6.0	5.6	Felt.Recorded Aust. stations and
					h =	33km*						5.6x		overseas
47	15 Jun	06	16	01*	(19.6*)	(106.3*)	1700	5.3				4.8	4.5	Indian Ocean. Recorded KLG.
					h =	33km*								Not shown in Plate 1

NOTES:

ADE - Adelaide, BRS - Brisbane, CAN - Canberra, CTA - Charters Towers, DAR - Darwin, MUN - Mundaring, KLG - Kalgoorlie, TOO - Toolangi

M_L, m_b - Determined from MUN records unless designated.

M_S Mean value determined from all suitable recording stations.

m Weighted mean from all listed magnitude values.

* Determined by USCGS

x Mean for W.W.S.S. stations, MUN excluded.

TABLE 3
Earthquakes with magnitude
M_L less than 3.5 recorded at Mundaring
(August 1959 through June 1965)

Date	P-arrival (GMT) h	m	s	M_L	Δ (km)	Bearing (degrees N through E)
1959						
Aug. 3	07	53	24	2.5	114	100
19	06	53	58	2.0	70	075
20	19	41	21	1.9	93	098
Sep. 29	04	23	34	1.6	102	029
30	19	28	42	1.9	101	036
1960						
Feb. 11	04	21	43	3.2	275	135±
Mar. 14	16	31	30	3.4	96	021
31	04	13	57	3.4	240	135
Apr. 18	09	54	22	3.0	240	135±
May 2	18	07	57	3.0	215	018
7	16	11	00	2.4	96	020
Jun. 25	01	12	29	2.4	101	036
28	12	43	14	2.3	77	059
Jul. 6	22	18	53	2.5	75	060
25	15	47	30	2.4	70	062
Aug. 4	19	40	41	2.2	72	067
Sep. 7	17	02	58	2.0	72	062
Nov. 8	12	40	22	1.8	76	060±
13	19	03	46	1.7	76	062
14	22	46	33	2.9	100	046
16	11	20	43	1.8	96	042
20	20	02	20	2.3	98	045
24	00	13	40	2.2	96	045
1961						
Feb. 5	20	57	12	2.2	84	122
Mar. 22	04	20	12	1.9	102	038
Apr. 3	20	54	49	2.2	74	063
3	21	33	29	2.4	75	063
4	19	29	42	2.3	75	063

TABLE 3 (Continued)

Date		P-arrival (GMT) h	m	s	M_L	Δ (km)	Bearing (degrees N through E)
1961							
Apr	27	07	53	20	2.4	75	060
May	8	15	23	39	2.3	100	109
	10	14	40	41	2.5	99	110
	12	11	03	30	3.0	98	109
	12	11	45	12	3.2	98	112
	15	13	28	36	2.0	95	112
	15	14	10	56	3.2	98	110
	15	14	13	44	2.2	97	112
	18	08	57	16	3.3	267	158±
	29	17	45	42	2.1	99	110
June	5	00	11	05	2.8	98	111
	5	23	48	21	2.6	98	111
	6	03	11	54	3.0	97	114
	6	03	15	16	2.2	97	104
	6	04	11	49	2.4	98	108
	6	06	47	32	2.4	98	109
	10	21	16	31	2.7	99	108
	11	12	02	07	2.9	98	107
	12	18	41	55	3.3	76	060
	23	04	40	19	3.0	98	108
	23	04	48	23	2.9	98	107
	23	08	16	25	2.6	94	025
	23	22	58	01	2.6	100	109
	25	18	09	24	2.7	97	108
	25	18	24	42	3.4	97	108
	25	18	39	05	2.5	97	109
	25	18	44	36	3.1	98	107
	25	18	52	35	2.2	95	109
	25	18	55	07	2.0	96	108
	25	19	26	28	2.7	98	109
	25	20	22	34	3.0	98	108
	25	20	57	05	2.9	96	109
	25	20	59	52	2.8	97	107
	25	21	10	28	2.4	98	108
	25	22	00	06	2.5	96	108
	25	22	14	16	2.4	96	109
	25	22	22	20	3.0	98	109
	25	22	24	52	2.9	98	109
	25	23	39	27	3.2	96	107
	26	02	02	35	2.7	98	107
	26	09	39	29	2.6	96	107
	26	14	36	02	2.5	96	108
	26	14	36	05	2.5	97	106
	26	23	06	31	2.4	97	112
	27	17	46	24	2.3	96	108

TABLE 3 (Continued)

Date		P-arrival (GMT) h	m	s	M_L	△ (km)	Bearing (degrees N through E)
1962							
July	1	15	10	16	2.6	82	124
	6	14	49	57	2.3	98	107
	6	02	22	37	2.4	82	121
	7	05	48	21	3.2	178	135±
	10	05	06	04	1.9	82	124
	10	06	57	30	1.9	82	119
Aug.	28	09	00	48	2.6	96	107
	28	09	08	40	2.5	96	107
	28	14	17	20	2.3	98	107
	28	14	44	33	2.8	97	108
	28	15	57	13	3.3	96	108
	28	17	27	00	2.8	97	106
	28	19	28	19	2.2	97	108
	29	01	11	35	3.1	96	106
	29	01	21	30	3.0	100	108
	30	04	24	05	2.2	100	106
	30	14	02	02	3.1	98	106
	31	20	22	19	3.3	98	108
Sep.	2	21	28	00	2.4	96	110
	3	18	32	37	2.3	96	107
	3	19	48	37	2.5	97	108
Nov.	13	10	03	08	2.2	98	106
	20	20	45	08	2.9	98	108
	20	21	08	05	2.8	98	105
Dec.	31	17	48	30	2.1	76	054
	31	22	27	30	2.8	76	058
1962							
Jan.	30	07	30	05	2.6	99	108
	30	10	49	19	1.9	99	108
Feb.	8	02	42	55	1.9	76	116
	8	05	53	42	1.9	76	116
	10	07	12	31	2.4	90	018
	17	06	44	36	2.4	76	065
	24	00	20	15	1.7	101	108
May	10	06	15	00	1.4	48	065
	18	10	12	31	2.0	75	049
July	31	00	35	42	2.6	208	055±
Dec.	17	00	29	38	3.0	250	135±
	30	03	21	42	1.1	109	018±
	30	06	15	11	2.0	95	108
	30	06	26	42	1.5	95	108
	30	15	42	28	1.9	94	108
	31	17	01	19	1.9	110	010

TABLE 3 (Continued)

Date		P-arrival (GMT) h	m	s	M_L	Δ (km)	Bearing (degrees N through E)
1963							
Jan.	5	02	14	11	3.1	95	110
	5	02	20	44	2.3	95	108
	5	02	25	12	2.3	95	108
	5	03	23	41	2.6	95	110
	5	06	52	56	2.1	95	108
	5	16	15	55	2.2	96	108
	5	18	44	21	2.1	95	108
	8	00	40	18	2.9	97	108
	8	08	26	51	3.1	97	109
	18	05	56	59	2.9	96	108
	18	05	59	18	2.7	96	108
	18	07	58	23	2.8	98	110
	18	13	19	57	2.2	97	108
	18	18	47	30	2.3	97	110
	19	05	08	37	2.6	96	106
	19	18	40	50	2.4	97	111
	21	11	15	57	2.2	97	108
	22	14	29	36	2.1	97	104
	22	15	55	15	2.1	95	115
	23	08	40	27	2.7	99	111
Feb.	4	02	17	50	2.1	95	108
	13	07	58	37	3.2	310	140±
	27	23	09	20	2.2	99	108
	27	23	31	35	2.6	99	108
Mar.	12	20	40	28	2.9	94	108
	12	21	28	28	2.5	94	108
	15	07	54	34	2.0	95	108
	16	18	54	52	3.1	96	106
	16	20	14	03	2.4	95	111
	16	21	59	25	2.1	96	112
	17	03	23	49	2.2	98	115
	17	03	28	00	2.5	98	110
Apr.	17	03	17	18	2.1	96	113
	17	03	21	26	2.6	96	110
	17	03	36	50	2.4	98	110
	17	04	49	43	2.4	98	112
	17	04	54	08	2.2	98	108
	19	05	39	43	2.3	98	110
	19	10	16	14	2.1	95	108
	19	17	56	20	2.1	96	110
	19	18	01	16	2.1	96	110
	19	19	40	55	2.1	96	110
	19	19	43	14	2.1	96	110
	20	15	33	05	2.1	96	110
	20	18	59	36	2.7	97	113

TABLE 3 (Continued)

Date		P-arrival (GMT) h	m	s	M_L	Δ (km)	Bearing (degrees N through E)
1963							
Apr.	20	19	00	19	2.4	97	113
	22	18	17	55	3.3	98	110
	23	07	21	36	2.7	100	112
	28	09	18	26	2.5	111	009
	28	11	37	51	2.2	104	011
May	3	21	53	20	2.4	98	110
	6	19	38	31	2.4	98	108
	13	15	31	14	2.9	98	108
June	2	06	27	20	2.4	97	112
	8	02	46	22	2.1	94	116
	11	22	00	29	2.5	255	130
	15	19	45	56	2.8	310	202
Aug.	20	03	14	09	2.2	94	024
	27	20	51	30	2.2	96	106
	29	07	04	48	3.1	94	022
	29	07	24	14	1.8	94	024
	29	11	31	17	2.3	94	020
Sep.	2	12	50	09	2.3	96	112
	21	11	26	31	2.5	93	111
	22	15	04	41	2.6	95	114
Nov.	15	22	07	13	2.9	107	006
	16*	00	35	35	3.2*	440*	180*
	16	22	50	07	2.7	107	006
1964							
Jan.	8	23	40	47	2.2	99	111
	9	01	24	36	2.7	99	111
	15	02	31	45	2.9	97	112
	27	22	59	02	2.2	98	112
Feb.	6	04	08	19	2.4	95	111
	6	06	04	17	2.3	95	111
	6	06	08	26	2.8	96	110
	8	15	51	47	2.3	96	112
	26	15	42	34	2.2	97	108
Mar.	20	02	56	47	2.9	100	111
	20	13	35	15	2.5	97	111
	20	13	39	33	2.5	98	111
	27	18	16	08	1.9	89	104
June	11	20	02	42	2.8	145	000±
	23	10	24	20	3.4	250	135±
Aug.	16	06	30	14	2.0	90	101
Sep.	19	18	50	38	2.7	97	076
	19	22	33	40	2.7	97	076

TABLE 3 (Continued)

Date		P-arrival (GMT) h	m	s	M_L	$\triangle$ (km)	Bearing (degrees N through E)
1964							
Oct.	10	09	34	43	2.2	98	110
	26	22	18	19	2.8	145	000±
Nov.	5	18	15	23	3.2	43	100
	6	04	00	34	3.0	44	100
	23	17	30	43	2.4	43	100
	24	14	50	42	2.5	43	100
1965							
Feb.	2	23	55	37	2.2	92	108
Mar.	13	20	20	33	1.8	95	108
	14	00	29	20	1.8	95	108

Notes: ± Epicentre less accurate

* Not plotted in Plate 2A.

TABLE 4

Western Australian earthquakes recorded at Watheroo

(31st March 1958 to 12th January 1959)

Date 1958		P-arrivals (GMT) h	m	s	Magnitude M_L	$\triangle$ (km)
Mar.	31	19	03	46	3.3	247
	31	19	06	40	3.3	247
Apr.	8	17	52	11	3.3	243
	19	03	50	14	2.2	95 or 116
	22	05	15	35	3.2	248
	25	05	56	37	2.5	95
	25	07	48	20	2.5	95
June	9	19	53	06	2.7	215
July	11	12	55	41	2.7	243
	12	05	56	--	2.2	215
Aug.	3	19	33	08	3.1	243
	3	20	00	23	3.1	243
Oct.	27	21	54	45	4.5	1150
Nov.	5	08	09	06	3.0	249
	8	19	07	48	2.7	245
	8	20	46	37	3.0	245
	13	13	18	41	1.4	95
	26	03	29	50	2.3	71
Dec.	8	04	30	11	2.8	285
	14	04	12	11	1.6	71
	20	16	48	25	5.1	1150

TABLE 5

Western Australian earthquake record and damage from the year 1904

Date (120°EMT)	Location	Remarks
30.10.04	Grennough Flats, Glengarry Newmarracarra, Moonyonooka	Two mild but distinct shocks occurred in the evening. Geraldton escaped all trace of the tremors.
16. 1.05	The Lighthouse Cape Naturaliste	A severe earth-tremor was felt at midnight. The lighthouse and quarters were shaken, but no damage was done.
22.11.05	Geraldton	Earth tremor at 6.34 a.m. of about 5 seconds duration, noted at the Post Office.
22. 8.06	Balladonia	A slight earth tremor, accompanied by a loud rumbling noise was recorded by the postmaster at midnight. It appeared to travel from east to west and lasted about 10 seconds.
19.11.06	Throughout the State	One of the most severe ever recorded at the Observatory, but no damage in Perth. Cracked walls and plaster at Cue. Recorded at Perth at 3 h 21 m 6 s p.m. Also felt in Kalgoorlie. Epicentre 22°S, 109°E. Felt on R.M.S. Omrah at 21.3°S, 105.5°E.
22.11.06	Perth	A slight earth tremor was recorded at the Observatory at 4.28 p.m. The seismograph showed a slight agitation, but the shock was evidently mild and was not generally noticed in the city.
10. 4.07	Perth	Earth tremor felt about 4 p.m. Recorded on seismograph.
12. 7.07	Carnarvon	Slight but distinct tremor felt here; also felt at Hamelin Pool and Shark Bay. No damage.
28. 9.07	Marble Bar	Earth tremor at 6.35 a.m., duration 25 seconds.
29. 1.08	Broome	Distinct earth tremor. No damage.
9. 5.08	Turkey Creek	Reported by postmaster. Severe earthquake shock at 4 p.m. lasting about 3 minutes. Houses rocked violently, earth rumblings very loud, appeared to come from WNW.
15.10.10	Marble Bar	Two distinct earthquakes - the first at 5.45 a.m. and the second 10 minutes later. A sound as of distant thunder was heard by people 20 miles away. The shocks travelled from a southerly to a northly direction and caused crockery etc. to rattle in almost every dwelling.

Date (120^{o}EMT)	Location	Remarks
15. 8.11	Quellington	Earth tremors and rumblings 8 p.m.
19. 8.11	Quellington York	Distinct tremors felt; noise deafening but no damage. Not recorded at Perth. Later report gives damage - cracking of walls etc.
26. 4.12	Albany and Grassmere	Postmaster reported:-"Earthquake reported about 7 p.m., severe enough to shake articles of furniture. Also experienced at Grassmere, 7 miles distant". Recorded at the Observatory.
27. 5.12	Nullagine	Earth tremor at 6.15 a.m. - one minute duration.
31. 5.13	Perth	A Mr X at Mrs Y's house, St George's Terrace, felt shaking of house at 4.10 a.m. and again at 5.30 a.m.
June, 1913	Marble Bar	Slight earth tremors accompanied by audible sounds like distant thunder on mornings of these dates, lasting in each case for a few seconds.
1914	Day Dawn (Murchison)	Earthquake shock on Great Fingall Mine, which resulted in considerable under ground disturbance.
10. 1.14	Cape Leveque (King Sound, Derby)	Two distinct earth tremors, accompanied by low rumbling sound, which shook both dwelling and lighthouse. 8.20 p.m.
10. 8.14	Cape Leveque and Pender Bay	At sunrise fast tremble shook lighthouse and apparatus - windows rattled. Lasted from 4 to 6 seconds. Constable Rea, Pender Bay, 35 miles to southwards, reported that shock was felt, lasting 8 to 10 seconds.
22.11.14	Wahroonga Station and Gascoyne District	Wahroonga report: At about 6.30 a.m. two reports, south of west from here, resembling dynamite explosions were heard only two or three seconds between each explosion at 6.30 a.m. Meedo reported: Severe earth tremor accompanied by two rumblings, close together travelling from west to east. Natives report same, saying "ground shook making great noise." About 6 a.m.
21.12.14	Marble Bar	Earth tremor at 9 a.m. lasting one second travelling NW to SW.
6. 4.15	Marble Bar	Distinct earth tremor, at 12.13 p.m., appeared to be travelling NW to S.

Date (120°EMT)	Location	Remarks
3. 5.16	Ravensthorpe, Hopetoun (Phillips River G.F.)	The warden at Ravensthorpe and the postmaster at Hopetoun both reported distinct shocks of earthquake throughout the two districts. The message from the first named place stated that the courthouse and other buildings shook, crockery on shelves rattled, and miners working underground were alarmed by the shock. No damage was done. At 9.45 a.m.
2. 6.16	Quellington	The schoolmistress, Miss Peacock, reported earth tremor accompanied by loud rumbling and shaking of school house. The phenomenon was noted by residents.
16. 8.16	Day Dawn (Murchison)	Two distinct earth tremors were felt on the Great Fingall Mine - the first at 10.30, when a long rumbling sound ran through the earth and the second at 10.45. Several falls of earth occurred. The shock was felt as far out as Meehan Station to the south and in a northerly direction as far as the Cue Hospital.
Sept. and Oct. 1916	Meckering	Earth tremors and noises.
4.10.16	Meckering	Local tremors. Shook Bank Building midnight to 1 a.m. 4th Oct. No record in Perth.
1.12.16	Meckering	Between 11 a.m. and noon on the 1st several earth tremors reported. Shook buildings and rattled crockery, etc.
1.12.16	Day Dawn (Murchison)	Severe earth tremors felt in Great Fingall Mine at 8 p.m. lasting 5 to 7 seconds. They were accompanied by two violent reports such as might be expected from the explosion of a magazine. At the 16 level there was a very considerable fall of rock and much of timber-work was crushed in. Damage was done to other parts of the mine, more particularly in the breaking of pipe connections.
11.12.16	Kalgoorlie	Report from mine manager: severe, like explosion of magazine and falls of rock 8 p.m. on the 11th.
3. 6.17 to 10. 6.17	York	Underground rumbling noises, like thunder, experienced throughout the district during the evening.
3. 6.17	York and surrounding districts	Local tremors. Floors shook and windows rattled during the evening. No record in Perth.

Date (120°EMT)	Location	Remarks
10. 6.17	Breaksea	The lighthouse keeper at Breaksea reports:- "The severe shocks of earthquake between 6 and 7.30 p.m. - resembling falling of heavy boulders - lighthouse and quarters shaken."
28. 8.17	Kalgoorlie	An earth movement occurred towards midnight resulting in a fall of rock in the Great Boulder. One man was killed and several injured. The fall of rock occurred at the 2250-ft level where ten men were working in a stope when a peculiar rumbling noise was heard. There were slight earth tremors followed by a loud report and a large mass of rock fell from the roof of the stope. The stope immediately below was also affected and altogether it is estimated that about 1000 tons of rock fell and heavy timber was smashed like matchwood.
28. 8.17	Day Dawn	The postmaster at Day Dawn also reported: "Severe earth tremor, followed by cannon-like reports, shook town at 7.50 p.m. The postmaster Cue also reported: "Earth tremor felt here at 7.50 p.m."
30. 8.17	Wyndham	Slight earth tremor at 12.7 p.m., lasting five seconds.
21. 9.17	Kalgoorlie	A loud report, followed by a rumbling noise such as might have been caused by an earth movement, was noticed by workers in some of the mines of the Golden Mile on this date. No serious fall of earth has been detected in any of the mines.
3. 6.18	Onslow	Tremor lasting a few seconds.
5. 1.19	Eyre, Balladonia, Eucla, Isrelite Bay	Violent tremors felt locally. In each case its time was given from 5.34 a.m. - 5.38 a.m.
15. 7.20	Leonora	Report of earth tremor. House and windows shook etc.
30. 9.23	Kwolyin	House shook between 4 and 5 p.m.
7.12.23	Kulyalling	Earth tremors locally. No damage.
10. 1.28) 14. 1.28) 16. 1.28) 23. 1.28)	Brookton District	Local tremors.
27. 7.29	Woodanilling	Distinct earth tremors. Shook houses and articles of furniture etc. at 11.45 p.m.
16. 8.29	La Grange	Very pronounced earth tremor, shook Post Office. Distinct earth tremor lasting two minutes. Recorded in Perth. (Epicentre 16½S 121°E).

Date (120 EMT)	Location	Remarks
2. 8.30	Wagin	Slight earth tremors. Shook houses and rattled windows at 8.15 p.m.
5. 8.30	Katanning	Tremors, not severe but rattled windows, shortly after 9 p.m. Passed the Marracoonda and Moojebing districts. No record in Perth.
2. 3.31	Off Dirk Hartog	Marine upheaval at 12.30 p.m.
28. 3.31	Darwin and Timor (1700 miles from Perth)	Recorded in Perth. Earth movements felt in Wyndham, Derby, and Broome at 8.45 p.m.
16. 3.32	Muresk	Earth tremor. Loud report like explosion; chimney fell at Muresk College between 9 and 10 a.m.
1.11.32	8 miles NE of Northam	Underground rumblings and tremors during the evening. Window frames rattled and verandah posts shook. No record at the Observatory.
2.11.32	Northam	Several earth tremors during the evening. Shook verandah and rattled windows.
17. 6.33	Yalgoo	Tremors felt at Narryer, Boolardy, Meeberrie, Wooleen, and Murgoo about 10 a.m. Distinct and travelling north to south.
24. 5.34	Kanowna	Severe tremors travelling NNE to SSW caused considerable alarm but no damage. No record at the Observatory.
3.10.35	Onslow	Severe earth tremor felt on Yanrey Station. No damage.
29. 4.36	90 miles E. of Onslow	Tremors between 4.30 p.m. and 5.30 p.m. Ground trembled and windows shook. Recorded at Observatory.
4. 5.36	Eyre	6.15 p.m. Loud rumbling, crockery rattled.
May 36	Bulading	Numerous tremors, sounds resembled blasting.
18. 8.36	30 miles ENE of Katanning	Severe earth tremors at 10.30 p.m. Windows and all loose furniture rattled. Also felt at Brookton.
2. 2.37	Albany	Distinct earth tremor. Vibration caused crockery to rattle in homes. Recorded at Observatory at 8 h 29 m 20 s a.m.
12. 2.37	Albany	Earth tremor. House shook and trembled.
March) April) and May) 1937	30 miles NE of Katanning	Frequent occurrences. Brick walls cracked, general alarm. No record at Perth.

Date (120°EMT)	Location	Remarks
27. 4.37	Gnowangerup	Earth tremor at 8.30 a.m. Houses shook and iron roofing rattled. No record at Perth.
20. 1.40	Northampton	Tremor at 3.50 a.m. Windows rattled and crockery shook. Part of ceiling in a house came down.
4. 5.40	Nullarbor Plain	
5. 5.40	Nullarbor Plain	
25. 6.40	Boulder and Kalgoorlie	Tremor at 12.10 p.m. Strongest for many years. Electric light fittings shaken from ceilings. One office severely shaken, interior appointments badly damaged.
25. 6.40	Fremantle	Rattling and cracking of iron casement windows in Fremantle hospital at 8.50 a.m. No record at Observatory.
18.12.40	Beverley	Earth tremor or quake felt at 5.15 a.m. Houses shook, windows rattled, etc. Recorded at Observatory as tremor.
29. 4.41	East of Geraldton Meeberrie Station	Tremors felt from Port Hedland to Albany and Kalgoorlie. Widely felt over the state. Many buildings in Perth shook. Local damage at Geraldton. Extensive area affected. Centred at Meeberrie Station. Epicentre 26.8°S 116.1°E. Magnitude 6 3/4.

Extract from report of Meeberrie Station

(Latitude 26°57.5'S and longitude 115°58.5'E)

"At approximately 9.45 a.m., a slight tremor was noticed, and this increased in severity and noise until the buildings began to shake in an alarming manner, and then appeared to roll considerably. Loose articles were shaken off shelves, cupboard doors were blown open and the contents strewn on the floors, walls cracked and plaster fell from same, both from inside and outside the buildings and was scattered everwhere. This sort of thing went on for about five minutes, when the shaking and tumbling gradually died down. From outside, it was easy to see the buildings rolling from side to side.

"At first glance the damage did not appear to be very great, but after a thorough examination it was found that every wall in the homestead, quarters, engine room, meathouse, and cellar had been cracked right through; some from floor to ceiling, and nearly all in the corners and over window and door heads.

"Strange as it may seem, not a pane of glass was cracked, and there are over 900 panes in the windows and doors of the homestead and adjacent buildings.

"A 700-gallon rainwater tank rocked on its foundations, and eventually burst at the bottom, and the precious contents lost, also all other rainwater tanks were found to be leaking. A 500-gallon tank, near the homestead, used for garden purposes also burst.

"A survey of the property resulted in two stock watering tanks being found blown.

"At the Woolshed, 10 miles north of the homestead, there are two large rainwater tanks, situated in the engine room. They are placed within eighteen inches of each other, and one of them was blown completely off the bottom, and the bottom rim (one sheet of corrugated iron) was blown off the remainder of the tank. The other tank was undamaged. Both were full of water before the disturbance started.

"Several of the stock watering tanks were damaged in a similar manner to the shearing shed tank and will have to be rebuilt.

"Cracks in the ground have been found on the run - definitely caused by the earthquake - and these range from 28 feet to 61 feet in length, and from ½ inch to 2½ inches in width. It was possible to push a two-foot rule down these cracks to depths averaging 12 inches. The deepest crack measured 17 inches. Probably they went much deeper.

"Meeberrie buildings are mainly, and strongly, constructed of granite, and the walls are from 12 to 19 inches thick. With the exception of a particularly large cart shed and stables (some distance from the homestead), all the stone buildings are enclosed by 10-ft concrete verandahs. The stables and cart shed suffered no damage at all.

"Subsequent to the big shock, smaller ones were felt during the day and night, and about 1.0 o'clock on the morning of 30th ulto, what appeared to be an electrical disturbance struck the roofs of the buildings, and appeared to run along the corrugated iron. The sound resembled a vehicle being driven over a wooden decked bridge, and was quite as rhythmical to the ear. This shock, as well as the quake, appeared to come from the north, and after passing over the station, could be plainly heard moving in a southerly direction for nearly a quarter of an hour.

"Again on 1st instant, a small shock was felt about noon, and small shocks have been felt intermittently since.

"This morning about 8.30 o'clock, a shock was felt that shook all the buildings. It lasted about a minute and the accompanying noise was reminiscent of the electrical distrubance felt on 30th April.

"Mt Narryer station, distant about 28 miles due north of Meeberrie, and Wooleen station 15 miles south of east from here, both received damage of similar nature to Meeberrie when the quake occurred, but they got off far more lightly.

"All other stations in the lower Murchison felt the big shock, and some of them suffered damage, but not to any great extent.

The general opinion in the district is that Meeberrie, Mt Narryer, and Wooleen were right in the track of the disturbance."

15. 4.41	Northam	Experienced severe earth tremor. No record at Perth.
31. 5.41	Beverley	Earth tremor shook house.
5. 8.41	Morawa	Slight but distinct earth tremor at 1h 7m p.m. No incident or damage.
12. 8.41	Broome	Earth tremor. No record at Perth.

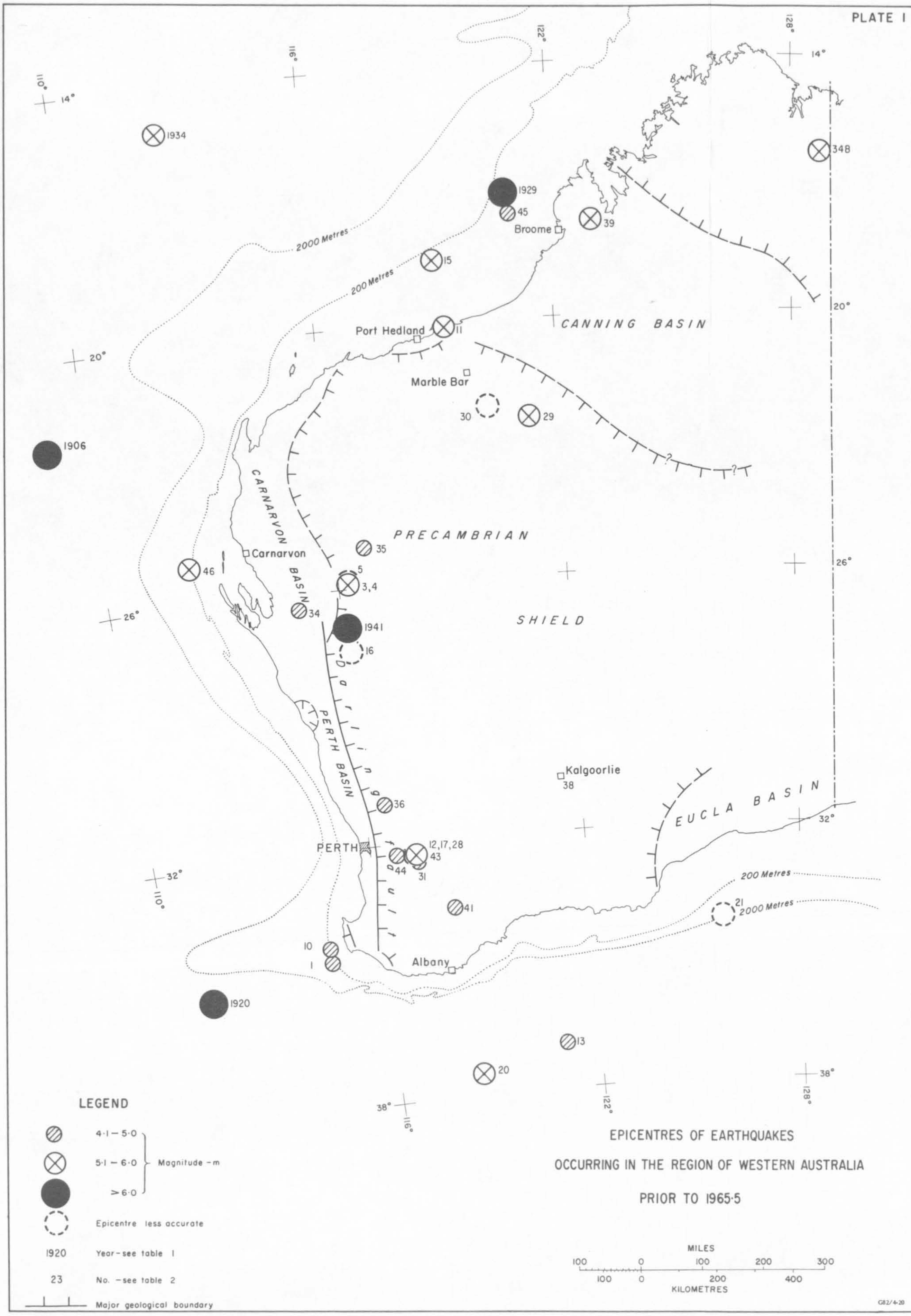
Date (120°EMT)	Location	Remarks
17. 6.42	Northcliffe Eclipse Island	Distinct earth tremor at 4.4 p.m. Shook buildings, moved light furniture, etc. Windows and crockery rattled.
11. 5.43	Fitzroy Crossing	Tremors felt locally.
14. 5.44	Perenjori	Earth tremor at 9.30 p.m. No damage. No record at Perth.
1. 4.46	Subiaco	Resident felt earth tremor at 9 p.m. No record at Perth.
30. 4.46	Yallingup	Tremor felt at Caves House at 5.30 a.m. Also felt at Busselton.
20. 4.46	East Kirup	Tremor reported. Bedroom furniture rattled at 5.10 a.m. Recorded at Perth.
7. 5.46	Yallingup and Geraldton	Reports of tremors from Yallingup and Geraldton. No damage. Recorded at Perth 5.13 a.m.
17. 9.46	Beverley	Report, earth tremor felt. Recorded at Perth 11.12 p.m.
18. 9.46	Brookton Pingelly	Severe earth tremor felt at 11.15 p.m. Building shook, articles fell to floor.
26. 5.48	Mukinbudin	Reported earth tremor at 7.25 p.m. No damage.
30. 6.48	Muradup	Earth tremor, sounded like explosion. Shook building at 10.30 a.m.
2. 5.49	Walebing	Earth tremors at 6 p.m. Houses shook, etc. Also noticed at Wongan Hills, Ballidu, New Norcia, and Waddington.
2. 5.49	Lower Chittering	Report of tremor at 6 p.m. House shaking and creaking. Also felt at Bencubbin.
2. 5.49	New Norcia Wongan Hills Ballidu	Reports of buildings swaying, crockery rattling but no damage. Recorded at Perth 6h 0m 20s.
8. 5.49	Wongan Hills	Windows in hotel rattled loudly. Guests reported beds shook at 1.12 a.m. No damage reported.
18. 9.49	Boulder	District tremor at 7.15 p.m. Houses shaken but no damage.
29. 9.49	Perenjori	Mild earth tremor at 2.16 a.m. Windows, iron, and loose objects rattled. No record at Perth.
5.10.49	Goolarancah Station	Reports quite severe earth tremor. Pictures rattled and doors slammed at 3.55 p.m. Also felt at Moothuna and Warrawagine.
18.12.49	South Pingrup	Report of earth tremor at 10.15 p.m. No damage.

Date (120°EMT)	Location	Remarks
13. 8.50	Tambellup	Report of tremor at 6.45 p.m. Shook and woke children.
2.11.50	Banda Sea	At Darwin, buildings swayed, but only superficial damage. Also felt at Derby and Wyndham. Recorded at Observatory as severe at 11.33.58 p.m.
6.11.50	Kukerin	Local tremors strong enough to vibrate windows, crockery to rattle, and beds to move throughout the day. No record at Observatory.
1.12.50	Onslow	Slight earth tremor felt at 7.10 a.m.
26. 1.51	Esperance Lake King Lake Varley	Tremor at 6.45 a.m. No damage.
14. 3.51	Pemberton	Earth tremor at 5 a.m. House shook and all the windows rattled. Also felt at Northcliffe.
8.12.51	Kalgoorlie	Tremor at 6.10 p.m. Plaster walls in at least one house were cracked and windows broken.
28. 1.52	Kalgoorlie	Tremor at 3.5 a.m. shook Kalgoorlie. Shook walls, rattled windows, dislodged loose objects in homes.
11. 3.52	Bolgart	(Recorded at Perth at 2h 9m 15s p.m.) Tall buildings in Perth swayed. Post Office in Bolgart rocked. Ceilings were cracked in the new school. A substantial earth movement centred at Bolgart. (31S 116½E) Felt over a wide area.
12. 3.52 to 28. 4.52	Bolgart	After-shocks of earthquake felt between these dates. Caused walls and ceilings to crack.
26. 3.52	Boulder Kalgoorlie	Severe earth tremors. Buildings rocked but no damage. 3.10 p.m. and 5.30 p.m.
25. 8.52	Mount Lawley	Phone report of lights swaying at 6.45 p.m.
22. 8.53	Chinocup via Nyabing	Earth tremors at 2.0 a.m. Ground and windows shaken.
24. 2.54	Tambellup	People reported repeated minor earth tremors. No damage.
11. 7.54	Marble Bar	Report of severe earth tremor. No damage. Not recorded in Perth.
27.11.54	Darlington	House swayed. Cracks in wall widened. Recorded at Observatory 8h 35m 40s GMT.
9. 2.55	Badgebup Dyaliabing	Tremor at 01.15 GMT. Prolonged rumbling, ground shook, crockery rattled, window broken, one wall probably cracked. Not recorded at Observatory.

Date (120°EMT)	Location	Remarks
16. 2.55	Elcho Island Goulburn Island Cape Don	Slight earth tremor 11.30 GMT. Recorded at Observatory.
30. 4.55	Calingiri	Located by macroseismic data of Carrigy and Main. Felt approximately 80 miles radius. Recorded Perth Observatory.
19. 5.55	Dowerin Ejanding Goomalling Toodyay Bickley	More severe than previous quake. Recorded Perth Observatory.
29. 8.55	Yericoin ?	See following shock. Felt in area enclosed by Perth, Moora, and Cunderdin. Recorded Perth Observatory. (38 miles NE of Perth).
30. 8.55	Yericoin	Located by macroseismic data of Carrigy and Main. Felt same area as previous shock and as far north as Dongara. Recorded Perth Observatory. (103 miles NE of Perth).
31. 8.55	Yericoin ?	Felt over same region as previous two shocks. Recorded Perth Observatory. (103 miles NE of Perth).
22.12.55	Bolgart	After shocks.
7. 2.56	Walebing	
24. 2.56	Moora Konnongorring	Recorded Perth Observatory.
25. 2.56	Moora Yericoin	
6. 4.56	Kununoppin Konnongorring	Recorded Perth Observatory
5. 5.56	Walebing	
2. 7.56	Forrest River Mission	
28. 3.57	Marble Bar	
23. 6.57	Turkey Creek	
10. 9.57	Konnongorring	
18. 9.57	Bickley Glen Forrest	
19. 9.57	Glen Forrest	
23. 2.58	Southern Brook	(Near Northam)
20. 3.58	Beverley Pingelly Brookton	Felt over wide area including Perth. Recorded Perth Observatory.

Date (120°EMT)	Location	Remarks
7. 4.58	Beverley	
21. 1.59	Madura	
22. 2.59	Moora	
3.10.59	SW of Cape Leeuwin	Felt Busselton, Yallingup, Margaret River, Bunbury, Manjimup, Cape Naturaliste, and Cape Leeuwin. Recorded Perth Observatory. Epicentre - see Table 2.
28. 6.60	Southern Brook	Epicentre - See Table 3.
7. 7.60	Southern Brook	
17. 7.60	Southern Brook	
30.10.60	Turkey Creek	
30. 5.61	Kununoppin Trayning	
13. 6.61	Dunsborough	Epicentre - See Table 3.
13. 6.61	Toodyay	Epicentre - See Table 3.
19. 6.61	Port Hedland Marble Bar	Felt Hooley to Mandora. USCGS Epicentre - see Table 2.
26. 6.61	Brookton	Epicentre - See Table 2. Felt in wide area including Perth and Goomalling.
13. 9.61	Kalgoorlie	Damage 2350-ft level Great Boulder mine. Miner injured.
19. 4.62	Dumbleyung	
14. 5.62	Albany	Recorded weakly at Mundaring. Epicentral distance 300 km.
31. 7.62	Welbungin	Epicentre - see Table 3.
18. 1.63	Beverley-Brookton	See isoseismal map (Plate 5) and Table 2.
17. 4.63 and 19. 4.63	Mt Kokeby-Beverley	Several felt. Epicentre - See Table 3.
15. 8.63	Ullaring Rock	Not recorded.
2.10.63	Southern Brook	Epicentre - see Table 3.
20.11.63	Carani	Felt Walebing and Korrelocking. Epicentre - see Table 2.
23. 2.64	Kalgoorlie	Recorded MUN - 3.36 a.m.
9. 3.64	Kalgoorlie	Recorded MUN. Rock falls, miner killed - see Table 2.
24. 3.64	Broome Derby	Broome intensity at least MM6 - see Table 2.

Date (120°EMT)	Location	Remarks
12. 6.64	Badgebut	Badgebut - Nyabing district. Numerous shocks felt, intensity up to MM5 - see Table 2.
3. 7.64	Wittenoom Gorge Mine	Rock fall. Recorded MUN - see Table 2.
20.11.64	Ongerup	Window broken 7 miles north of Ongerup.
19. 5.65	Carnarvon	Two shocks felt - see Table 2.



EPICENTRES OF EARTHQUAKES OCCURRING IN THE REGION OF WESTERN AUSTRALIA PRIOR TO 1965·5

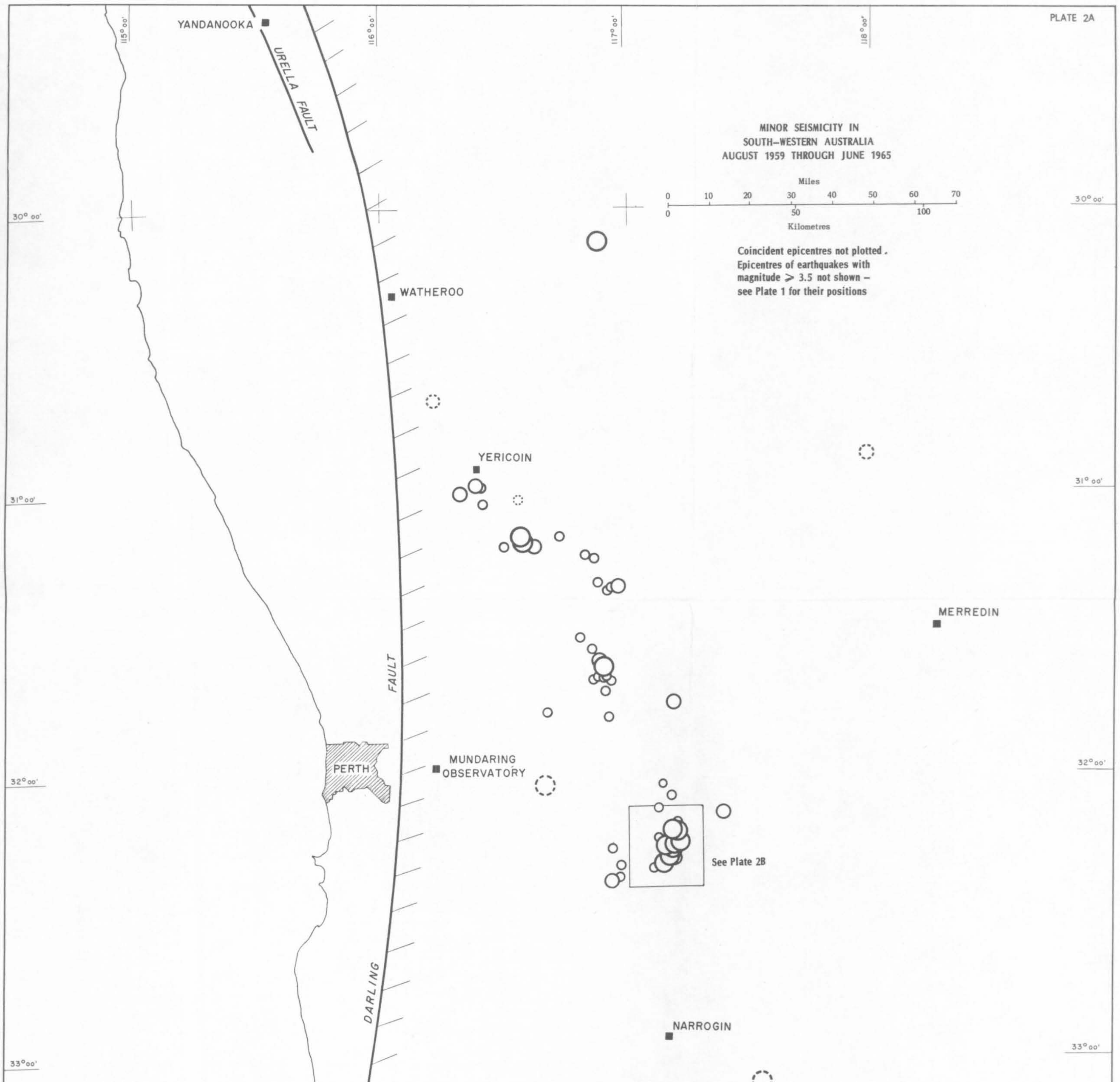
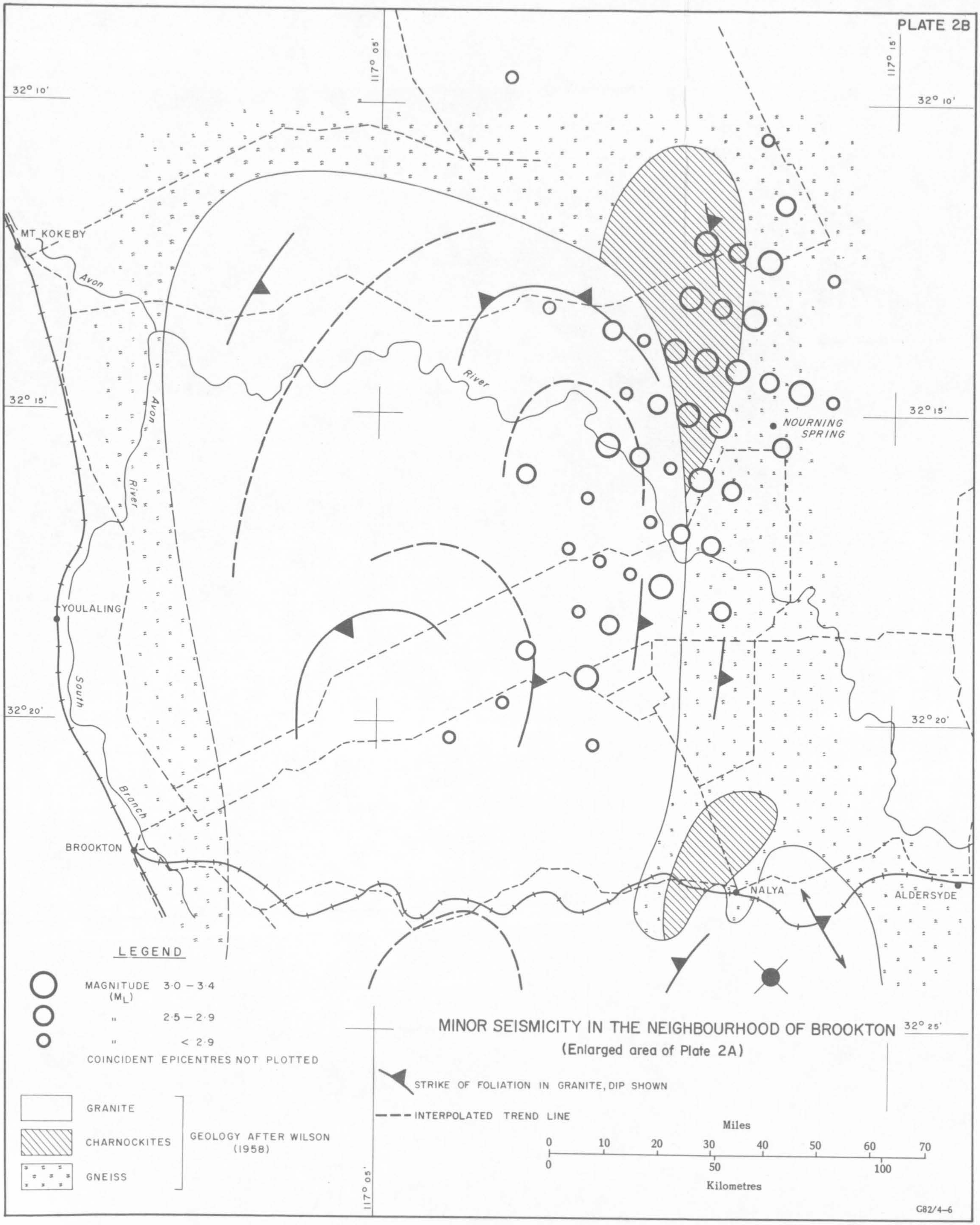


PLATE 2A
MINOR SEISMICITY IN
SOUTH-WESTERN AUSTRALIA
AUGUST 1959 THROUGH JUNE 1965
Miles
0 10 20 30 40 50 60 70
0 50 100
Kilometres
Coincident epicentres not plotted.
Epicentres of earthquakes with
magnitude ≥ 3.5 not shown –
see Plate 1 for their positions
YANDANOOKA
URELLA FAULT
WATHEROO
YERICOIN
MERREDIN
PERTH
MUNDARING
OBSERVATORY
DARLING
FAULT
See Plate 2B
NARROGIN
BUNBURY
KATANNING
BRIDGETOWN
CAPE LEEUWIN
CAPE
RICHE
ALBANY
115°00'
116°00'
117°00'
118°00'
30°00'
31°00'
32°00'
33°00'
34°00'
35°00'
LEGEND
FAULT
PRECAMBRIAN MARGIN
MAGNITUDE (M_L) 3·0 – 3·4
" 2·5 – 2·9
" < 2·5
EPICENTRE LESS ACCURATE
G 82/4-5-1

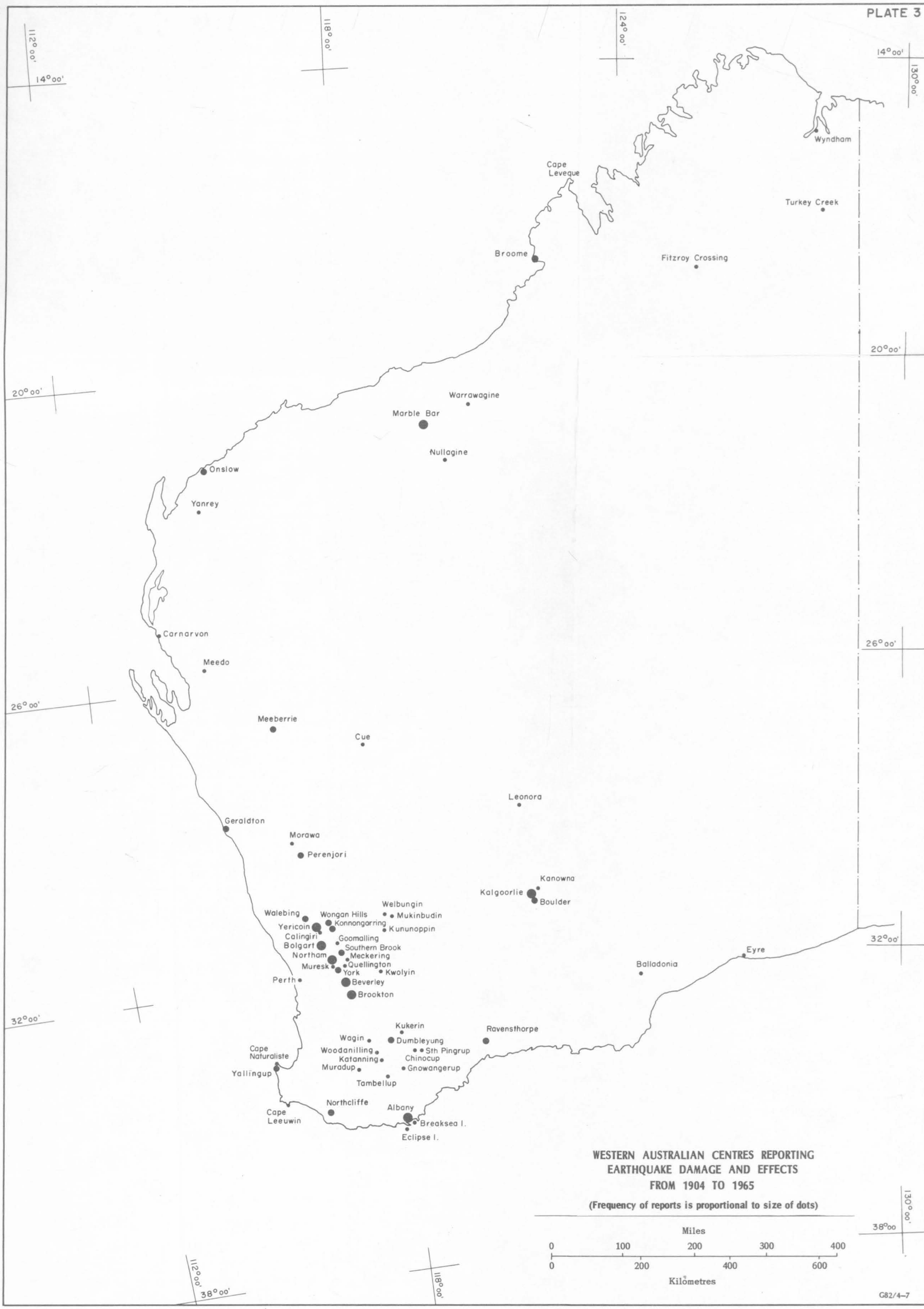
PLATE 2B



MINOR SEISMICITY IN THE NEIGHBOURHOOD OF BROOKTON

(Enlarged area of Plate 2A)

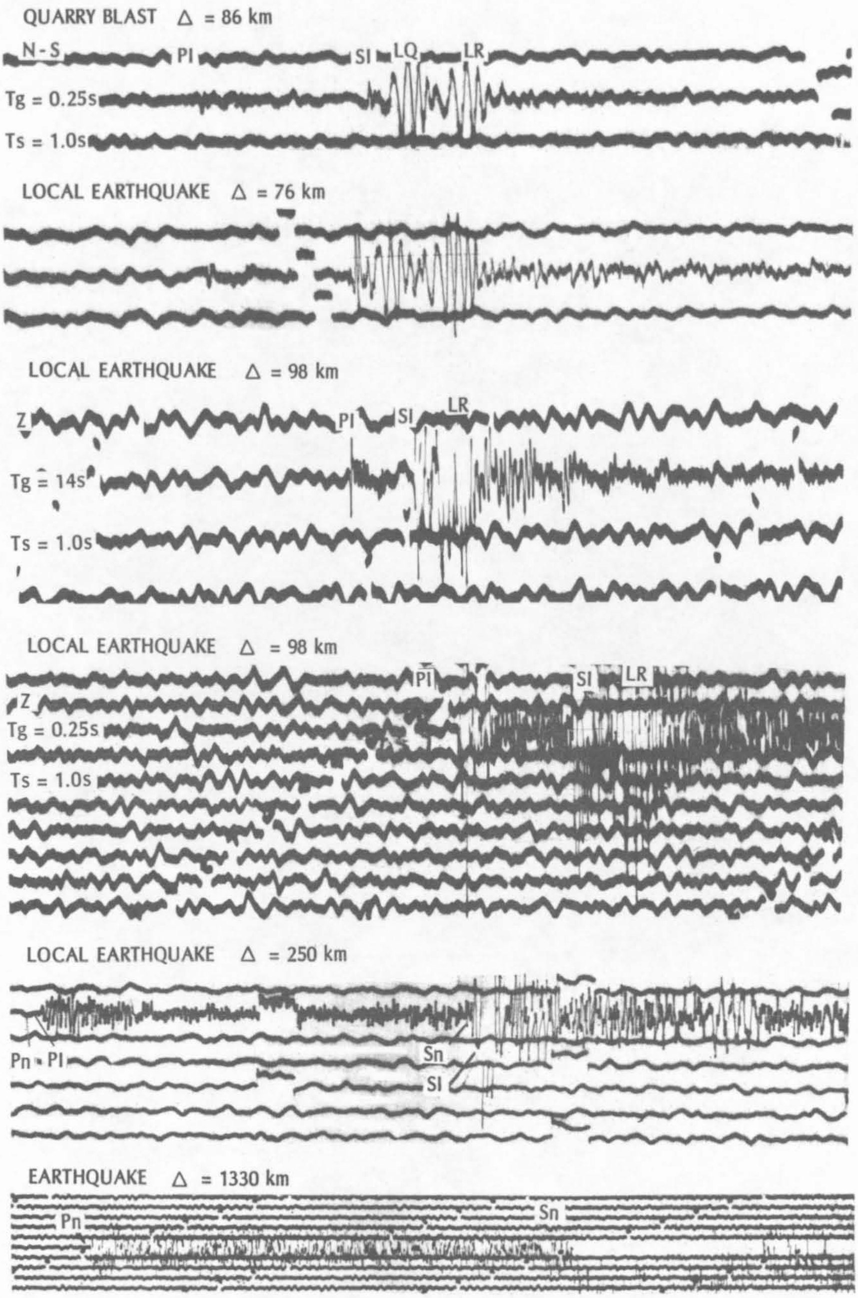
PLATE 3



WESTERN AUSTRALIAN CENTRES REPORTING EARTHQUAKE DAMAGE AND EFFECTS FROM 1904 TO 1965

(Frequency of reports is proportional to size of dots)

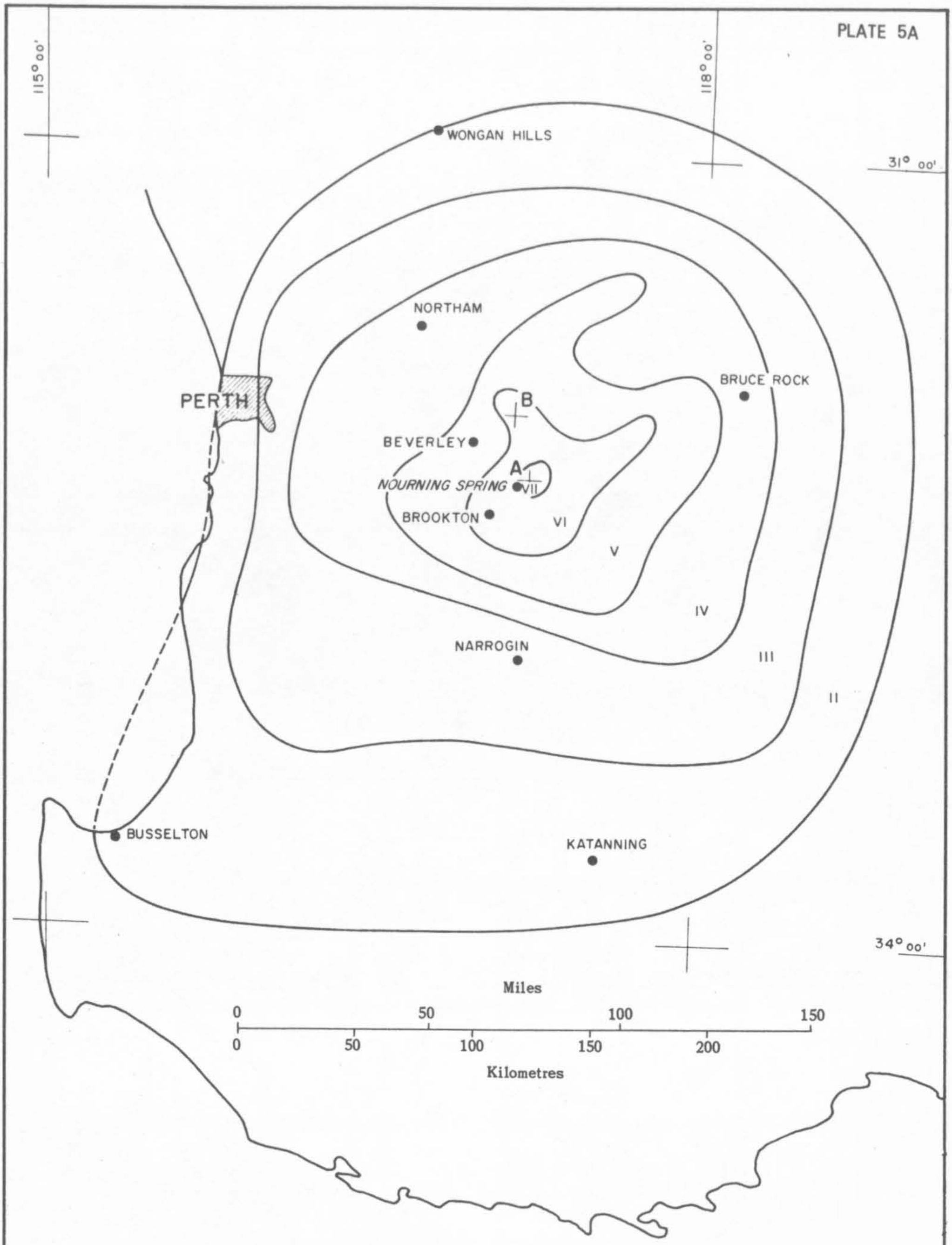
PLATE 4



TYPICAL SEISMOGRAMS

G82/4-12

PLATE 5A



LEGEND

— Lines of equal intensity of shaking

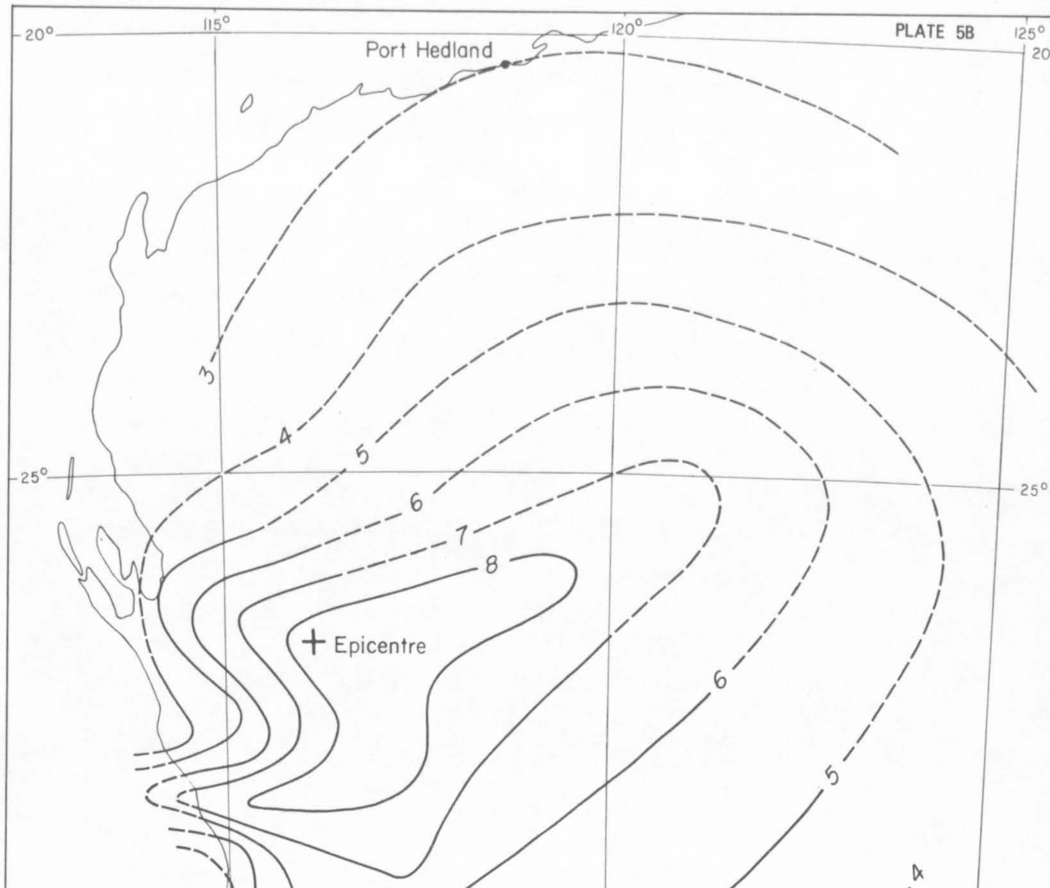
IV Modified Mercalli intensity scale (1956 version)

A+ Epicentre determined from Mundaring instrumental data

B+ Preliminary determination of epicentre by USCGS

ISOSEISMAL MAP OF THE NOURNING SPRING EARTHQUAKE (18 JANUARY 1963)

G82/4–4



ISOSEISMAL MAP OF THE 1941 APRIL 29 EARTHQUAKE

ROSSI – FOREL SCALE

The following table after Richter (1958, p 651) shows the relation between the Rossi-Forel and Modified Mercalli Scales:

MM	*I*	*II*	*III*	*IV*	*V*
RF	*I*	*I-II*	*III*	*IV-V*	*V-VI*
MM	*VI*	*VII*	*VIII*	*IX*	*X-XII*
RF	*VI-VII*	*VIII–*	*VIII+ to IX–*	*IX+*	*X*

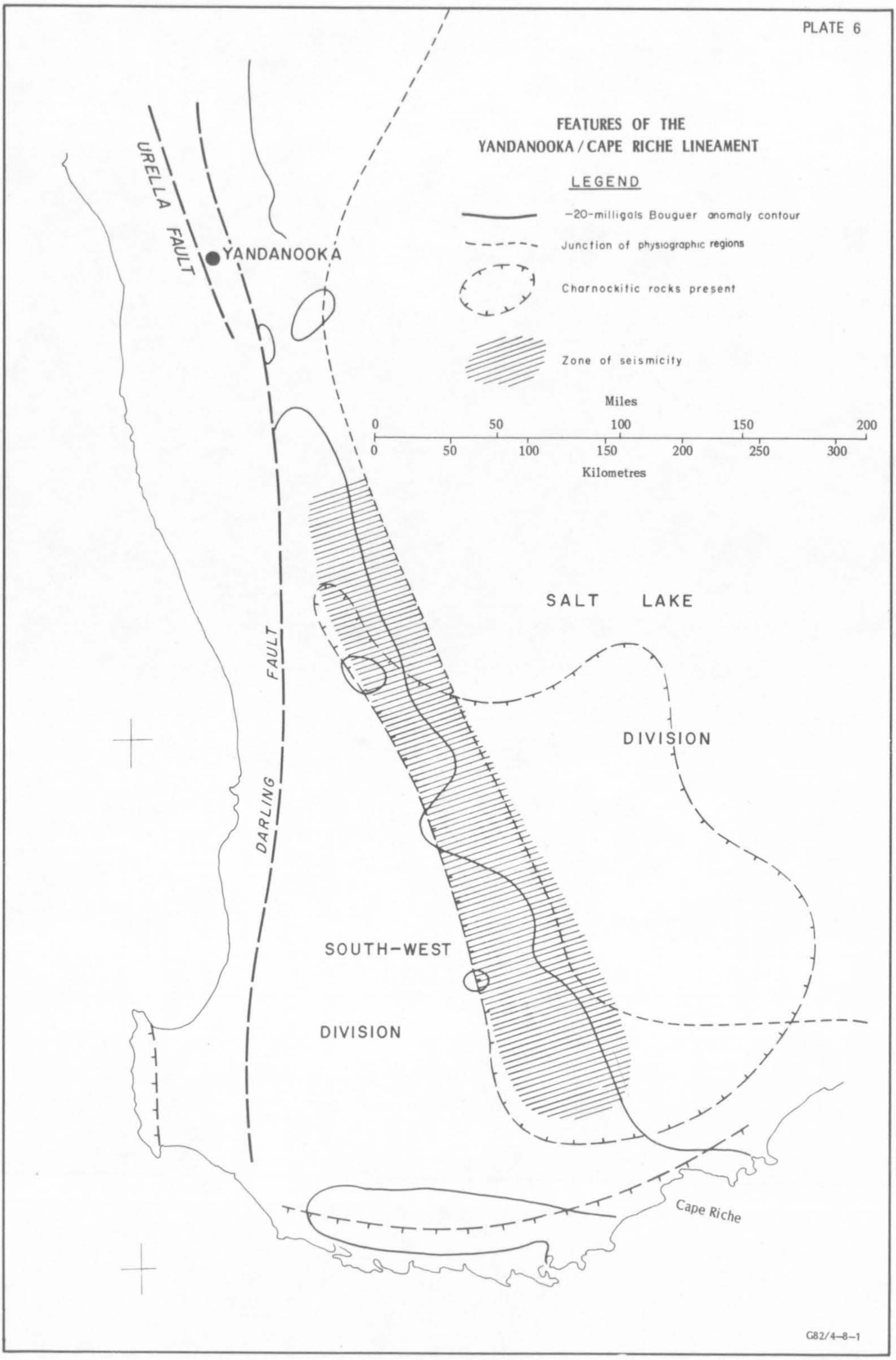


PLATE 6
FEATURES OF THE
YANDANOOKA / CAPE RICHE LINEAMENT
LEGEND
-20-milligals Bouguer anomaly contour
Junction of physiographic regions
Charnockitic rocks present
Zone of seismicity
Miles
0
50
100
150
200
0
50
100
150
200
250
300
Kilometres
URELLA FAULT
YANDANOOKA
DARLING FAULT
SALT LAKE
DIVISION
SOUTH-WEST
DIVISION
Cape Riche
G82/4-8-1

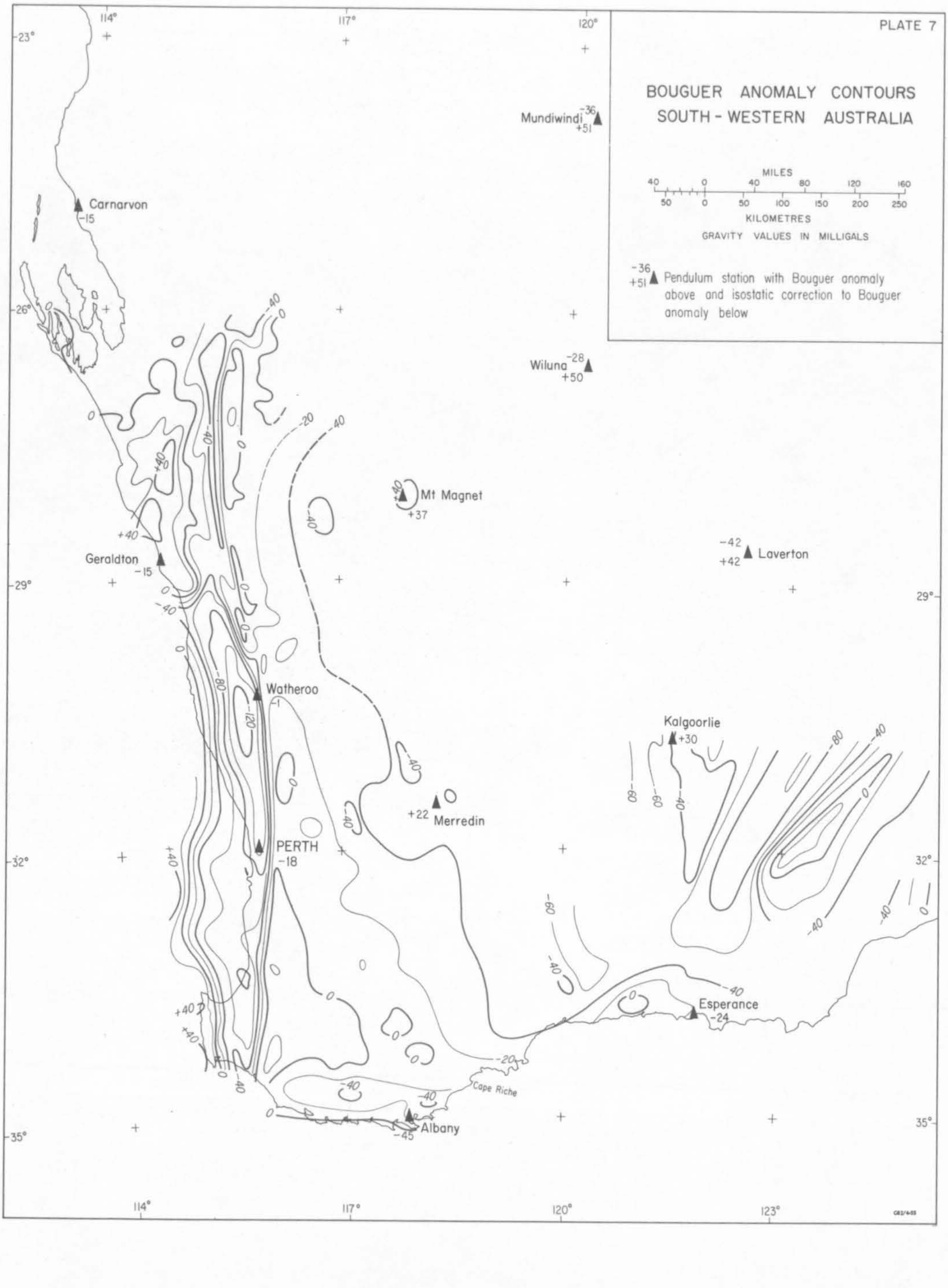


PLATE 7
BOUGUER ANOMALY CONTOURS
SOUTH - WESTERN AUSTRALIA
MILES
KILOMETRES
GRAVITY VALUES IN MILLIGALS
Pendulum station with Bouguer anomaly above and isostatic correction to Bouguer anomaly below
Mundiwindi
Carnarvon
Wiluna
Mt Magnet
Geraldton
Laverton
Watheroo
Kalgoorlie
Merredin
PERTH
Esperance
Cape Riche
Albany