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MECKERING EARTHQUAKE INTENSITIES AND NOTES ON EARTHQUAKE RISK FOR WESTERN AUSTRALIA

by

I.B. EVERINGHAM and P.J. GREGSON

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SUMMARY

The 1968 Meckering earthquake with magnitude (M) 6.8 was felt within a radius of about 700 km (440 miles). Intensities in the range MM VII to MM IX were observed within 14 km (9 miles) of the earthquake fault trace. The isoseismal (of mean radius of 80 km (50 miles)) enclosing the area of MM VI intensity bulged to the east, indicating that damaging energy was best propagated in that direction. This effect probably decreased damage to Perth considerably.

A comparison of the isoseismals of the Meeberrie (1941) and Meckering earthquakes revealed that the Meeberrie magnitude was previously underestimated because the focal depth was probably greater than assumed. A depth of 70 km (44 miles) and magnitude (M) 7.5 were determined from the isoseismals.

The combined isoseismal and seismicity data showed that statistically Perth and central wheatbelt towns could suffer earthquake intensities of MM VII or more on an average of every few hundred years. Broome and Port Hedland, the towns with highest risk, could suffer more often. Of the larger towns Dampier and Kalgoorlie are least likely to be affected unless new zones of seismicity are discovered.

Comparison of results for W.A., Adelaide and Canada suggests that risk in or near the Australian zones of seismic activity is similar to that in parts of eastern Canada and much less than along the western Canadian seaboard.

Further improvements in risk analysis would result from geological or geomorphological researches for evidence of past seismic activity, from regional investigation of subsoil conditions and from further studies of current seismicity.

INTRODUCTION

At 1059 Western Standard Time (0259 UT) on 14th October, 1968 a shallow earthquake of magnitude (M) 6.8 wrecked the town of Meckering, on the Precambrian Shield area of Western Australia. The epicentre calculated from the instrumental data of the Mundaring Observatory was at latitude 31°37' S longitude 116°58' E, two and a half kilometres north-west of the township which is in the eastern area of a zone of known seismic activity extending across the south-western part of the Shield (see Plates 6, 7).

The earthquake was remarkable in that it was associated with faulting clearly seen at the surface along an arcuate zone 32 km in length trending north-south and convex westwards. Immediately east of this fault the land was uplifted by up to 1.5 metres and over-thrust to the west by up to 2.0 metres to form a scarp. A preliminary description of the earthquake and its effects is given by Everingham (1968).

The purpose of this paper is to present and to discuss macroseismic data, i.e. the earthquake's effects observed on a large scale without instrumental aid, which are of interest because of their relationship to earthquake risk and to the depth and magnitude of the earthquake.

The distribution of the macroseismic effects is represented by isoseismals or lines showing boundaries between regions of successive ratings of intensity (degree of shaking) rated on the Modified Mercalli (MM) scale described by Richter (1958). The report does not describe details of damage used in some intensity assessments, such information being available elsewhere, i.e. Institution of Engineers, Australia (1969), Beresford (1968), Lay (1968), Gordon (1968), and unpublished preliminary reports of the State and Commonwealth Works Departments.

A comparison of the intensity data from the Meckering earthquake with those from the 1941 Meeberrie earthquake (550 km north of Perth) is made in order to relate the magnitude and depth of the two events. Aspects of earthquake risk in Western Australia are then discussed in the light of available seismicity and isoseismal information.

Isoseismal maps and intensities are shown on Plates 1 to 5 and regions of known seismicity on Plates 6 and 7.

For this text all magnitudes have been converted to surface wave magnitudes M (commonly designated M_s).

2. ISOSEISMAL MAPS

Four hundred and twenty intensity questionnaire forms were distributed to about five observers in the region of each township in a network selected to cover the State south of latitude 22°S, whilst a further eighty were distributed to residents of Perth, Fremantle and suburban areas. Although the response from the latter area was poor (fifty percent) overall results were satisfactory as eighty percent of the questionnaires were answered.

Each town or centre (from which there were up to five replies) was allotted an intensity rating which is shown on either Plate 1 or 2. Field visits were made in the region of Meckering in order to assess the higher intensities near the earthquake epicentre. On Plate 3, showing intensities for the suburban area, each intensity shown was assessed from one questionnaire reply or from building damage.

Intensities in the range VII to IX were observed within roughly 14 kilometres of the earthquake fault zone, and the isoseismals were about parallel to the fault. Because of the sparse population and rapidity with which the intensity decreased away from the fault, the isoseismals are relatively inaccurate. Gordon (1968) noted that houses were rendered useless up to 19 km east of the fault and 5 km west of the fault and that severe damage occurred in northerly and southerly directions along the fault trend to a distance of 30 km from Meckering. Gordon's first observation indicates that the energy sufficient to cause say MM VIII intensities was propagated better towards the east than towards the west. However, asymmetry would be less pronounced if damage was related to the east dipping fault plane rather than to the fault trace.

In the region with intensity VII or greater most old brick or stone buildings were unsafe after the earthquake. Car passengers in this region at the time of the earthquake reported feeling that the tyres were flat and that wind was unusually strong. Ground waves were reported to have been seen by several people in the open during the earthquake. Railway-lines, pipe lines and roads were all fractured at the fault zone, and extensive cracking of the ground occurred in its immediate vicinity. Old brick houses within 100 metres of the fault were flattened but timber framed sheds and open or enclosed verandahs remained upright. Away from the fault, cracks due to slumping were common, particularly along river banks, around salt lakes, and where roads run along embankments.

In Meckering (MM IX) a bank, hotel, shire hall, three churches and sixty of about seventy five houses were wrecked. Few of the remaining buildings were habitable, fibro and galvanised iron clad timber-framed structures being outstanding because of the comparative lack of damage to them.

The MM V-VI isoseismal (mean radius 80 km, see Plate 2) indicates that energy at the level required to cause MM VI intensity was best propagated towards the east. This was most likely due to the mechanism of the earthquake. A similar effect occurred with the Meeberrie earthquake (see Plate 5), and uneven propagation has also been noted on numerous Mundaring and Kalgoorlie recordings of the Meckering aftershocks.

The region of intensity MM VI was characterised by notable cracking of oldest brick and masonry buildings, and alarm caused to many residents. Changes of water flow in wells and springs were noted at several localities.

It is of interest to examine an independent assessment of an intensity level made by the W.A. Government Relief Advisory Committee when examining damage claims. Areas where relief claims were paid after damage was proven by a close inspection are shown on Plate 4. The areas of proven damage (which were drawn by the Committee without reference to the authors) generally coincide with the area where the intensity rating was MM VI or more and confirm the shape of the MM V-VI isoseismal. Their results show that notable damage would not be expected where the intensity was less than MM VI.

The isoseismal surrounding the region of MM V intensities is fairly irregular, with bulges to the east and to the south-west. Relatively high values at Collie, on a minor sedimentary basin, and further to the south-west in the Perth Basin area are probably the result of local sub-soil conditions. Similarly the locally high intensity ratings of MM VI occurring in the Perth area, mostly in the vicinity of the Swan River (see Plate 3), can be attributed to sub-soil conditions there. In many parts of Perth, minor cracking of plaster and slight opening of existing cracks in walls in many buildings were possibly effects arising from increased settlement rather than the direct result of the transient vibrations.

The accuracy of the outer isoseismals is not good because they are based on fairly scattered observations and because high winds influenced perceptibility in most areas. The most distant felt reports were from east of Carnarvon, 720 km north of the earthquake epicentre and to the east of Kalgoorlie at a distance of 640 km.

NATURE OF GROUND MOTION

Of prime interest in earthquake resistant design is the nature, period, duration and amplitude of the ground motion in an earthquake. Although seismographs at Mundaring were too sensitive to properly record the violent motion from the nearby Meckering earthquake, very rough estimates of maximum ground motion at Mundaring could be made. These are given below.

Wave type	Shear (S)	Raleigh (LR) (Short-period)	Raleigh (LR) (Long-period)
Period (sec.)	0.3	1.0	12
Max. Disp. (mm)	1	6	1
Max. Vel. (mm/sec.)	25	37	0.52
Max. Accel. (mm/sec^2)	520	240	0.26

The movements of the bedrock (granitic rocks) will be essentially the same at a given distance from an earthquake of given magnitude but complexities of the spectrum of movements at a given point at the surface arise from the behaviour of the local sub-soils and any softer sedimentary rocks between this point and the bedrock (Eiby, 1965). For example, periods of ground motion in Perth might differ from those at Mundaring even if intensities were the same. Notwithstanding, shear waves and short period Raleigh waves would cause most damage because (a) their period is in the range of free periods of the larger structures, (b) they have a large horizontal component of motion and (c) the maximum ground acceleration and velocity are associated with them.

Unfortunately, although intensities can be assessed with a fairly high degree of mutual consistency they cannot be closely correlated with ground accelerations, so that it is not possible to derive accelerations from intensity with any degree of certainty (Eiby, 1965). However, some idea of acceleration can be gained from what Richter (1958, p. 140) describes as a "passable empirical relation", namely:

$$\log a = J/3 - 1/2$$

where a is the acceleration in mm/sec^2, and J is the MM intensity. Accelerations derived from this relation are:

MM V	150 mm/sec^2
MM VI	300 " "
MM VII	600 " "
MM VIII	1200 " "

A useful acceleration value for a city area of Perth (MM VI) was obtained by Mr. R.S. Minchin of the University of Western Australia (personal communication). At St. George's Cathedral bells rolled over from the inverted set position. From the physical dimensions of the bells he calculated that the acceleration at the top of the bell tower required to do this was at least 650 mm/sec^2 (0.07g) in the east-west direction. Also Mr. J. Wheeler (personal communication) calculated that in the Perth suburb of Claremont, where the intensity was rated MM V, acceleration was in the range 950-1400 mm/sec^2 in the east-west direction. His values were based on the fact that of two similarly orientated ornaments having matched elongated rectangular bases but slightly unmatched positions for their centres of gravity, one was toppled by the earthquake whilst the other with the lower centre of gravity remained upright.

4. DEPTH OF FOCUS

Using the isoseismal maps (Plates 1 and 2) a depth of focus for the Meckering earthquake was estimated from the empirical formula of Blake (1941);

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

where J = maximum intensity (MM) = IX at Meckering

RJ = radius (km) of area enclosed within isoseismal j

h = depth of focus (km)

s = empirical constant = 4.0

The mean depth was 13 $\pm$ 5 km which agrees for practical purposes with instrumentally determined depths calculated by the United States Coast and Geodetic Survey, 0 $\pm$ 8 km and from the Mundaring Observatory network, 7 $\pm$ 5 km.

5. MEEBERRIE EARTHQUAKE MAGNITUDE

Initially it was considered that the Meckering earthquake was the largest earthquake to have occurred beneath the Australian continent (e.g. Doyle, Everingham and Sutton, 1968 p. 296). This conclusion was based on the preliminary determination of the surface wave magnitude being slightly greater than Gutenberg & Richter's (1954) determination for the previously largest known earthquake, which occurred at Meeberrie on 19th April, 1941. The impression was strengthened by the devastation caused at Meckering.

However, the map of Clarke, Prider and Teichert (1955) shows that the isoseismals for the Meeberrie earthquake (converted from the Rossi Forell to the MM scale) include much larger areas than isoseismals with the same values for the Meckering event (see Plate 5), which indicates that the magnitude of the Meeberrie earthquake was the greater of the two.

The degree of shaking caused by an earthquake is related inter alia to the earthquake magnitude and depth. Isoseismal radii increase with increasing magnitude and the maximum intensity decreases with increasing depth.

Near-surface geological conditions also contribute to the shaking effects but because isoseismals considered for both earthquakes cover similar terrains, the larger radii for Meeberrie isoseismals cannot be due to geological effects.

Blake's empirical formula was applied to the Meeberrie data and a focal depth of 70 km was found for the earthquake. Some confirmation for this focal depth is given by Bolt (1956) who stated that the Meeberrie event was "the only recorded inland Australian earthquake with appreciable focal depth". He computed a depth of 32 km but in such determinations errors are often considerable. (Appreciable depth would explain the lack of faulting at the surface from the Meeberrie earthquake).

In magnitude determinations using surface wave amplitudes, focal depth is of importance because deep earthquakes generate relatively weak surface waves, and determinations are made for earthquakes only with focal depth less than 50 km. Hence, because the Meeberrie earthquake was deeper than previously assumed, the original magnitude determination was too small.

Magnitudes for the Meckering and Meeberrie earthquakes were therefore determined from their maximum intensity and focal depth using Shebalin's (1956) relationship with magnitude:

$$J = 1.5M - 3.5 \log h + 3$$

where J = maximum intensity (MM) and h = focal depth (km)

Shebalin's equation was determined empirically from data for North America mainly. There, because of local geological conditions, intensities are generally higher than from a similar earthquake beneath a shield. Therefore use of a maximum intensity half a rating higher than that observed, i.e. a normalised intensity, is considered justifiable for magnitude estimates for inland Western Australian earthquakes. This assumption is supported by the agreement between the value of the Meckering magnitude using the normalised intensity (column b below) and the value of the relatively accurate instrumental determination (M 6.8). Results are as follows:

	Meeberrie		Meckering	
	(a)	(b)	(a)	(b)
Max. MM Intensity	VII to VIII	VIII	IX	IX to X
Focal Depth	70	70	13	13
Magnitude	7.2	7.7	6.6	6.9

Note: (a) observed intensity (b) normalised intensity.

It may be seen from the table that the Meeberrie earthquake magnitude is greater than for the Meckering earthquake. The most likely value is considered to be about 7.5.

6. EARTHQUAKE RISK

Introduction

Isoseismal and seismicity data are essential bases for estimating earthquake risk. The data available for Western Australia are very limited and therefore it is emphasized at the outset that it is not possible to make a good assessment of earthquake risk. Accurate predictions of the size, place or time of earthquakes cannot be made, even in well studied regions such as California (U.S.A.) or Japan. For this report the risk is expressed in the form of intensity return periods. The results are of a very preliminary nature designed to give a rough idea of earthquake risk in W.A. and a more refined treatment of the data needs to be carried out before the results can be regarded with any finality.

Earthquake frequency

The general approach is to assume that over a long term the rate of seismic energy release in a given zone is fairly constant. Therefore, once this rate is established, the average frequency of occurrence of earthquakes with given magnitudes, and hence their statistical return periods, can be calculated for the zone. The standard equation is:

$$\log N = A - bM$$

where N is the number of events with magnitude M or greater occurring in a given zone during a given period.

A is a parameter which varies regionally and indicates the level of activity.

b is a parameter which relates the number of events with magnitude M to those with M + 1.

Generally average frequencies are valid only for the smaller shocks which have been frequent enough for statistical treatment and even the zones of activity are difficult to define.

Western Australian zones of seismicity, identified by letters A to N, are shown on Plate 7. The information for the zoning has been gathered mostly since 1959, when short-period seismographs were installed at Mundaring. Prior to this data were sparse.

The frequency and distribution of earthquakes is best known for Zone A, an area of approximately 35,000 km^2 east of Perth. Using data for the period October 1959 - December 1968 inclusive for earthquakes with M in the range 2.5 to 5.0, the magnitude/frequency relation for this zone was found to be

(a) $\log N = 3.27 - 0.82\ M$ (all events)

(b) $\log N = 3.24 - 0.92\ M$ (excluding 1968 Meckering aftershocks)

where N is the number of events per year

The inclusion of Meckering aftershocks decreases the parameter b because the aftershocks have a greater than normal proportion of relatively larger events (for aftershocks alone b = 0.60). Benioff (1951) showed that this effect is a feature of aftershocks sequences of many earthquakes.

Average earthquake frequencies for other well defined zones (B-G) in W.A. have not been determined but judging by the larger events recorded so far (see Doyle et al, 1968) the average frequencies appear to be of the same order per unit area as for Zone A.

Apparent return periods (1/N) calculated for Zone A from the above equations are given in Table 1.

Intensity Information

To obtain some idea of risk (i.e. MM intensity versus average return period) for any area of interest it is necessary to combine the magnitude/frequency data with intensity data. The latter are scarce for Western Australian events but overseas data can also be employed.

To date, examination of newspaper reports, lists of events given by the Bureau of Meteorology (1929), and data discussed by Everingham (1966), have revealed that the earliest Western Australian earthquake noted was felt (MM V?) in Perth on 4th August 1849, and that prior to the Meckering event, only two earthquakes (Indian Ocean off North West Cape, 1906, and Meeberrie, 1941) had been felt over a large portion of the State. Smaller events which did not cause appreciable damage were occasionally felt over areas up to approximately 100,000 km^2. Isoseismal maps are available only for the Meeberrie and Meckering earthquakes as discussed above, and the 1963 Nourning Spring earthquake with M 5¼ (Everingham, 1966).

First, curves of intensity versus distance and magnitude were plotted from the W.A. isoseismal data for shield areas. These were then smoothed and adjusted so that at any given distance intensity was proportional to 1.5M (for intensities of MM VI or more). The factor 1.5 has been used in various investigations in the U.S.A. (Cornell, 1968 p 1586) and is compatible with the W.A. data. Next, similar curves were derived from the empirical data for areas underlain by thick unconsolidated earth (such as the Perth area). These showed that intensities are one unit higher for an unconsolidated area than for a shield area, at a given distance from an earthquake.

Results are listed in Tables 2 and 3 in the form of isoseismal radii for various earthquake magnitudes.

Comparison of shield data (Table 2) with those for the geologically similar areas of Canada (Milne and Davenport, 1969) shows that, for a given magnitude the W.A. shield isoseismal radii are smaller and that the averages of the eastern and western Canadian isoseismal radii lie between values given in Tables 2 and 3.

Risk to Perth

Consider Perth: here intensity MM VI caused slight damage; intensity MM VII would possibly cause appreciable damage; and intensity MM VIII would possibly cause a great deal of damage and loss of life.

Using the isoseismal results in Table 3, circles centred on Perth were drawn within which earthquakes of given magnitudes would cause a given minimum intensity in Perth. For example circles for an intensity MM VII or greater are shown on Plate 7. The "source area" of events of given magnitudes producing this minimum intensity is then the sum of the parts of active zones enclosed by the particular circles.

Over a given period the number of these events likely to affect Perth depends on the average frequency of events per unit area in the active zones and on the size of the "source area", i.e. frequency of events = (n) x (source area), n being the average frequency per unit area. Taking Zone A as unit area (so that N for Zone A = n) and assuming that (a) activity is distributed evenly within each zone, (b) Zone B has the same activity/unit area as Zone A, and (c) undefined zones of weaker activity (I & J) have one fifth of this activity/unit area, approximate return periods at Perth for intensities above MM V were determined using equations below:

$$\frac{1}{R_J} = \frac{1}{R_{5.5}} + \frac{1}{R_{6.0}} \cdots\cdots\cdots\cdots + \frac{1}{R_{8.5}}$$

where $R_{5.5} = 1/(N_{5.5}$ x source area for intensity J)

R_J is the apparent return period for intensities MMJ or greater.

$R_{5.5}$ is the return period for intensity MMJ or greater from events with M in the range 5.5 $\pm$0.25 and

$N_{5.5}$ is the average frequency of events with M in the range 5.5 $\pm$ 0.25 as derived from Table 1.

Results are listed in Table 4.

The return periods using Zone A equation (a) are about one fifth of those given by equation (b); they may be regarded as maximum and minimum values of risk estimates for Perth but periods derived from equation (a) are considered to be more applicable. The reasons are that, although equation (a) includes some aftershocks of the 1968 Meckering earthquake:

(a) because of their scarceness all (three) events with M greater than 5 were omitted from the analysis. This meant that only about eighteen percent of the total energy release of the Meckering earthquake sequence is included in the result.

(b) most of the earthquakes in Zone A occur in its northern region close to Perth so that the frequency per unit area (for Perth) could be double that used in calculation of return periods in Table 4 (i.e. return periods would be halved).

The results shown in Table 4 and on Plate 7 suggest that:

(a) Perth could possible experience an MM VI intensity (as from the Meckering event) on an average of about every one hundred years.

(b) An earthquake could possibly cause an intensity of MM VII in Perth on an average of every several hundreds of years.

(c) The chance of Perth suffering the badly damaging intensities of MM VIII or more is small.

(d) The most likely source region for earthquakes affecting Perth is Zone A, east of the city.

(e) Only major events to the west or southwest in Zones B or J could cause intensities of MM VII or more in Perth.

(f) There is little likelihood of notable effects in Perth from earthquakes with M less than 6.0.

Regional aspects of risk

In the same manner as for Perth and assuming Zone A average frequencies per unit area for Zones B to F and one fifth of this activity for Zones H to K, apparent return periods for intensities of MM VI or greater were estimated for larger centres of population in W.A. These are listed in Table 5 in order of decreasing risk. Adelaide return periods were also included for comparison (discussed below).

From the Port Hedland and Adelaide values shown in Table 5 it can be seen that the risk in an area of unconsolidated subsoil could be three times as great as for a normal shield region where seismic activity is the same in each region. In the risk assessment only two types of foundation were assumed, unconsolidated sediments (poor) and shield rock (good) but obviously there is a continuous range of subsoil conditions and for each locality a subsoil or foundation factor should be determined in order to improve prediction of earthquake effects.

Return periods given by equations (a) and (b) for Zone A average frequencies could tentatively be used as maximum and minimum values except for Meckering for which equation (a) may be more representative for the same reasons that it is considered more accurate for Perth.

The results show that the minimum values of return periods for the probable damaging intensities of MM VII or greater at the main W. A. centres are all over 200 years except at Broome and possibly Port Hedland. However, historical records suggest that the minimum return periods for these latter towns as listed in Table 5 are too low; perhaps the quality of the foundations has been underestimated or earthquake frequencies in surrounding active zones could be closer to those given by the Zone A equation (b). Wheatbelt towns in the northern part of Zone A (e.g. Meckering) could, on an average experience MM VII intensities at 2-300 year intervals and MM VIII intensities every 1000 years or more. On present evidence there appears to be negligible chance of earthquake damage at Kalgoorlie, Dampier and Albany. (However, rockbursts could cause very localised damage at Kalgoorlie).

It is of interest to compare W. A. return periods with those from Adelaide and Canada.

Return periods for Adelaide were calculated in the same manner as for W. A. stations. Zone A, equation (a) has a similar b factor to that obtained by Sutton & White (1968 p 30) for South Australia and average frequencies calculated from the equation agree reasonably well with the South Australian data listed by Doyle et al (1968). The foundation effect in the Adelaide area is probably somewhere between that of the shield and basin types of subsoil so that the apparent return period for intensities of MM VII or greater is possibly in the order of 100 years. The return period for damaging intensities of MM VIII is possibly about 400 years.

The results in Table 5 have been related to the Canadian results of Milne and Davenport (1969), by converting intensities to accelerations (via Richter's formula) and using 100 year return periods. For example, accelerations (100 year return period) for Adelaide and Perth are 0.06g and 0.03g respectively. These values are low compared with the values (0.06 to 1.00g) along the western Canadian seaboard but are similar to results for the southern part of the Province of Quebec, where the maximum value of the acceleration is 0.20g.

Alternatively approximate return periods for 0.1g can be calculated for comparisons with Canadian data. Values are Adelaide 250 years, Meckering 600 years, Perth 1100 years (Australia), Quebec 406 years, Ottawa 602 years, Montreal 1087 years (eastern Canada) and Massett 37 years, Seattle 39 years and Vancouver 170 years (western Canada).

7. CONCLUSIONS

The Meckering and Meeberrie earthquake occurrences are convincing evidence that Perth and many country towns in Western Australia could suffer damage by earthquakes if building standards remain as they are. The Meckering event was particularly important in that it aroused public interest in earthquake risk, and provided good basic data for its assessment.

The Perth area was comparatively unaffected by the earthquake but suffered a "near miss" in that the damaging energy was best propagated to the east of Meckering away from Perth. Had the propagation pattern been reversed it is probable that Perth intensities would have been at the MM VII level in which case more serious damage could have occurred to numerous buildings not designed to withstand the earthquake shaking.

The seismicity and intensity data suggest that Perth and the majority of the more heavily populated parts of Western Australia are likely to suffer relatively dangerous intensities of MM VII or more on an average of every few hundreds of years. Thus, working on say sixty years as the life-time of human beings and buildings, there is about a one in ten chance that either will be affected by an earthquake, and it appears logical to ensure that injuries and financial loss from these earthquakes do not occur. This need not necessarily involve extensive revision of building codes but more attention to structural details would probably be required.

Further improvements in risk analysis could arise from more detailed seismicity studies, geological or geomorphological researches for more evidence on the rate of seismic activity, and from engineering investigation of foundation subsoils and building methods.

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TABLE 1

EARTHQUAKE APPARENT RETURN PERIODS - ZONE A

M range	Return period (R) (years) (a)	(b)
5.25 - 5.75	18	60
5.75 - 6.25	46	170
6.25 - 6.75	120	500
6.75 - 7.25	310	1400
7.25 - 7.75	760	4200
7.75 - 8.25	2000	12000
8.25 - 8.75	5000	34000

Note: Data for the period October 1959 - December 1968 inclusive and earthquakes with M in the range 2.5 to 5.0, column (a) all events; column (b) excluding 1968 Meckering aftershocks.

Return periods for events within the 0.5 ranges of M are almost equal to those for earthquakes with magnitude equal to or greater than the mid-magnitude of the range e.g. apparent return periods for $M \geqslant 5.5$ are (a) 17 years and (b) 66 years.

TABLE 2

ISOSEISMAL RADII-SHIELD TYPE SUBSOIL

M	Radius (km) MM V-VI	Radius (km) MM VI-VII	Radius (km) MM VII-VIII
4.5	-	-	-
5.0	20	-	-
5.5	30	15	-
6.0	50	25	10
6.5	80	40	20
7.0	120	60	30
7.5	180	90	45
8.0	260	130	65
8.5	400	200	100

Note: MM V-VI isoseismal encloses area with intensity MM VI or more.

TABLE 3

ISOSEISMAL RADII-UNCONSOLIDATED SUBSOIL

M	Radius (km) MM V-VI	Radius (km) MM VI-VII	Radius (km) MM VII-VIII
4.5	20	-	-
5.0	40	20	-
5.5	60	30	15
6.0	100	50	25
6.5	160	80	40
7.0	240	120	60
7.5	360	180	90
8.0	520	260	130
8.5	800	400	200

Note: MM V-VI isoseismal encloses area with intensity MM VI or more.

TABLE 4

APPARENT RETURN PERIODS OF INTENSITY - PERTH

M range ± 0.25	Return period MM$\geq$ VI (years)		Return period MM$\geq$ VII (years)		Return period MM$\geq$ VIII (years)	
5.5	1200	4200	-	-	-	-
6.0	320	1200	-	-	-	-
6.5	220	920	1700	7000	-	-
7.0	300	1300	1100	5200	-	-
7.5	430	2400	1100	6100	7600	-
8.0	720	4700	1600	9800	6600	-
8.5	850	5800	2600	-	6400	-
All M	60	270	290	1500	2300	-

Notes: For values in columns (a) average frequencies for Zone A equation (a) were used (see Table 1).

For values in columns (b) average frequencies for Zone A equation (b) were used.

Return periods greater than 10,000 years omitted from the Table.

TABLE 5

APPARENT RETURN PERIODS OF INTENSITY - W.A.

PLACE	ASSUMED SUBSOIL TYPE	Return period MM≥ VI (a)	(b)	Return period MM ≥ VII (a)	(b)	Return period MM≥ VIII (a)	(b)
Broome	Basin	20	84	60	250	190	810
Port Hedland*	Basin	30	120	90	400	300	1280
	Shield	90	400	300	1280	900	4000
Meckering	Shield	60	220	220	790	910	4400
Perth	Basin	60	270	290	1500	2300	-
Bunbury	Basin	80	400	540	3200	4100	-
Carnarvon xx	Basin	120	680	910	5800	-	-
Geraldton xx	Basin	200	1200	2100	-	-	-
Albany	Shield	1500	-	-	-	-	-
Dampier xxx	Shield	2200	-	-	-	-	-
Kalgoorlie	Shield	6300	-	-	-	-	-
Adelaide*	Basin	24	100	60	270	200	830
	Shield	60	270	200	830	660	2700

Notes:

Shield type subsoil - isoseismal radii as in Table 2.

Basin (unconsolidated) type subsoil - isoseismal radii in Table 3.

* Subsoil type probably between shield and basin.

xx Effects from Zone L also possible.

xxx Effects from Zone M also possible.

Other notes as for Table 4.

APPENDIX I

Modified Mercalli Intensity Scale (1956 version)

(After Richter, 1958, pp 136-138)

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a heavy ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frame creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken. Knick knacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visibly, or heard to rustle-CFR).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments-CFR). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving-in along gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry C heavily damaged, sometimes with complete collapse; masonry B seriously damaged. (General damage to foundations-CFR). Frame structures, if not bolted, shifted off foundations. Frames wrecked . Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dykes, embankments. Large landslides. Water thrown on banks of canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Masonry A, B, C, D. To avoid ambiguity of language, the quality of masonry, brick or otherwise, is specified by the following lettering (which has no connexion with the conventional Class A, B, C construction).

Masonry A. Good workmanship, mortar and design; reinforced, especially laterally, and bound together by using steel, concrete, etc; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed in detail to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; not extreme weaknesses like failing to tie at corners, but neither reinforced nor designed against horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

APPENDIX 2

EARTH TREMOR REPORT

Please underline suitable words and fill in answers where applicable as soon as possible while your memory is clearest. Also return report if not felt, as that information is also important.

PLACE (Relate to nearest township)
....

TREMOR FELT Yes No

and/or HEARD Yes No

INTENSITY OR STRENGTH was faint, moderate, strong.

MOTION - rapid, slow LASTED FOR.........sec./minutes

FELT LIKE - sudden jolt, passing heavy truck, slow vibration, swaying.

Remarks..

LOUDNESS (if heard) - faint, moderate, very loud.

Sounded like - low rumbling, passing truck, passing train, thunder, distant explosion, underground explosion, building being struck, creaking of building structure, loud roaring.

Remarks..

DIRECTION - tremor appeared to come from N, NE, E, SE, S, SW, W, NW, can't say.

Direction of shaking was.........................

your LOCATION was - outdoors, indoors..........................

walking, standing, sitting, sleeping........................

Remarks..

Type of BUILDING was - concrete, stone, modern brick, older brick, brick veneer, fibro, weather-board.

You were on - ground, 1st 2nd........ ....floor of building.

GROUND BENEATH LOCATION was rock, soil, sand, loose, compact, filled in, marshy, unknown.

<u>NUMBER OF OBSERVERS</u> was - you only, two, several, many, everyone in house, almost whole neighbourhood, everyone.

<u>AWAKENED</u> - no one, few, many, everyone.

Remarks..

<u>EFFECTS ON OBJECTS</u>

<u>Rattling</u> of windows, doors, crockery.

<u>Creaking</u> of walls, frames of buildings.

<u>Swinging</u> produced in lights, doors, gates. Swung N, NE..................

<u>Shaking</u> of - trees, bushes, poles, overhead wiring.

<u>Shifted</u> furniture, small objects.

<u>Overturned</u> - furniture, small objects, vases.

<u>Fall</u> of - books, small objects, pictures, plaster, monuments, walls, chimneys.

<u>Cracked</u> - plaster, windows, walls, chimneys, ground.

<u>Damage</u> - none, slight, moderate, considerable, great.

<u>to</u> - chimneys, walls, columns, water tanks, plaster, furniture, crockery.

<u>Type of structure damaged</u> - concrete, stone, modern brick, older brick, brick veneer, fibro, weatherboard.

<u>General Remarks</u>

Address ....

....

Date.....................

....

APPENDIX 3

MAGNITUDE DETERMINATION

Magnitude is a quantity that is intended to rate earthquakes according to their 'size'. It is determined from the trace amplitude on a seismogram and ideally, of course, all such determinations from seismograms obtained at different locations should yield the same value of magnitude for a particular earthquake. Intensity, on the other hand, refers to the degree of shaking at a specified place. This is not based on measurement but is a rating assigned by an experienced observer using a descriptive scale (Richter, 1958); it is the figure that usually interests insurance assessors and others concerned with earthquake damage.

The procedure for determining magnitudes is far from straightforward and the complexities involved are clearly indicated by Richter (1958) and others. Chiefly because of the different characteristics of seismograms of earthquakes at different epicentral distances and depths of focus, three main types of magnitude scale have emerged: local earthquake magnitude scales (M_L); surface wave magnitude scale (M or MS); and body wave magnitude scale (m or m_b).

The original local magnitude scale (M_L) was devised by Richter for earthquakes in Southern California using standard Wood-Anderson seismographs and is the value frequently referred to as the 'Richter magnitude' or 'magnitude on the Richter Scale'. With the installation of many short-period, high-magnification, electromagnetic seismographs (e.g. Benioff instruments), it has been possible in some regions to obtain consistent Richter local magnitudes from the records of such instruments after allowing for the different magnification and assuming the same amplitude-to-distance relation found by Richter for Southern California. This is the procedure adopted by Australian stations close to an earthquake.

In general it is difficult to extend a local magnitude scale to distances beyond about 600 km, and an alternative scale has been developed by Gutenberg and Richter, which uses the computed ground amplitude of surface waves with periods near 20 seconds. This scale (designated M or MS) was particularly useful when few stations were equipped with high-magnification, short-period instruments.

Because deep focus earthquakes do not register surface waves of appreciable amplitude with periods near 20 seconds, a magnitude scale for such earthquakes must be founded on records of body waves. This scale (m or m_b) was devised by Gutenberg, and requires a knowledge, obtained from seismograms, of log (A/T) where A is the amplitude of the ground motion and T the corresponding period. The value of m is determined from the equation.

$$m = A_o + \log (A/T)$$

where A_o is an empirical constant which is a function of distance.

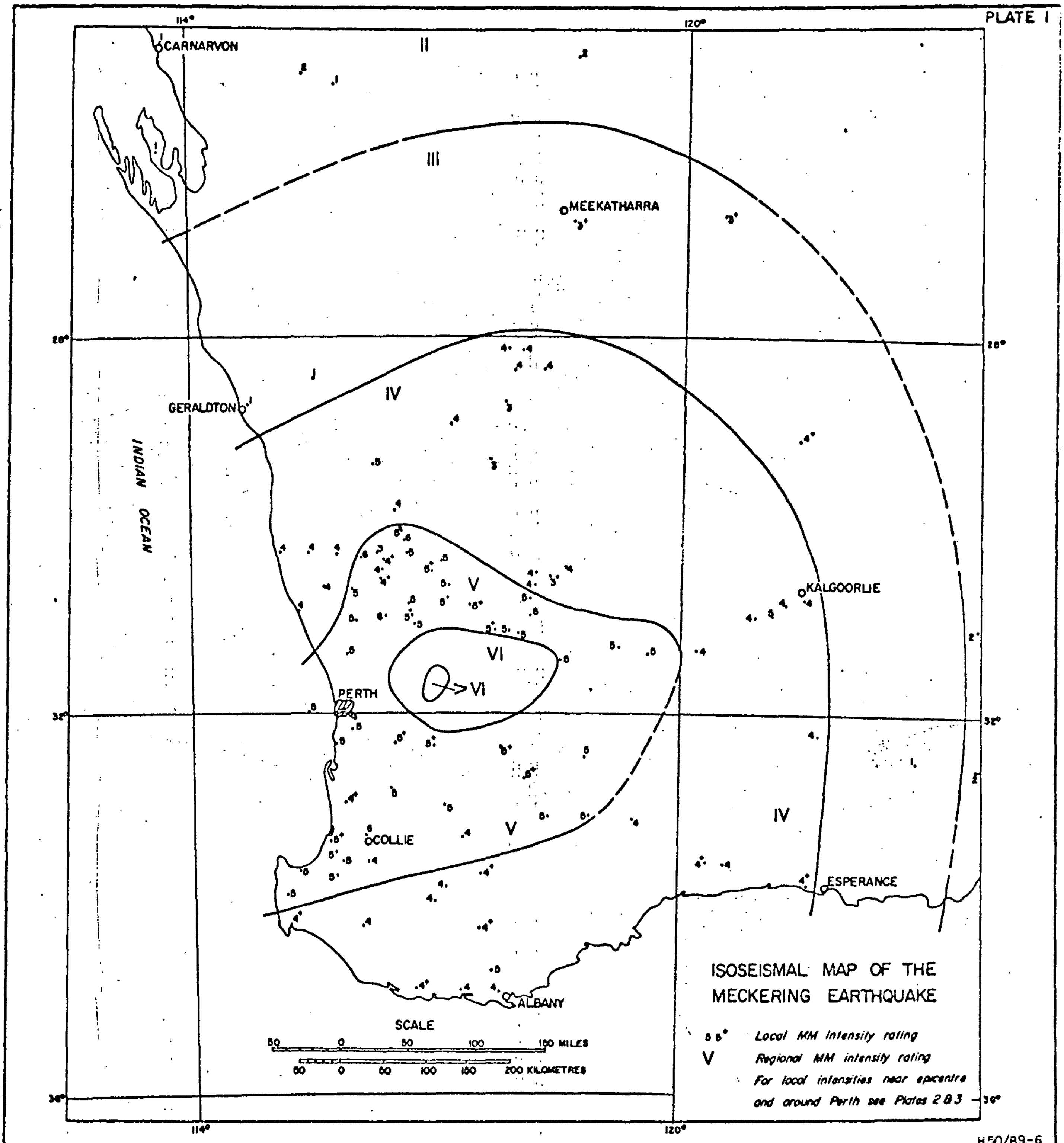
Several transformation formulae relating the three scales have been published by different authors. For example, Richter (1958) suggests:

$$m = 1.7 + 0.8\ M_L - 0.01\ M_L^2) \quad \text{within the } M_L$$
$$1.8 + 0.73\ M_L \quad) \quad \text{range 1 to 6}$$

and $m = 2.5 + 0.63\ M$

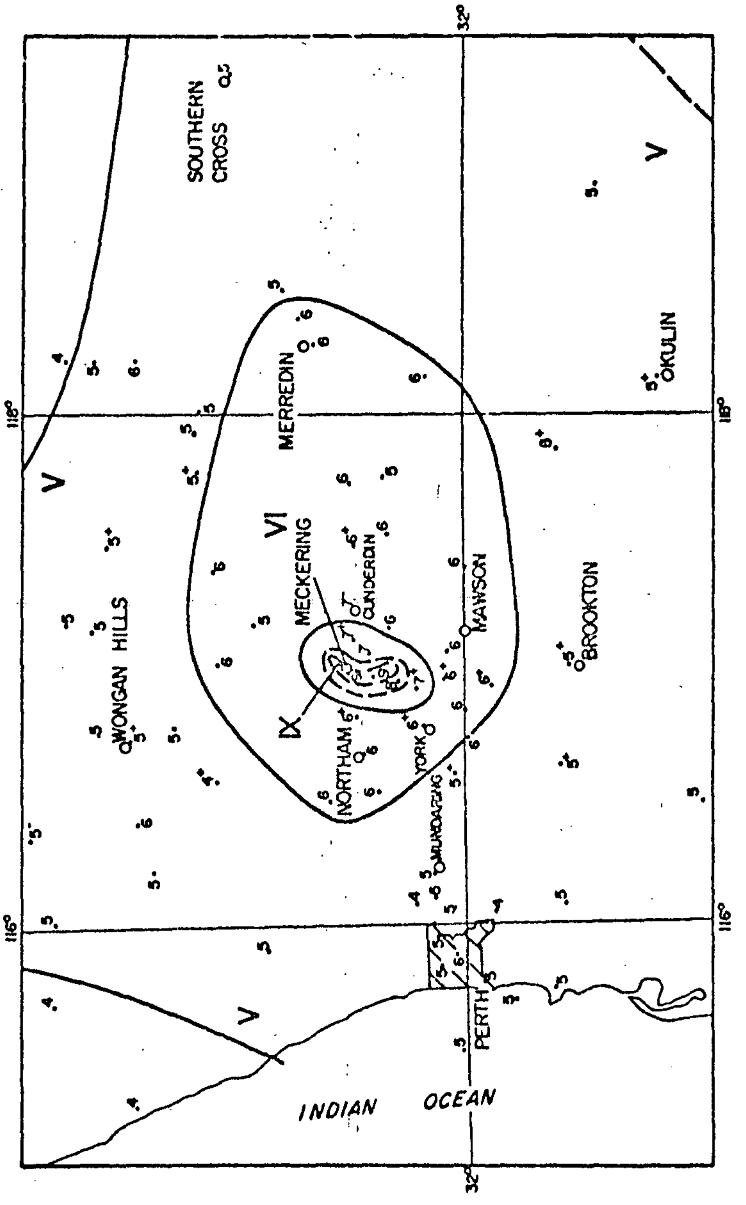
Because these relations have been determined empirically, independent magnitude estimates (M_L, M, m) for a single event are often not mutually consistent when compared using these, or similar, formulae.

PLATE I



H50/B9-6

PLATE 2



MECKERING EARTHQUAKE INTENSITIES
NEAR EPICENTRE

6 6+ Local MM Intensity rating
V Regional MM intensity rating

SCALE

50 0 50 100 MILES
50 0 50 100 KILOMETRES

H50/89-5

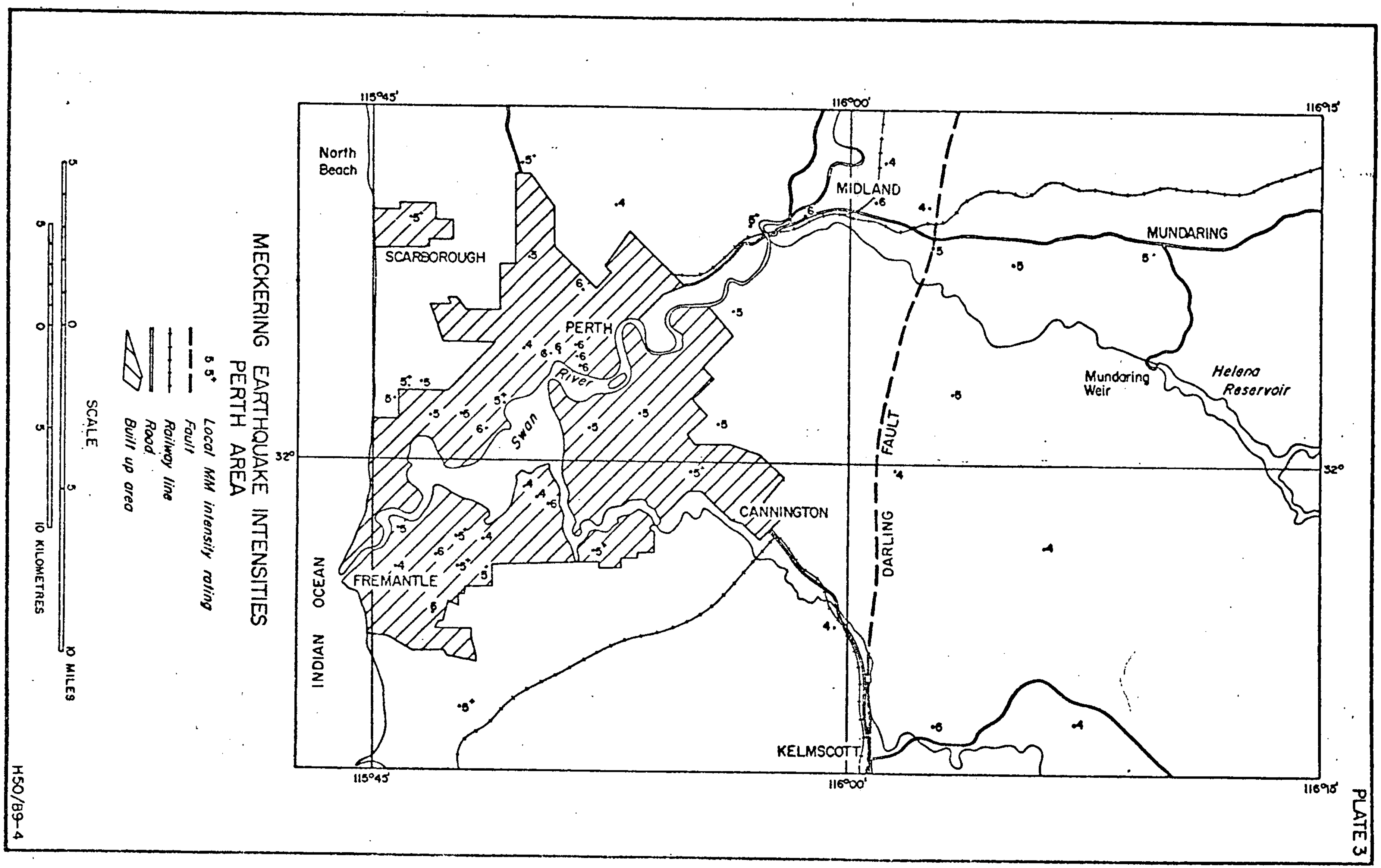
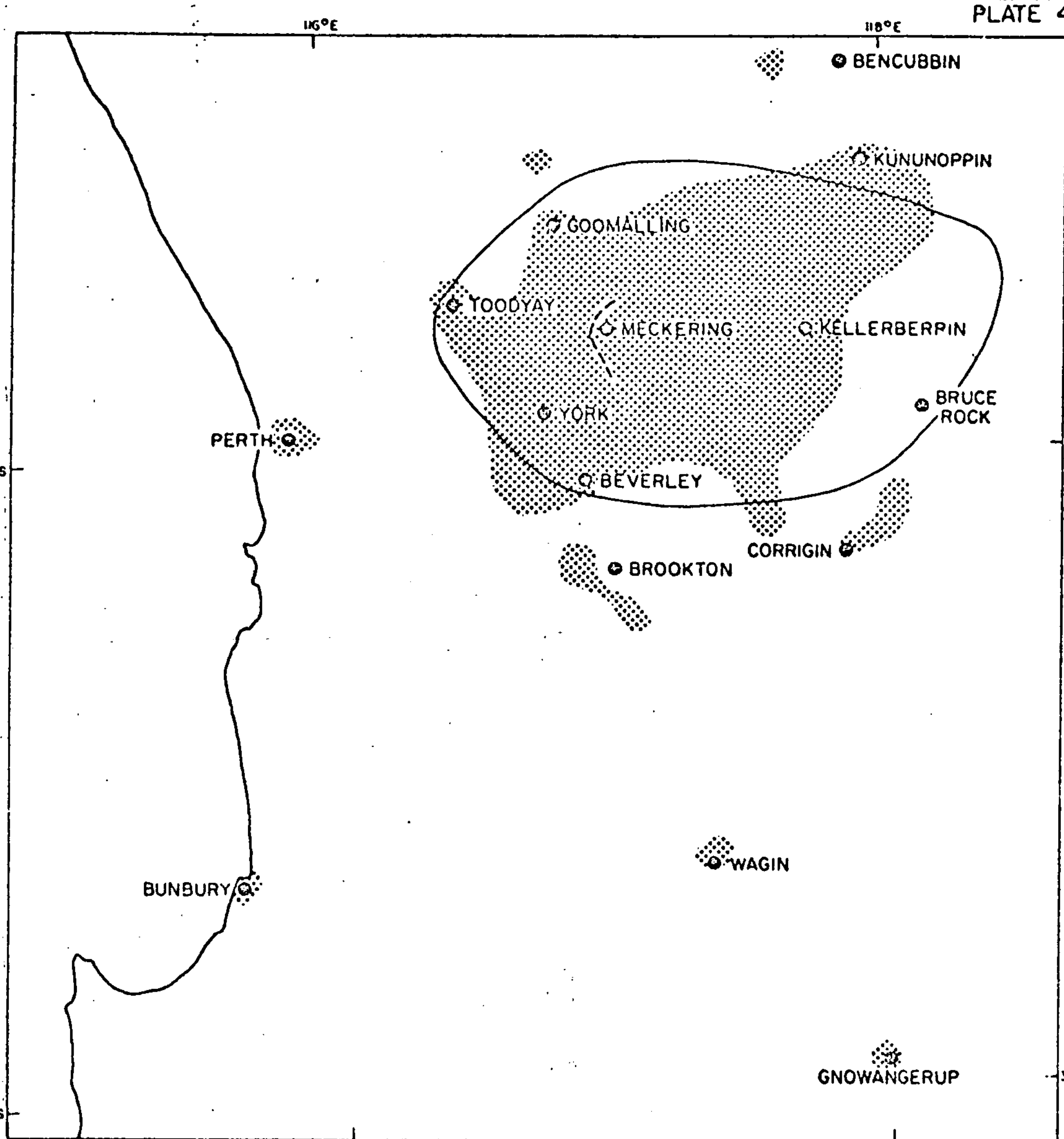

MECKERING EARTHQUAKE INTENSITIES
PERTH AREA
5 5+ Local MM intensity rating
Fault
Railway line
Road
Built up area
SCALE
5 0 5 10 MILES
5 0 5 10 KILOMETRES
115°45'
116°00'
116°15'
32°
North Beach
SCARBOROUGH
PERTH
Swan River
FREMANTLE
INDIAN OCEAN
MIDLAND
MUNDARING
Mundaring Weir
Helena Reservoir
CANNINGTON
KELMSCOTT
DARLING FAULT
PLATE 3
H50/B9-4

PLATE 4



AREAS OF PROVED DAMAGE CLAIMS

Isoseismal enclosing area with intensity MM VI or greater.

Areas of damage proven by the WA Government Relief Advisory Committee

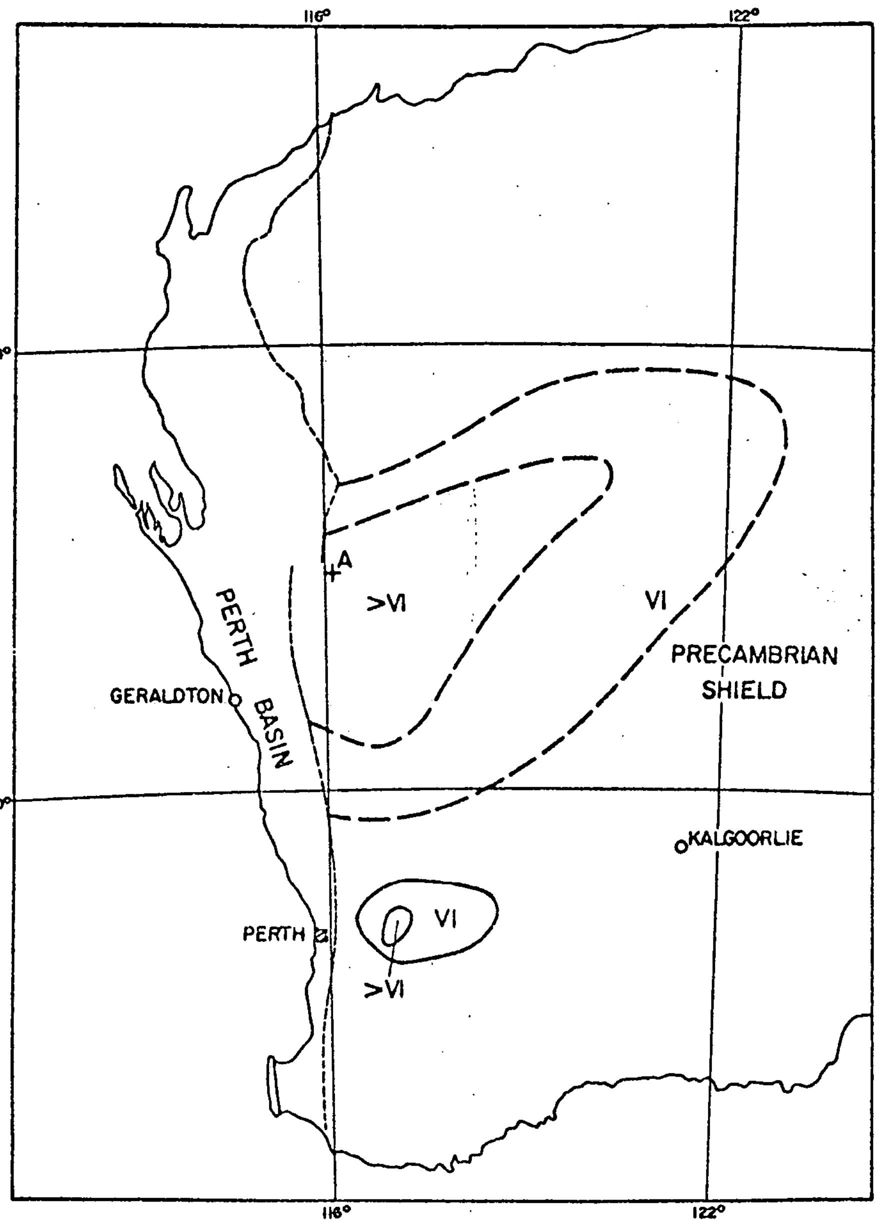
Earthquake fault trace.

SCALE

50 0 50 100 MILES

50 0 50 100 150 KILOMETRES

H50/89-7



COMPARISON OF MECKERING AND MEEBERRIE EARTHQUAKE INTENSITIES

VI *MM intensity*

A *Meeberrie earthquake epicentre*

— — *Meeberrie earthquake isoseismal*

—— *Meckering earthquake isoseismal*

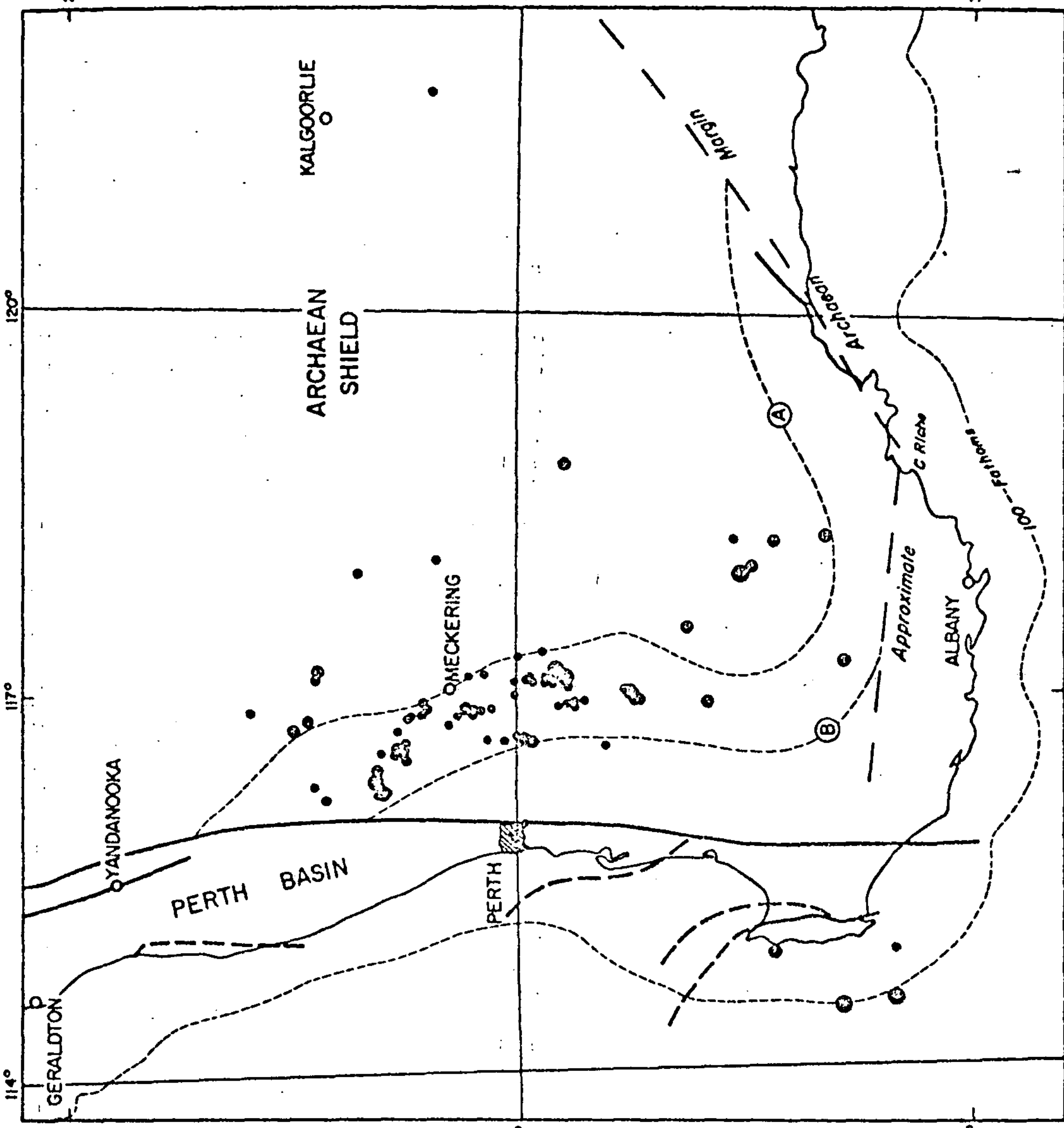
SCALE

100 0 100 200 MILES

100 0 100 200 300 KILOMETRES

H50/89-2

PLATE 6



SOUTH-WESTERN AUSTRALIAN SEISMICITY
(Known earthquake epicentres Oct 1959 – Dec 1967)

- *Epicentre $M_L < 3{\cdot}0$*
- *Epicentre M_L 3·0 to 3·9*
- *Epicentre M_L 4·0 to 4·9*
- *Fault*
- *Buried fault*

Approximate margins of landscape zones (after Mulcahy 1967)

------A---- *Salt lakes and sandplains–younger laterites*

-----B---- *Younger laterites–detrital laterites*

SCALE

50 0 50 100 150 MILES

50 0 50 100 150 200 KILOMETRES

H50/B9-3

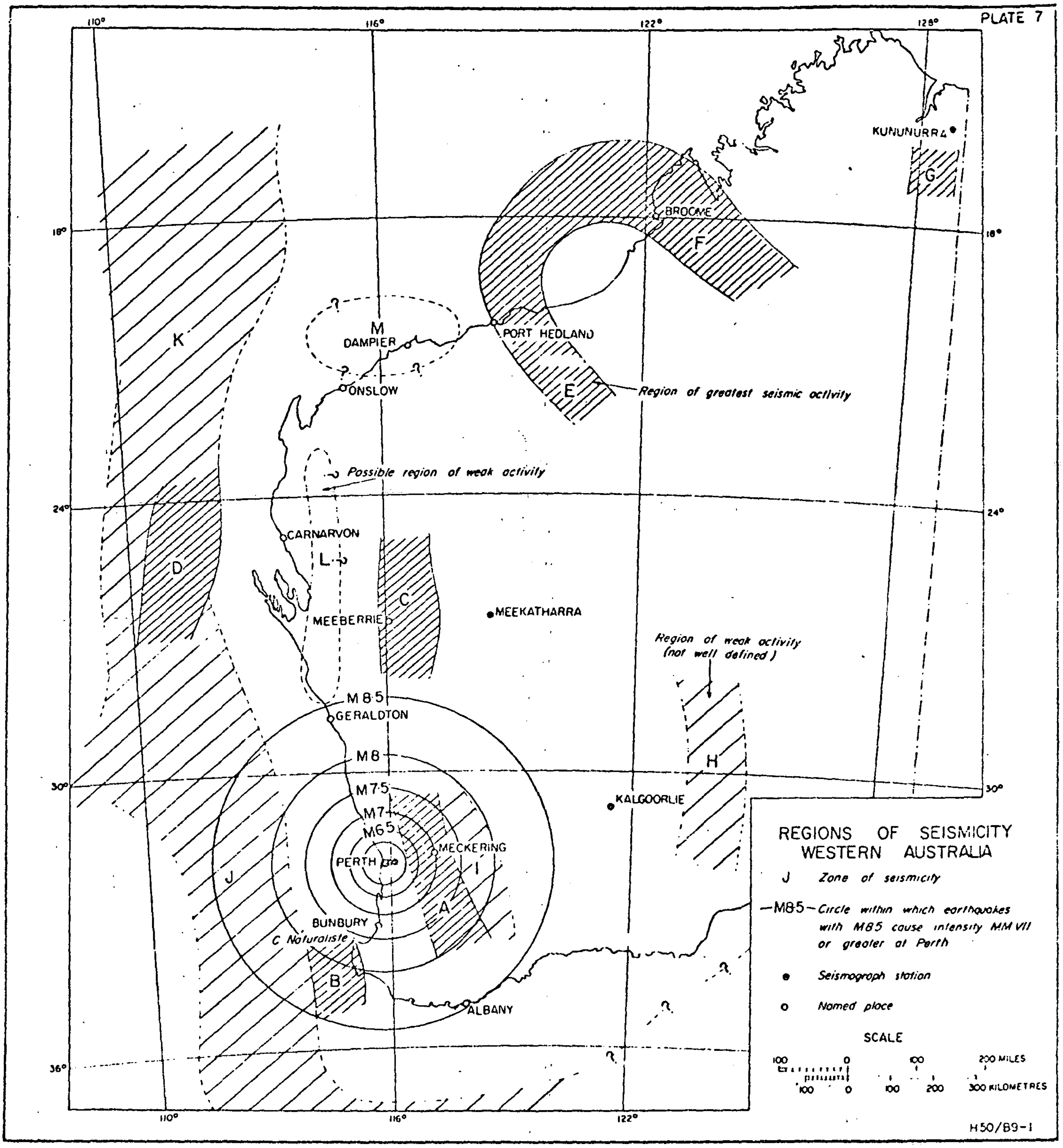


PLATE 7
110°
116°
122°
128°
18°
24°
30°
36°
KUNUNURRA
G
BROOME
F
PORT HEDLAND
E
Region of greatest seismic activity
M
DAMPIER
ONSLOW
K
Possible region of weak activity
CARNARVON
L
D
C
MEEBERRIE
MEEKATHARRA
Region of weak activity (not well defined)
H
M 8·5
GERALDTON
M 8
M 7·5
M 7
M 6·5
KALGOORLIE
PERTH
MECKERING
I
J
A
BUNBURY
C Naturaliste
B
ALBANY
REGIONS OF SEISMICITY WESTERN AUSTRALIA
J Zone of seismicity
M8·5 Circle within which earthquakes with M8·5 cause intensity MM VII or greater at Perth
Seismograph station
Named place
SCALE
100 0 100 200 MILES
100 0 100 200 300 KILOMETRES
H50/B9-1