DEPARTMENT OF NATIONAL RESOURCES

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THE INDONESIAN EARTHQUAKE OF 19 AUGUST 1977: EFFECTS IN WESTERN AUSTRALIA

by

P.J. Gregson, E.P. Paull, & B.A. Gaull

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SUMMARY

The Indonesian earthquake of 19 August 1977 with a magnitude (M) 8 was felt in Western Australia up to distances of 2600 km from the epicentre. The maximum ground intensity felt was MM V in northwest towns up to 1100 km from the epicentre.

The ground intensity in Perth, 2300 km from the epicentre, was MM III or less. Resonance of multi-storey buildings resulted in an eight-fold amplification of peak ground acceleration on the upper floors. Only minor damage occurred in Perth.

Seismic sea waves up to six m in height were reported several hours after the earthquake at towns along the northwest coast. There were no reports of damage associated with these waves. They arrived along the coast near low tide, otherwise there could have been some flooding.

An examination of data from the Sunda arc region, for the period 1900-1974, suggests that about eight earthquakes of magnitude greater than 7.5 could occur in this region every hundred years. Of these two or three may be felt in Western Australia. The 1977 earthquake was the largest and closest to Western Australia since 1900 and its effects are the maximum likely to be experienced from this region.

Consideration should be given to installing accelerographs in selected buildings in Perth, and to providing a tsunami warning service for the northwest coast.

1. INTRODUCTION

A large area of Western Australia was shaken by a major earthquake which occurred on 19 August 1977. The earthquake epicentre was located about 900 km northwest of Broome, in one of the world's most active seismic areas, the Sunda arc.

There were no casualties in Australia and only a few reports of minor damage. However, as happened during the 1968 Meckering earthquake (Everingham, 1968a), concern was expressed by some office workers in Perth, and residents of several Western Australian towns. The area over which the earthquake was felt was considerably larger than for the Meckering earthquake. The most severe effects were felt in the northwest towns of Port Hedland, Broome, and Derby. Although the ground movement in Perth was less than for the Meckering earthquake the duration of shaking was longer for the Indonesian earthquake and resonance of the tall buildings produced easily detectable movements on the upper floors.

Extracts from The West Australian newspaper give some indication of the effects:

> 'High-rise buildings in Perth were evacuated yesterday afternoon as Western Australia was shaken by shock waves from one of the world's largest earthquakes. Western Australia felt the tremor from Kununurra to Albany, but the worst effects were at Port Hedland, where parked cars bounced and buildings rocked.'

> 'A tidal wave washed the northern Western Australian coast yesterday evening. Reports of the size varied from two metres to four metres.'

> 'Workers from the 31st floor at City Centre (Perth) reported feeling sick as the building swayed, and many made their way downstairs to the ground.'

> 'In Port Hedland, the town's power supply was cut by the tremor. Shoppers ran from the shops as the lights went out and buildings began to shake and roll.'

'In the Indonesian Islands, one hundred and eighty seven lives were lost, seventy-six missing, ninety-eight injured, and three thousand homeless, as a result of the earthquake and the ensuing tsunami.'

2. INSTRUMENTAL DATA

The shock waves from the earthquake saturated all the seismographs in Western Australia, with the exception of the Wood-Anderson seismograph at Mundaring. Preliminary results, using P arrival times at Western Australian stations and amplitudes from the Mundaring Wood-Anderson seismograph are:

Epicentre:	Latitude 11.0° S
	Longitude 118.2° E
Depth:	Shallow
Origin time:	06 08 51 UTC
Magnitude:	8.4 (M)

Magnitude determinations from the Mundaring Wood-Anderson seismograph were mB = 7.6, ML = 8.5 and MS = 8.2. To determine ML, it was necessary to extend the Richter attenuation curve beyond 600 km (Eiby & Muir, 1961). Using the magnitude relation given by McGregor & Ripper (1976), mB is equivalent to M = 8.4.

Digital short and long-period recordings from the Narrogin Seismic Research Observatory were saturated and could not be used to determine a reliable magnitude.

Preliminary results supplied by the United States National Earthquake Information Service are:

Epicentre:	Latitude 11.1°S
	Longitude 118.4°E
Depth:	20 km
Origin time:	06 08 52.6 UTC
Magnitude:	7.75 - 8.0 (MS)

Ground motion at Mundaring

The maximum trace amplitude recorded on the Mundaring Wood-Anderson seismograph occurred 40 s after the arrival of the S-phase. The amplitude was 85 mm at a period of 0.9 s and corresponded to a ground acceleration of 4×10^{-3} m/s^2. For about seven minutes the peak ground acceleration remained greater than 1×10^{-3}m/s^2 with the period varying from about 0.5 to 1.3 s, during the passage of P and S waves.

The subsequent surface waves were recorded at Mundaring for several hours. Peak ground amplitudes resulting from the surface waves were approximately 10^{-2} to 10^{-3} m with periods from 10 to 100 s. The corresponding ground acceleration was at least a factor of 10 less than that for the S waves.

Ground motion at Marble Bar

Trace amplitudes could not be measured from the Marble Bar vertical component seismograph for the main earthquake because the seismograph was saturated. It was possible to measure amplitudes of several aftershocks with magnitude (mB) 5. The maximum trace amplitude of the S-phase was 60 mm with a period of 0.5s, (ground amplitude 0.36×10^{-6} m). The estimated maximum ground amplitude for the main earthquake was 0.15×10^{-3} m with the same period of 0.5 s. This corresponds to a vertical ground acceleration of 2.3×10^{-2} m/s^2. The peak horizontal acceleration was probably several times greater than this.

Foreshocks and aftershocks

One foreshock, with the same epicentre, preceded the main earthquake. It occurred on 19 August at 05 08 39 UTC and had a magnitude of mB = 6.2.

It was impossible to determine the number of aftershocks in the four and a half hours after the main earthquake. This was because the main earthquake disturbed the seismographs for a considerable time, during which there were numerous aftershocks, whose recordings overlapped so that individual earthquakes could not be differentiated.

The seismograms from Marble Bar (MBL), which was the closest Australian seismograph to the earthquake, were examined closely for all aftershocks with magnitude (mB) greater than or equal to 4. In the period from 1045 to 2400 UTC on 19 August 1977, there were 45 earthquakes. In the next forty-two days, up to 30 September inclusive, another 403 earthquakes were recorded; Table 1 lists the times and magnitudes for all having a magnitude greater than or equal to 4.8. Several of the larger events listed in the table were felt in Perth by those suitably situated in tall buildings.

Daily numbers of earthquakes (Pl. 2) show a general diminution except for short periods of increased activity (e.g. 30 August and 16 September).

3. ISOSEISMALS

Over 200 questionnaires were distributed to postmasters in towns throughout Western Australia and adjacent areas seeking information to allow Modified Mercalli intensities (MM, see Appendix 1) to be assigned to the various centres. About 75 percent of the questionnaires were returned. Owing to the large sparsely populated areas information is sporadic, but sufficient to give some idea of the extent of intensities MM II to IV (Pl. 1). The effects in Perth are treated separately in the next chapter.

The survey revealed that the maximum ground intensities were close to MM V. Intensities of IV and III were experienced up to distances of 1150 and 1650 km respectively. The earthquake was felt in Albany and Esperance (2600 km) with intensity II. One experienced observer felt the earthquake in Adelaide (3300 km). Some elongation of the isoseismals in a southerly direction is evident.

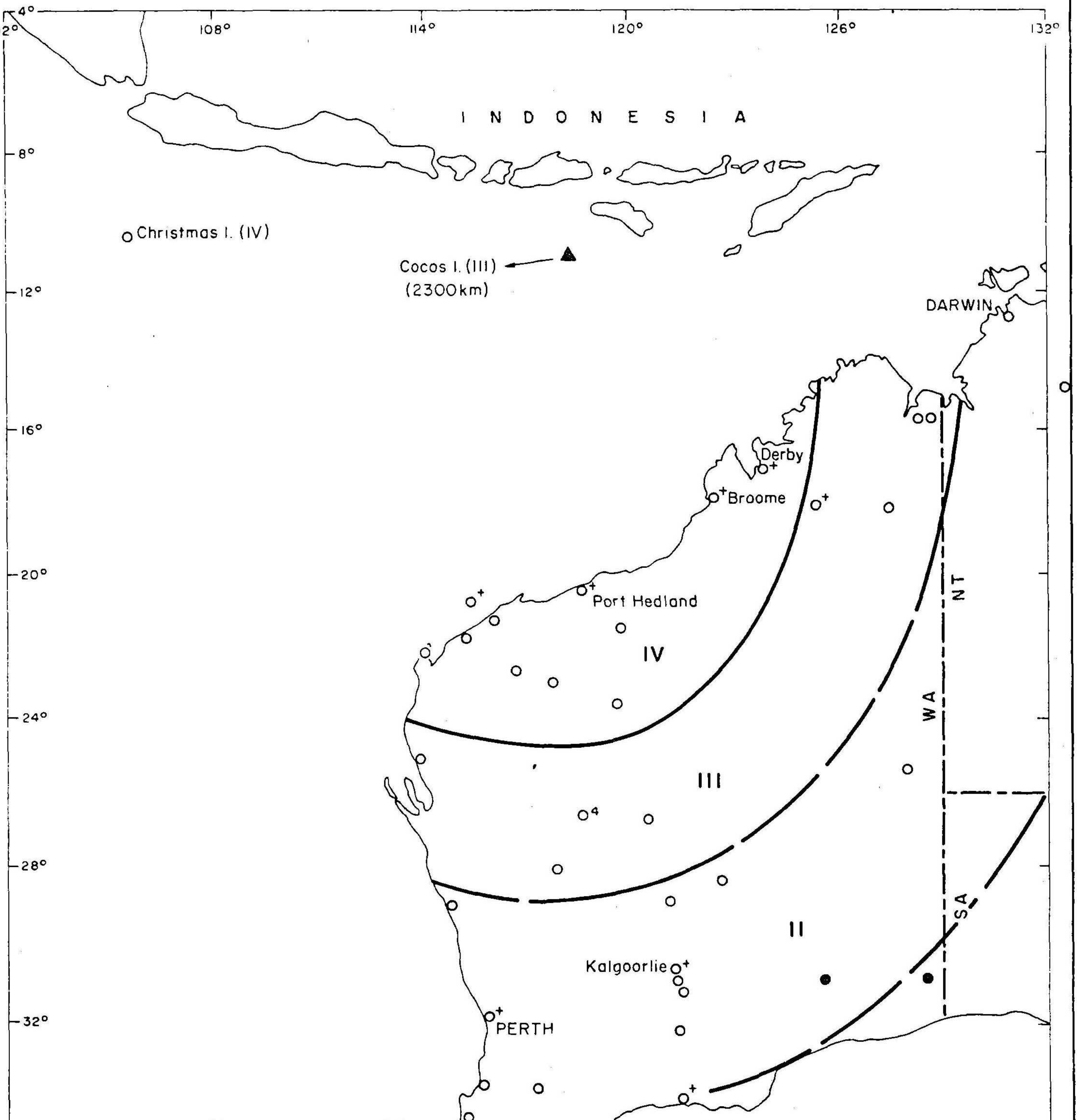
Applying the following formula (Gaull, unpublished data) to Mundaring data (M = 8.4, h = 33 km), reasonable agreement is obtained between the radii of the theoretical and mean actual isoseismals:

$$I = 1.5\,M - 2.5 \log (d^2 + 3h^2/2) + 1.5 \log h + n$$

where
- I = MM intensity
- M = Magnitude
- h = depth (km)
- d = radius of isoseismal (km)
- n = 4 (empirical constant)

PLATE I

ISOSEISMAL MAP OF THE INDONESIAN EARTHQUAKE 19 AUGUST 1977



DATE : 19 AUGUST 1977

TIME : 06:08:51 UT

MAGNITUDE : 8·4 M

EPICENTRE : 11·0°S 118·2°E

DEPTH : SHALLOW

▲ EPICENTRE

○ EARTHQUAKE WAS FELT

● EARTHQUAKE WAS NOT FELT

IV ZONE INTENSITY DESIGNATION (MM)

Small figure beside open circle indicates intensity is different from zone designation

Small cross beside open circle indicates intensity is approaching higher zone

DAILY NUMBER OF EARTHQUAKES IN THE SUNDA ARC REGION 19 AUG TO 30 SEPT 1977

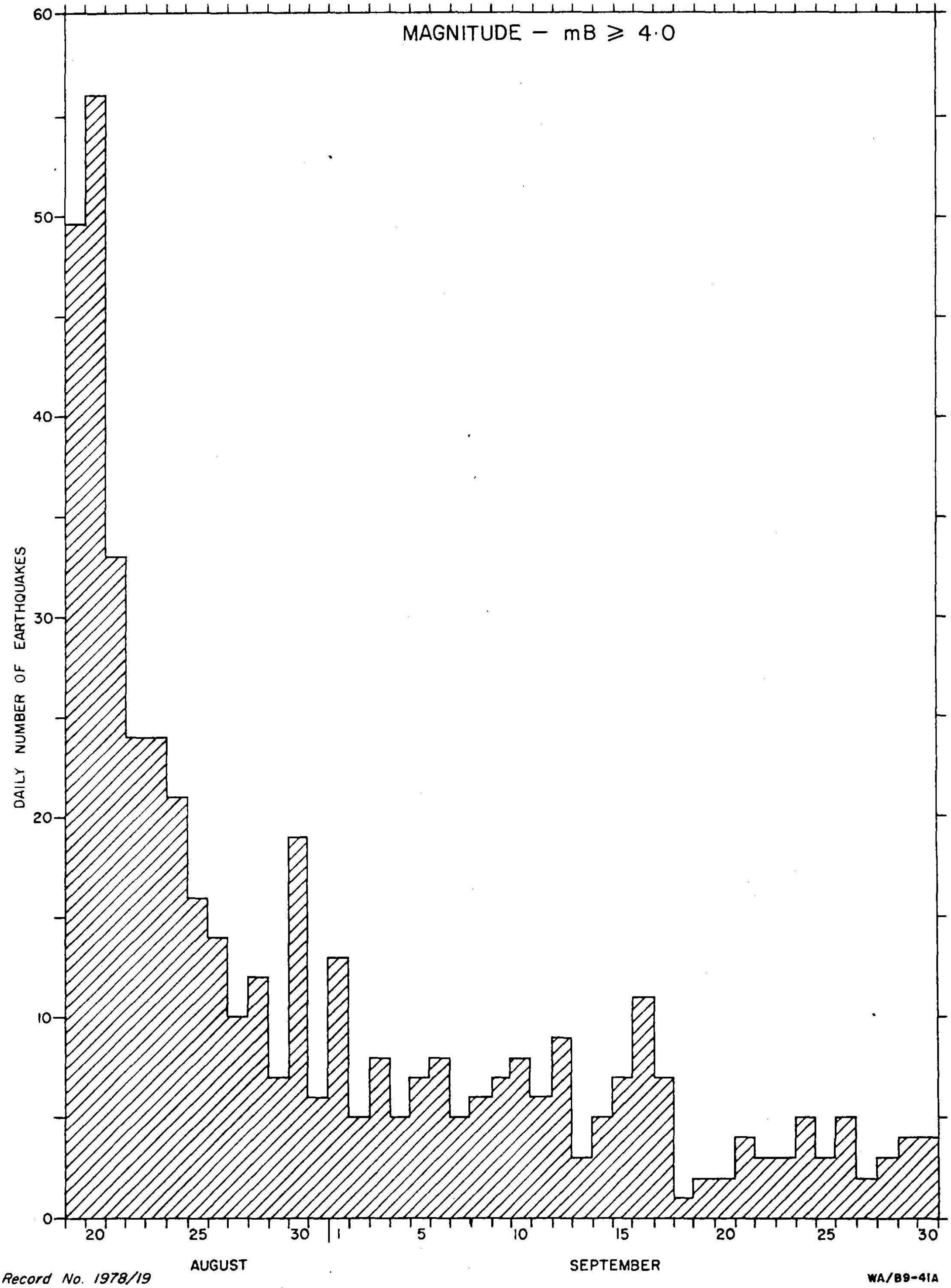
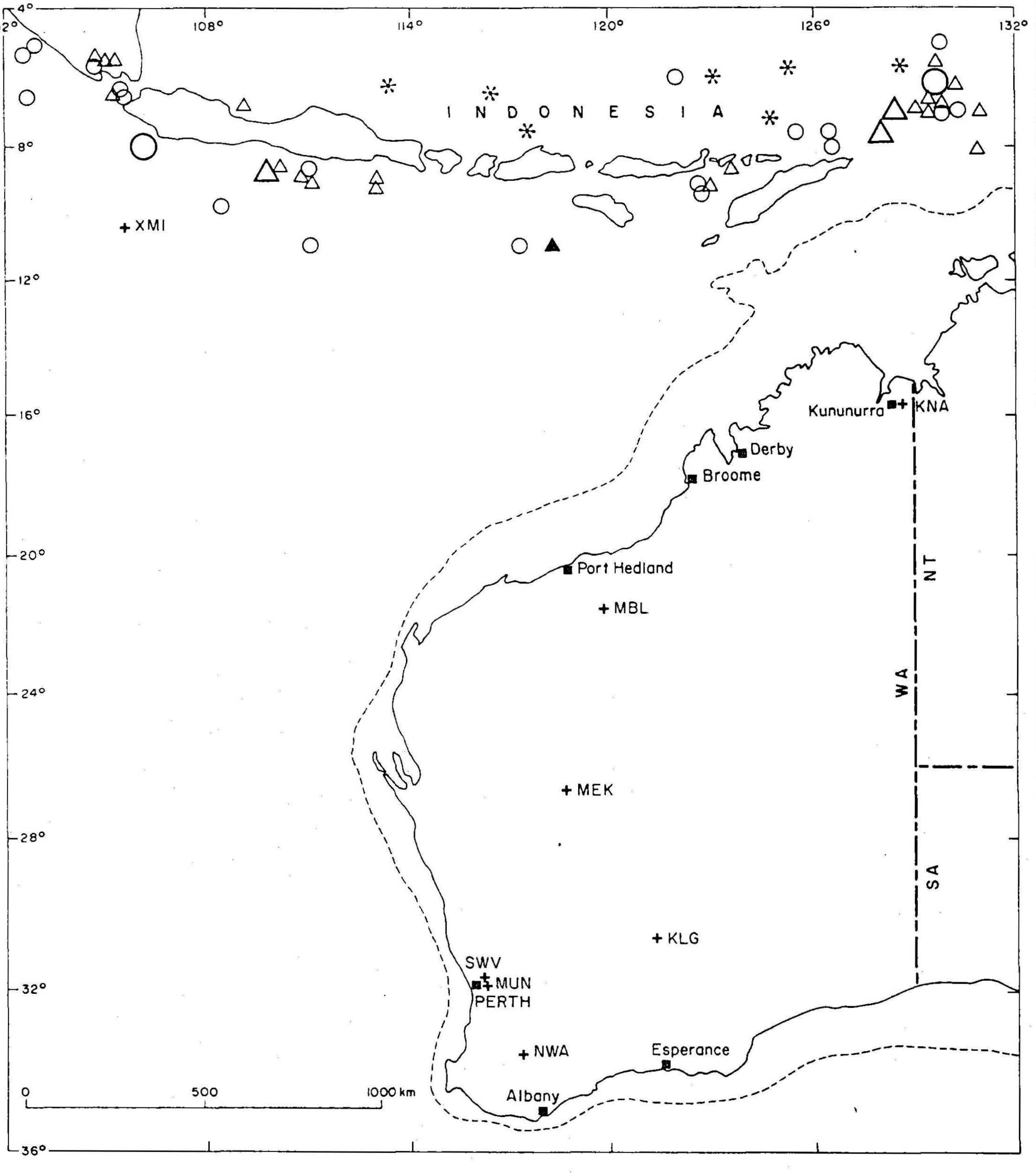


PLATE 3

LARGE EARTHQUAKES IN THE SUNDA ARC REGION, 1900–1974



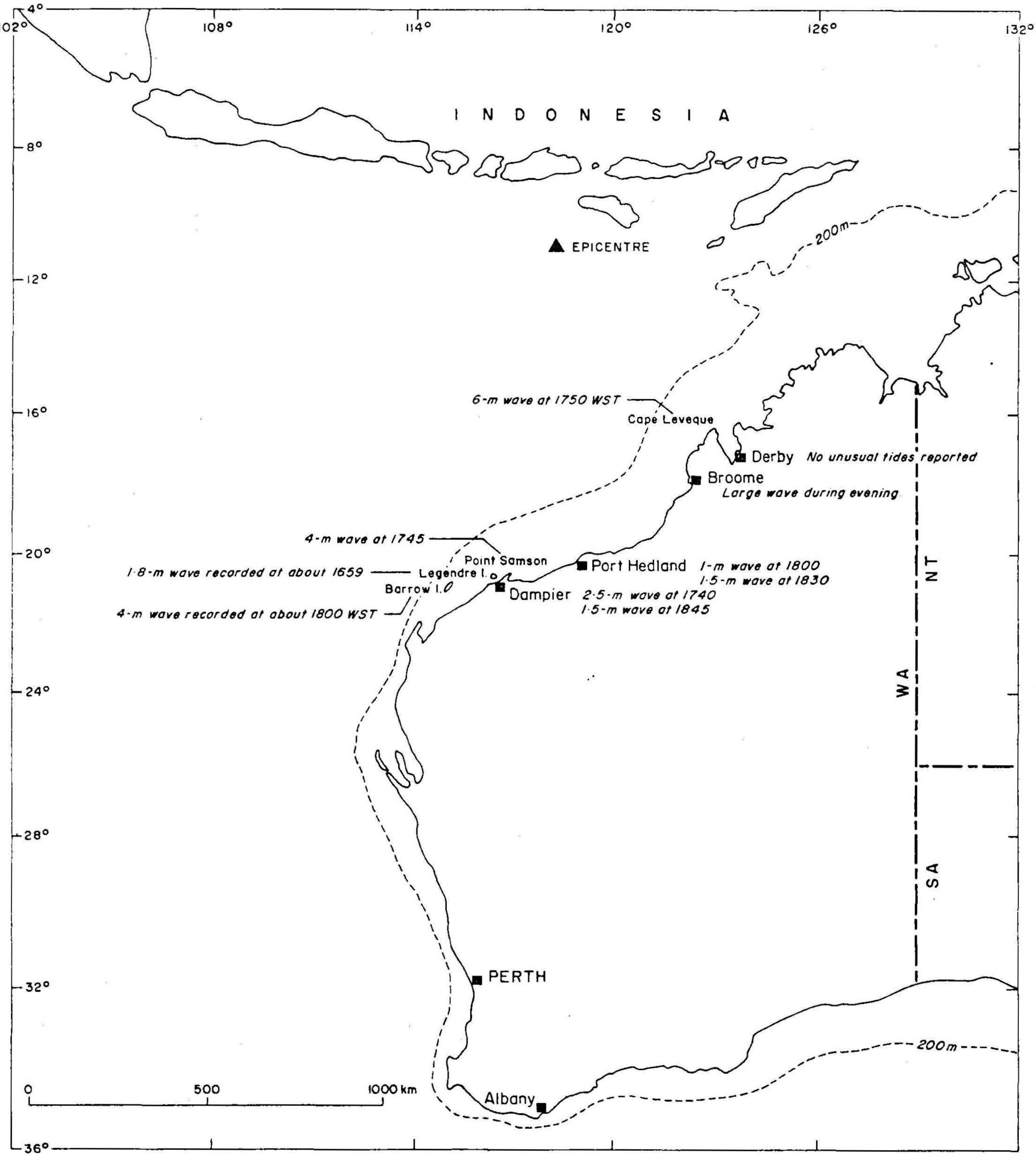
EARTHQUAKES

DEPTH (km)	MAGNITUDE 7·0–7·7	MAGNITUDE >7·7
<70	○ (small)	○ (large)
70–300	△ (small)	△ (large)
>300	✳ (small)	✳ (large)

\+ *Seismograph station*

\- - - - - *200m bathymetric contour*

▲ *Epicentre, 19 Aug 1977*



TSUNAMI EFFECTS OF INDONESIAN EARTHQUAKE 19 AUGUST 1977

Isoseismal	Theoretical (km)	Mean actual (km)
IV	950	1150
III	1550	1650
II	2400	2200

4. EFFECTS ON PERTH BUILDINGS

The effects of the earthquake in Perth were determined by personal interviews with the occupants on various floors in multi-storey buildings, supplemented by information from returned questionnaires. The quantitative assessments made can be only an estimate of an order of magnitude. If accelerographs had been installed in some high-rise buildings, they would almost certainly have been triggered on upper floors, and direct quantitative measurements would have been obtained.

Although the estimated ground intensity in Perth and adjoining areas was MM III or less, the multi-storey buildings within the city amplified the ground motion so that the maximum intensity on the upper floors was MM V-VI. Table 3 gives a summary of the intensity estimates at various levels in the buildings. The amplification of ground motion in the upper floors is attributed to building resonance.

Ground motion in Perth

The ground intensity (I) in Perth of MM II-III can be related to peak ground acceleration (A, m/s^2) by using the empirical relation (Gaull, unpublished data):

$$\text{Log } A = (I/3.1) - 2.3$$

Appendix 2 lists the approximate values of acceleration for each unit on the Modified Mercalli scale.

The estimated acceleration was 3×10^{-2} m/s^2 and was about 7.5 times the peak acceleration recorded at Mundaring. An amplification of acceleration of this order is to be expected between the Precambrian granite at Mundaring and the unconsolidated sediments of the Perth basin. Gaull (1976) has previously reported similar amplifications in New Guinea.

Damage

No structural damage occurred. The only damage reported is summarised below.

Eight-storey load-bearing brick building.

(a) Re-opening of horizontal cracks around the parapet brick wall on the 8th floor. These cracks developed initially during the 1968 Meckering earthquake.

(b) Shear-cracks in brick pillars on the 8th floor, with an associated offset of up to 5 mm.

(c) Diagonal cracks in east-west brick walls on the 8th floor.

(d) Other miscellaneous cracks on the 8th floor including minor fracture.

(e) Minor spalling from expansion joints.

Twelve-storey reinforced concrete building.

(a) The plaster air-conditioning duct on the top four floors moved about 2 mm away from the concrete wall.

(b) Re-opening of cracks in gypsum wall on the 9th floor.

(c) Extension of minor plaster cracks on the 12th floor.

Thirteen-storey reinforced concrete building.

(a) Re-opening of cracks on the 11th floor.

Fifteen-storey reinforced concrete building.

(a) Part collapse of one area of acoustic tiles in the ceiling on the 12th floor.

(b) Enlargement of an old crack in a corner of the building.

(c) Small ornamental stone chips on the exterior wall of building flaked off at the time of the earthquake.

Typical felt effects at various levels

Single storey or ground floor. Felt by only a few observers (MM II-III).

Less than five storeys. Some amplification of ground motion was experienced (MM III-IV).

More than five storeys. The maximum intensities within buildings of five or more floors was generally MM V, independent of structural design or total height. However, slightly greater intensities, MM V-VI, were probably experienced in the upper floors of buildings ranging from eight to fifteen storeys. The only damage reported was from these buildings. The fundamental periods of these buildings are in the range of periods of ground motion at which most of the earthquake energy was propagated, i.e. 0.5 to 1.3s for the P and S waves.

Building response

The fundamental period (T) of vibration of a building can be approximately determined using the empirical formula $T = 0.10n$ where T is the period in seconds and n is the number of storeys (Standards Association of Australia, 1976).

The validity of the above formula is supported by a report on the motion of two suspended lamps on the 10th floor of a twelve-storey building. One lamp with a 'pendulum length' of about 30 cm (natural period = 1 s) swung with an amplitude about double that of a second lamp which had a length of about 60 cm (natural period = $1\frac{1}{2}$ s). Therefore the natural period of the building must have been close to 1 s.

Assuming that the power spectra of the ground motion were about the same in Perth and Mundaring (peaking between 0.5 and 1.3 s), then buildings between five and thirteen storeys should have been affected most. Analysis of data in Table 3 shows that the average estimated felt intensity in the top 25 percent of floors was:

No. of storeys	< 5	5 to 15	> 15
Average intensity	III+	V	IV - V

The maximum intensity MM V-VI was reported from buildings in the range of 8-15 storeys.

An estimate of the acceleration experienced on the 3rd floor of the five-storey Red Cross Transfusion Centre was made from an observation of the motion of saline solution in a trough. It was estimated that wave motion inside the 20 cm trough had a peak amplitude of about 2.5 cm at a period of 0.5 s. By reproducing these conditions in the laboratory, the acceleration was found to be 1.3×10^{-1} m/s^2, which corresponds to an intensity of MM IV-V (Appendix 2). This is in reasonable agreement with the MM scale definition which states that liquids becoming disturbed is indicative of MM V(Appendix 1).

During the San Fernando earthquake of 1971 peak acceleration at the roof level of tall buildings was about four times the ground acceleration when the ground motion approximated the natural period of the building (Murphy, 1973). The maximum amplification of ground acceleration in Perth buildings was about eight, probably because the period of ground motion in Perth matched the natural period of the middle-rise buildings for a much longer duration than in San Fernando. This would allow a much greater resonance effect to take place.

The tallest buildings in Perth were probably resonating mainly in the second mode of vibration. This is considered to be so because:

(a) the period of the second mode of vibration of a 30 storey building is normally close to 1 s - corresponding to the period of waves carrying most of the earthquake energy.

(b) the intensity in a 30 storey building in Perth did not increase with floor level - possibly owing to a nodal effect (Table 3).

(c) it would account for the fact that the average maximum intensity was lower in the 30 storey buildings than in the middle-rise buildings, which were probably resonating in the first mode of vibration.

Earthquake risk in Perth buildings

The risk of damage during an earthquake increases as the period of ground motion approaches the natural period of the building.

The period of ground motion for P and S waves from large Indonesian earthquakes approximates the natural period of middle-rise buildings (8-15 storeys). However, even with amplification of the ground movement, the resultant acceleration is not likely to exceed the equivalent of MM VI. The amplification in middle-rise buildings will be greater than in low-rise or high-rise buildings.

The large amplitude surface waves have periods far greater than the natural period of the existing tall buildings in Perth and the resultant acceleration is too small to present a threat. Considerable amplification could be experienced if buildings ever approach a hundred storeys.

In contrast, the power spectra of moderate to large earthquakes at epicentral distances of about 100 km generally peak at ground periods of 0.15 to 0.5 s (Denham, Small & Everingham, 1973). This means that accelerations generated in single storey and low-rise buildings during an earthquake in the southwest seismic zone are likely to be greater than those in high-rise buildings. Most of the damage to Perth buildings from the Meckering earthquake (Everingham, 1968a) was in the older-style low-rise buildings. Part of the damage could be attributed to the age of the buildings, but the discussion by Everingham & Gregson (1970) indicates that resonance in the low-rise buildings amplified ground acceleration from 0.2 m/s^2 (MM V) to 1.0 m/s^2 (MM VII).

By comparison with the San Fernando earthquake (Murphy, 1973) it is estimated that during the Meckering earthquake, surface waves would have been amplified by about four. This would have resulted in an acceleration of 0.4 m/s^2 (MM VI) in middle-rise buildings.

Hence the risk of damage in Perth from a moderate to large earthquake in the southwest seismic zone is greater by about one unit on the intensity scale for low-rise buildings than for middle-rise and high-rise buildings. Therefore standards of earthquake-resistant design must not be relaxed for low-rise buildings.

Provided tall buildings are constructed to the high standard set by the suggested code (Standards Association of Australia, 1976), the occupants of a high-rise building are probably safer than those in a low-rise building. The wisdom of evacuating people from high-rise buildings is questionable. People standing in streets are in more danger from falling debris shaken from buildings than from being injured inside the building.

In the past ten years three earthquakes have occurred which probably would have triggered accelerographs, had they been located in Perth buildings:

1968 October 14	Meckering	M = 7.1
1969 March 10	Calingiri	M = 5.5
1977 August 19	Indonesia	M = 8.4

Data from these earthquakes would have provided information on the response of various types of buildings in Perth.

5. EFFECTS IN NORTHWEST TOWNS

The maximum effects from the earthquake were experienced in the northwest towns of Port Hedland, Broome, and Derby. The typical effects of rattling windows, shifting or overturning of small objects and ornaments, and liquids being disturbed, indicate intensity MM V. The major ground movement reported was east-west which corresponds to the passage of the S-wave.

A report from the Port Hedland Port Control Tower (27 m high) stated that there was a strong and rapid vibration increasing in intensity to such an extent that the observer left the building. Another report from the sixth floor of a six-storey building indicated an intensity of MM V+. These two reports show that the ground movement was amplified in the taller buildings.

Earthquake risk in multi-storey buildings

As elsewhere, the risk of earthquake damage increases as the natural vibration period of the building approaches the period of ground motion. The Marble Bar seismograms showed that the period of ground motion at which peak acceleration was reached was about 0.5 s which is the natural period of five-storey buildings.

By comparison with Mundaring data, the peak ground acceleration probably remained above 2×10^{-2} m/s^2 for about three minutes, and the ground acceleration was amplified two times to give an intensity differential of one. Therefore intensities close to VI could have been experienced on the upper floors of five-storey buildings.

6. TSUNAMI EFFECTS

Seismic sea waves were reported at towns along the northwest coast of Western Australia from North West Cape to Cape Leveque. Tide gauge recordings of unusual tide and wave activity were obtained from several places and from a wave-rider buoy at Legendre Island. As far as is known, no damage resulted from the tsunami. Plate 4 shows reported wave heights and times at northwest coastal towns. The maximum wave height reported was 6 m at Cape Leveque which was the closest point in Australia to the epicentre. However, the seismic sea wave arrived first at Legendre Island at 1659 WST, indicating a path across deeper water. The travel-time was two hours fifty minutes, giving an average velocity of 366 km/h. Wave heights given in the text are all trough to crest values to conform with common usage.

Instrumental data

The tide gauge and wave-rider buoy recordings are summarised below.

Instrument	WST 19 August	Event	Remarks
Wave-rider buoy			
Legendre Is.	1659	Wave height 1.8 m, period 30 s	About 34 km north of Dampier in 34 m of water.
	1706	Wave height 1.1 m, period 30 s	
	1711	Wave height 1.1 m, period 30 s	
Tide gauges			
Dampier (service wharf)	1740-1755	Not recording, presumably upset by initial wave of water.	Exposed position. Chart speed 18 mm/hr

Instrument	WST 19 August	Event	Remarks
	1755-2000	Surges in water level of about 0.5 m every 7 minutes.	
Dampier (tug jetty)	1730	Surges approximately every 15 minutes	Sheltered position in Hampton Harbour.
	1800	Wave train of period 34 minutes and height 0.7 m.	Chart speed 3 mm/hr
	2000	Wave height fallen to 0.4 m (same period)	
	1400 20 August	Surging still evident, amplitude 12 cm (same period).	
Geraldton	2120	Surges with periods between 22 and 38 minutes.	Chart speed 2.5 mm/hr
	2400	Maximum wave height 0.4 m	Maximum wave height for 24 hr prior to 2120 was 0.1 m.
Broome	1742	Waves of 12 min period, amplitude 2.5 cm.	The sea was mill-pond calm before this. Chart speed 10 mm/hr.
Wyndham, Fremantle, Albany, Esperance		No unusual wave action.	
Port Hedland, Carnarvon		Tide gauges not operational	

Wave reports

Cape Leveque. A wave six m high was observed about 1750 hours WST by the lighthouse keeper according to a report from the Bureau of Meteorology.

Derby. No unusual tidal effects were reported.

Broome. The harbour-master reported that during the evening a large wave crashed on to Cable Beach, causing people to run from its path.

Port Hedland. The harbour-master received a report from the pilot of an incoming ship that at 1800 WST, three distinct waves about 1 m high and about 0.5 to 0.8 km apart were observed. The master of the 'Iron Cumberland' lying at anchor 8 cables from No. 10 beacon (about 12 km north of Port Hedland) reported that at approximately 1830 WST, a wave about 1.5 m high passed through the anchorage. A considerably smaller wave followed fifteen minutes later.

Point Samson. Samson Fisheries reported that at 1745 WST, six to eight large waves about 5 m high were observed travelling south. These were followed by smaller waves. The waves hit towards low tide and pushed the sea up to about the half-tide mark. The water then receded and was back to normal in about fifteen minutes. The Bureau of Meteorology reported waves from the north at 1745 WST, 2 to 4 m high

The harbour master at Port Walcott received a report that a series of four waves passed Point Samson from north to south at about 1745. Samson Bay Beach was filled; later calculations indicate that the largest wave was about 2 m high.

Dampier. The Bureau of Meteorology reported a wave from the northeast at 1740 WST estimated to be 2 m high. Captain J.D. Holden of Pilbara Harbour Services saw a pronounced wave travelling south along Mermaid Sound at 1740 WST. A second wave occurred at 1742, and a third and fourth in close proximity at 1743. The estimated height of the waves was 2 to 2.5 m. Mr F. Rothleitner, the dredging project manager, measured the waves against the service wharf and reported the maximum to be 2.4 m. The wave had commenced to break.

Captain Holden also reported that no damage was done to the port, but a tug berthed at the service wharf broke mooring lines, and a 165,000 tonne DWT ore carrier, nearly loaded and berthed at East Intercourse Island, was moved considerably, controlled by her tension winches, on one of which the hawser was seen to have ranged about 12 m.

Mr K.C. Anning reported sighting a wave about 1.5 m high at about 1845 WST. The wave washed over Boat Rock and along the east coast of East

Intercourse Island and was followed by smaller waves. Apart from this the sea was calm at the time.

Barrow Island. Two West Australian Petroleum employees who were rock-fishing on the northwest coast of Barrow Island, reported observing a large wave 4 m high, followed by three more in decreasing size. The sea at the time was calm. The wave forced the employees to move to higher ground. Other rock fishermen were apparently not so fortunate, as they were wet and some lost fishing gear.

Discussion

The first wave arrived at the Legendre Island wave-rider buoy at 1659 WST and at Dampier about 34 km away, at about 1740. This gives an average velocity between those two points of 13.8 m/s (50 km/h).The average depth of water between Legendre Island and Dampier is estimated at 15 m. The wave velocity formula

$$\text{Velocity} = (gd)^{\frac{1}{2}}$$

where g = gravitational constant, and d = depth of water, gives an average velocity of 12.1 m/s, which is in fair agreement with the observed velocity. No similar waves were observed in the preceding or subsequent 24 hours, according to advice from Woodside Petroleum Development Pty Ltd who operate the buoy.

The observations at Legendre Island and Mermaid Sand do not give such good agreement. Three waves in twelve minutes were recorded at Legendre Island, but four waves were observed in three minutes at Mermaid Sand. Seismic sea waves are long-period waves, whereas the wave-rider buoy responds only to relatively short periods. This could explain the differences, as only tsunami waves with a significant high frequency component (having a crest and not a smooth sinusoidal shape) would be recorded by the wave-rider buoy. The maximum wave height of 1.8 m recorded near Legendre Island is in reasonable accord with the observed 2.4 m height at the Dampier service wharf, bearing in mind the shallower water at the wharf.

Table 4 lists predicted heights and times of high and low tides for some major northwest coastal towns on 19 August 1977. The information is taken from the Australian National Tide Tables (Department of Defence, Navy Office). At Point Samson, the predicted high tide for the day was 5.0 m at 1320 WST and a low tide of 0.3 m at 1944. The predicted tide at the time of the waves was 1.1 m and falling. To push the sea back to the half tide mark as reported by Samson Fisheries would have required a wave height of 3.2 m. This is more in keeping with the Bureau of Meteorology report of a 4 m maximum, than the Samson Fisheries estimate of a 5 m wave height, but is larger than the 2 m estimate at Samson Bay Beach. However, such comparisons may not be relevant, as a small tsunami at one beach can be a large tsunami a few kilometres away.

Only minor tsunami effects would be expected at Derby as the town lies at the head of King Sound in the lee of Cape Leveque. Also the entrance to the Sound is shallow and cluttered with small islands, coral reefs and shoals. Broome is situated in Roebuck Bay whose entrance faces south; only marginal secondary wave effects would be expected. However, the large wave reported at Cable Beach, an exposed ocean beach, was almost certainly a seismic sea wave.

Coastal towns south of North West Cape lie in the lee of the Cape and would receive only diffracted waves, and consequently feel lesser effects. The recorded maximum wave amplitude of 0.4 m at Geraldton would seem to bear this out. The tsunami arrived at Geraldton at about 2120, four hours twenty-one minutes after being recorded at Legendre Island. This gives an average velocity of about 230 km/h for this section.

No tsunami effects would be expected at towns on the south coast of Western Australia.

Surges, like those which were recorded on the Hampton Harbour tide gauge at Dampier or on the Geraldton tide gauge, may be characteristic of tsunami effects along the Western Australian coast. According to the Bureau of Meteorology there were no storms nearby which could possibly have generated surges of this nature. Why the more exposed Dampier service-wharf tide gauge did not record the waves remains a mystery.

The arrival of later tsunami waves could explain the sighting of waves at 1830 WST at Port Hedland and at 1845 at Dampier. Any subsequent waves would have arrived after dark and would probably not have been noticed.

Similar tsunami effects may have been observed along the Western Australian coast after the Krakatoa eruption of 27 August 1883. Reports for this event, extracted from the record published by the Bureau of Meteorology (1929), are presented for comparison in Appendix 3. As can be seen, the sea at Geraldton was observed to rise twice in half an hour, and at Carnarvon the sea rose and fell three times in one and a half hours. At Cossack, the tides were erratic for some days, and at Ashburton there were fully twelve tides in twenty-four hours.

Tsunami wave heights may exceed 30 m, e.g. Japan, 1896 (Weigel, 1974). However, for high waves to develop, the transition from deep-sea floor to coastline must be sudden. Western Australia is fortunate, having a wide continental shelf. It is therefore unlikely that severe tsunami effects like those which happened at the Indonesian islands of Sumba and Sumbawa, or like those which occur around parts of the Pacific, will ever be experienced in Western Australia. However, warning of a possible tsunami is desirable as loss of life could occur through people being washed into the sea. Probably those most at risk would be rock fishermen or people on low-lying islands. An earthquake felt in coastal areas, is of course, a natural tsunami warning. Residents should keep clear of low-lying coastal areas and listen to the radio for the location of the earthquake and any tsunami information.

Considering the infrequency and probable moderate size of tsunamis on the Western Australian coastline, perhaps only two every hundred years or so, it would not seem justifiable for Western Australia/Australia to establish a tsunami warning system in view of the large cost involved. However, consideration should be given to collaborating with the existing Pacific Tsunami Warning Centre, Honolulu. This centre routinely locates all earthquakes in the Pacific Ocean area of sufficient magnitude to generate a tsunami (this includes the Sunda Arc region; the earthquake of 19 August was located by the centre). If the epicentre is under or near the ocean, tsunami generation is possible and a tsunami watch warning is issued. When confirmation of a tsunami is received, the centre issues a tsunami warning. In the case of Australia the centre could issue a tsunami watch warning for distribution to appropriate coastal authorities if an earthquake occurred in the Sunda Arc, New Hebrides Trench, or Kermadec-Tonga Trench regions.

7. SEISMICITY AND EARTHQUAKE FREQUENCY

The Sunda arc region is among the most seismically active regions of the world. The region extends from the east through the lesser Sunda islands of Timor, Flores, Sumba, Sumbawa, Lombok , and Bali to the greater islands of Java and Sumatra, as far as the Nicobar and Andoman islands.

The seismic activity is caused by the northward movement of the Indian/Australian Plate relative to the Eurasian Plate. This movement has resulted in a typical island-arc structure in the Indonesian region with the following features:

(1) A deep-sea trench, the Java trench, on the southern side of the islands, and

(2) a zone of seismic activity along the arc, with shallow earthquakes on the southern side and deep earthquakes on the northern side.

The arc turns north at about longitude 105° E. Earthquakes north of this point are too far away to have significant effects in Western Australia. Earthquakes of magnitude 7 or more that have occurred in the region since 1900 are listed in Table 2 and shown in Plate 3. Earthquakes up to the end of 1952 are from Gutenberg & Richter (1954). Data for subsequent earthquakes have been compiled from ISC and ERL data. Unfortunately, because of uncertainties in the relation between magnitudes M and mB for large earthquakes, the pre-1952 data (giving M) and the later date (giving mB) cannot be compared readily; however, it is likely that there have been only six earthquakes in the Sunda arc region with a magnitude greater than 7.5 M since 1900. These were:

Year	Latitude $^{\circ}$S	Longitude $^{\circ}$E	Depth(km)	Magnitude(M)
1903	8	106	-	8.1
1917	$7\frac{1}{2}$	128	100	$7\frac{3}{4}$
1918	7.0	129.0	190	8.1
1943	8.6	109.9	90	$7\frac{3}{4}$
1950	6.5	129.5	60	8.1
1977	11.1	118.4	Shallow	8.4

The earthquake of 1917 is the only other which has been reported as having been felt in Western Australia (Everingham, 1968b). This was felt as a slight tremor at Wyndham lasting five seconds.

It would not be unreasonable to expect about eight earthquakes of magnitude greater than 7.5 to occur every hundred years in the Sunda arc region. Of these, two or three may be felt in Western Australia. Of the six earthquakes listed above, the most recent is the largest and also the closest to Perth and northwest coastal towns. It is therefore unlikely that the effects, with the exception of tsunami effects, will ever be greater than those for the recent earthquake.

8. CONCLUSIONS

Large earthquakes in the Sunda arc region can be felt in Western Australia and cause minor damage in some centres. Records show that of the eight or so earthquakes that are expected to occur in the Sunda arc region every hundred years, two or three could be felt in Western Australia. The earthquake of 19 August 1977 was the largest and closest to Western Australia recorded from the region this century, and the effects are likely to be the maximum experienced in Western Australia, with the possible exception of tsunami effects. The high-rise buildings of Perth are considered to be relatively safe, in terms of earthquake risk, compared with single-storey and low-rise buildings.

Significant effects from this earthquake were:

(1) The maximum intensity (without building amplification) of MM V was felt in the northwest towns of Port Hedland, Broome, and Derby. The intensity could have been almost MM VI on the upper floors of buildings about five storeys high.

(2) An eight-fold amplification of peak ground acceleration occurred in multi-storey buildings in Perth. This represents a differential of III on the Modified Mercalli intensity scale.

(3) Only minor damage occurred in Perth. This damage was typically re-opening of old cracks and occurred exclusively in middle-rise buildings (8 - 15 storeys). This probably because the period of the seismic waves matches the natural period of

vibration of these buildings.

(4) Intensities and estimated peak accelerations at various localities were:

	Modified Mercalli intensity	Estimated peak acceleration (m/s^2)
Mundaring	MM I	4×10^{-3}
Perth (ground)	MM II–III	3×10^{-2}
Perth (top floor 8–15 storey building)	MM V–VI	2.5×10^{-1}
Port Hedland	MM V	2.0×10^{-1}

(5) Seismic sea waves up to 6 m high occurred along the northwest coast between three and five hours after the earthquake. The waves arrived near low tide and no damage resulted. Had the waves arrived at high-water spring tide there could have been some coastal flooding.

9. RECOMMENDATIONS

(1) It is considered that the risk to occupants as a result of evacuating high-rise buildings in Perth during earthquakes in the Sunda arc region is greater than that resulting from remaining in the building.

(2) Ways and means of installing accelerographs in selected buildings in Perth should be investigated.

(3) The Pacific Tsunami Warning Centre (Honolulu Observatory) should be approached to see whether the Centre could issue a tsunami watch warning to Australia for earthquakes in the Sunda arc, New Hebrides Trench and Kermadec-Tonga Trench regions.

(4) The resonance effect from earthquakes should be considered in the design of buildings about five stores high at Port Hedland, Broome, and Derby.

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11. REFERENCES

BUREAU OF METEOROLOGY, 1929 - Results of rainfall observations made in Western Australia. Government Printer, Melbourne.

DENHAM, D., SMALL., G.R., & EVERINGHAM, I.B., 1973 - Some strong motion results from Papua New Guinea. Bureau of Mineral Resources Australia, Record 1973/13 (unpublished).

DEPARTMENT OF DEFENCE, NAVY OFFICE, 1977 - Australian national tide tables 1977, Australia, Papua New Guinea and Antarctica. Australian Government Publishing Service, Canberra.

DUDA, S.J., 1965 - Secular seismic energy release in circum-Pacific belt. Tectonophysics, 2, 409-452.

EIBY, G.A., & MUIR, M.G., 1961 - Tables to facilitate the study of near earthquakes. Seismological Observatory Bulletin S-109, Geophysics Division, New Zealand Department of Scientific and Industrial Research, Wellington.

EVERINGHAM, I.B., 1968(a) - Preliminary report on the 14 October 1968 earthquake at Meckering, Western Australia. Bureau of Mineral Resources Australia, Record 1968/142 (unpublished).

EVERINGHAM, I.B., 1968(b) - The seismicity of Western Australia. Bureau of Mineral Resources Australia, Report 32.

EVERINGHAM, I.B., & GREGSON, P.J. (1970) - Meckering earthquake intensities and notes on earthquake risk for Western Australia. Bureau of Mineral Resources Australia, Record 1970/97 (unpublished).

GAULL, B.A., 1976 - Accelerograph recordings of the Musa earthquake, 16 September 1972. Bulletin of the New Zealand Society of Earthquake Engineering, 9, 115-21.

GUTENBERG, B., & RICHTER, C.F., 1954 - Seismicity of the earth. 2nd Edition. Princeton University Press, New Jersey.

McGREGOR, P.M., & RIPPER, I.D., 1976 - Notes on earthquake magnitude scales. Bureau of Mineral Resources Australia, Record 1976/56 (unpublished).

MURPHY, L.M., 1973 - San Fernando, California earthquake of 9 February 1971. U.S. Government Printing Office, Washington.

RICHTER, C.F., 1956 - Elementary seismology. W.H. Freeman and Company, San Francisco.

STANDARDS ASSOCIATION OF AUSTRALIA, 1976 - Draft: Australian standard rules for the design of earthquake-resistant buildings. Standards Association of Australia Committee BD/12.

WEIGEL, E.P., 1974 - Tsunami. NOAA, Volume 4.

APPENDIX 1

MODIFIED MERCALLI INTENSITY SCALE (1956 VERSION)

'CFR' identifies additions to the 1956 version (Richter, 1956)

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

II. Felt by persons at rest, on upper floors, or favourably 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 frames 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 (see below) 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 effected, 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

MM INTENSITY - ACCELERATION

$$\text{Log } A = (I/3.1) - 2.3,$$

where A is acceleration in m/s^2, and I is MM intensity

MM	ACCELERATION (m/s^2)
II	2.2×10^{-2}
III	4.6×10^{-2}
IV	9.8×10^{-2}
V	2.0×10^{-1}
VI	4.3×10^{-1}
VII	9.1×10^{-1}
VIII	1.9
IX	4.0

APPENDIX 3

TSUNAMI EFFECTS OF THE KRAKATOA ERUPTION OF 27 AUGUST 1883

Extracted from the record published by the Bureau of Meteorology (1929).

Geraldton. On 27 August the tide rose to eight feet at 8 p.m. and again at 8.30 p.m.

Carnarvon. Mr C. Crowther wrote that on 28 August a succession of tidal waves from three to four feet high occurred, causing a rise and fall of the tide three times in one and half hours. He supposed it to be an earthquake. On 30 August, and the two following days, the tides were still irregular, rising and falling several times within twenty-four hours.

Cossack (Near Point Samson). Mr R.B. Martin stated that an extraordinary tide set in at 4.30 p.m. on 27 August, rose nearly five feet and then ebbed just as rapidly; the rising and falling occupying not more than thirty minutes. For some days afterwards, tides were erratic.

A report from Ashburton was to the same effect except that the tide occurred at midday. On the 28 August there were fully twelve tides in twenty four hours; an unheard of experience.

Derby. Mr D.B. Ord reported that on the morning of 27 August, sounds were heard as if the banks of the Sound, some three miles away, were falling in. Nothing extraordinary was noticed in the tide.

TABLE 1

LARGE EARTHQUAKES IN THE SUNDA ARC REGION
(19 August - 30 September 1977)

Date 1977	Time (U.T.)	Magnitude (mB)
Aug 19	05 08	6.2
	06 08	7.6
The list between 06 08 and 10 45 U.T. is incomplete for the reasons given in the text.		
	06 24	6.4
	06 36	6.4
	06 43	6.9
	07 10	6.7
	10 50	4.8
	11 12	4.9
	11 46	5.1
	13 23	5.6
	14 23	5.1
	15 28	5.2
	16 12	4.8
	17 40	5.7
	19 39	5.1
	20 15	5.1
	20 20	5.5
	20 51	5.3
	21 12	4.8
	21 35	5.1
	22 23	5.0
Aug 20	00 13	4.8
	02 04	5.1
	02 11	5.0
	02 20	4.9
	03 03	4.9
	04 23	5.3
	06 39	4.9
Aug 20	09 21	5.6
	09 55	5.0
	19 16	5.8
Aug 21	01 17	4.8
	02 12	5.3
	02 21	4.8
	04 32	4.8
	06 29	5.0
	06 50	4.8
	07 51	4.8
	09 29	5.8
	10 24	4.8
	10 39	4.8
	12 28	4.9
	15 36	5.3
	17 02	4.8
	17 30	4.8
	20 29	5.1
	20 37	4.8
Aug 22	05 39	4.8
	15 01	4.8
Aug 23	09 59	4.8
	10 24	5.6
	23 06	5.4
Aug 24	09 42	4.8
	20 24	4.8
	22 17	5.4
Aug 25	00 44	5.0
	06 20	5.1
	19 08	5.9
	21 40	4.8

TABLE 1 (contd)

Date 1977	Time (U.T.)	Magnitude (mB)
Aug 25	22 20	5.2
	23 11	5.1
Aug 26	01 41	5.8
	08 26	5.0
	17 27	4.9
Aug 27	07 13	5.2
	17 27	4.8
Aug 29	09 53	5.0
Aug 30	21 11	4.8
Sep 01	11 26	5.0
	13 59	5.2
	20 59	4.8
Sep 02	10 36	5.8
Sep 05	10 49	5.0
	11 17	5.9
Sep 07	08 12	5.1
	11 39	5.1
Sep 09	02 46	4.9
Sep 11	14 55	4.8
Sep 13	13 30	4.8
Sep 15	23 14	4.8
Sep 16	04 40	5.0
	06 30	5.6
	10 11	5.1
	12 23	4.8
Sep 23	05 58	6.1
Sep 25	18 31	5.3
Sep 26	00 49	4.9
Sep 28	17 49	5.2
Sep 29	02 17	5.7

TABLE 2

LARGE EARTHQUAKES IN THE SUNDA ARC REGION

1900-1974

	Date	Lat. °S	Long. °E	Depth km*	Magnitude M	mB(ERL)
	1903, Feb 27	8	106		8.1	
	1909, May 30	8	131	100	7.2	
	1911, Jul 05	7½	117½	370	7	
	1913, Aug 13	5½	105	75	7.2	
	1914, Aug 06	6	123	600	7	
	1916, Sep 11	9	113	100	7½	
	1917, Aug 30	7½	128	100	7¾	
++	1918, Nov 18	7.0	129.0	190	8.1	
++	Nov 23	7.0	129.0	190	7¼	
	1921, Sep 11	11	111		7.5	
	1926, Sep 10	9	111	80	7.0	
	1927, Mar 26	6	122		7.0	
	Jun 03	7	131	150	7.4	
	1930, Mar 26	7½	125½		7.2	
	1931, Feb 10	5¼	102½		7.1	
	Mar 28	7	129½	80	7.3	
	Sep 25	5	102¾		7.4	
	1933, Jun 24	5½	104¾		7.5	
	1937, Aug 11	6¼	116½	610	7.2	
∅	Sep 27	8.7	110.8	60	7.2	
∅	1938, Oct 20	9.2	123.0	90	7.3	
	1943, Apr 01	6½	105½		7.2	
∅	Jul 23	8.6	109.9	90	7¾	
∅	1944, Mar 22	8.3	123.4	130	7.5	
	Mar 31	7	130½		7.0	
++	1950, Nov 02	6.5	129.5	60	8.1	
∅	1951, Feb 14	7½	126½		7¼	
∅	1952, Feb 14	8.0	126.6	33	7.2	
∅	1953, Jun 25	9.2	123.0	33	7.0	
∅	Jun 25	9.2	123.0	33	7.1	
	1964, Jul 08	5.5	129.8	165		6.5
	1965, Jan 17	6.8	109.1	242		6.5
	Feb 26	6.7	102.7	33		6.1
	May 19	6.5	105.4	74		6.3
	Aug 20	5.7	128.6	327		6.2
	Aug 30	6.4	104.8	81		6.1

TABLE 2 (contd)

Date	Lat. °S	Long. °E	Depth km*	Magnitude M	mB(ERL)
1965, Nov 20	7.3	129.2	140		6.1
1965, Nov 21	6.3	130.3	132		6.6
1966, Jun 22	7.2	124.7	537		6.2
1967, Feb 19	9.1	113.0	94		6.1
Mar 19	6.7	129.9	89		6.1
Oct 12	7.1	129.8	45		6.2
1968, Jan 30	6.1	113.3	594		6.2
Sep 27	6.8	129.1	127		6.1
1969, Aug 04	5.7	125.3	521		6.2
1971, May 04	6.6	105.4	69		6.1
1972, May 28	11.0	117.1	33		6.3
1974, Sep 07	9.8	108.4	33		6.1
Oct 29	6.9	129.5	117		6.5
Nov 09	6.5	105.3	51		6.1
Dec 03	5.0	129.8	33		6.2

* Where depths are not shown the earthquake is shallow, i.e. less than 60 km.

ø ISC Data

++ Duda (1965)

TABLE 3

ESTIMATED INTENSITY INSIDE MULTI-STOREY BUILDINGS IN PERTH

Structural Type	No. Storeys	Observer's Floor	MM Intensity
Reinforced concrete	32	31	IV-V
		19	IV-V
Reinforced concrete	30	30	V
		29	V
		25	IV
		15 (2)	IV-V
		15	IV
		13	III-IV
		1	II
Reinforced concrete	20	20	IV-V
		10	IV-V
		1	III
Reinforced concrete	19	19	IV-V
		7	IV
		1	IV
Reinforced concrete	17	15	IV-V
		8	IV
		1	II
Reinforced concrete	15	15	IV-V
		13	V
		12	V-VI
		1	III
Reinforced concrete	14	12 (2)	V
		11	V
		7	IV-V
		6	IV
		1	III-IV
Reinforced concrete	13	13	V
		11	V-VI
Reinforced concrete	12	11	V
		11	IV-V
		6	IV
Reinforced concrete	11	9	IV-V
		5	IV

TABLE 3 (contd)

Structural Type	No. Storeys	Observer's Floor	MM Intensity
Reinforced brick	10	9 (2)	V
		4	IV
		4	III-IV
		1	II
Load-bearing brick	8	8	V-VI
Reinforced concrete	5	5	IV-V
		4	V
		3	V
		3	IV-V
		2	II-III
Reinforced concrete	4	4	III-IV
Brick	4	2-4	III-IV
Reinforced brick	3	3	III
		2	III
Brick	2	2 (2)	III
		1 (2)	II

TABLE 4

TIDAL PREDICTIONS AT NORTHWEST TOWNS, 19 AUGUST 1977

Barrow Island

Time(WST)	Height(m)
0057	3.3
0655	0.6
1312	3.2
1907	0.7

Dampier

Time(WST)	Height(m)
0103	3.9
0730	0.2
1318	3.7
1941	0.2

Point Sampson

Time(WST)	Height(m)
0107	5.0
0729	0.3
1320	5.0
1944	0.3

Port Hedland

Time(WST)	Height(m)
0114	6.8
0717	1.0
1327	6.6
1930	1.0

Yampi (Cockatoo Is.)

Time(WST)	Height(m)
0146	10.0
0757	1.0
1403	9.7
2010	1.0

Broome

Time(WST)	Height(m)
0050	8.4
0715	0.2
1305	8.2
1928	0.3