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RECORD 1976/31

EARTHQUAKE HAZARD IN AUSTRALIA

by

DAVID DENHAM

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ABSTRACT

Compared to countries which are situated in active tectonic zones, such as Japan, Turkey, and Chile, Australia has only a small earthquake hazard. There is no record of anybody being killed by an earthquake in Australia and the total damage since 1950 amounts to less than a modest $10 million.

One of the main problems of estimating earthquake risk parameters in Australia results from the uncertain statistical nature of earthquake occurrences. Over most of the continent very few earthquakes take place and those that do occur do not usually belong to any well defined zones. In addition, the causes of earthquakes in continental environs are poorly understood and our current knowledge of the state and behaviour of the crust precludes any realistic earthquake predictions.

However, there are some regions such as the South West Seismic Zone in Western Australia, the Central Flinders Zone north of Adelaide, and the Dalton/Gunning Zone near Canberra where earthquake activity is high enough to be taken into account. Furthermore, for special buildings such as nuclear power plants, large storage dams, and hospitals, earthquake risk must be taken into account because the community is not prepared to accept any structural collapse for buildings of this nature.

INTRODUCTION

Earthquakes have caused some of the most violent catastrophes known to mankind and it is hardly surprising that their possible causes have been the subject of conjecture and speculation from earliest antiquity. Theories attempting to explain them are almost as numerous as ethnic groups and have varied from giant snakes fighting in the bowels of the earth (East New Britain) to the Wrath-of-God inflicting justice on wayward mortals who have sinned.

Historical writings testify to mankind's long concern about earthquake hazards and most of the writing from early civilization contain some reference to earthquakes. Old Chinese records stored in provinical capitals for centuries were recently examined to compile a list of over 1000 damaging earthquakes dating from about 800 BC to the present time. Similar records in Japan go back to about 600 AD and these are often sufficiently detailed for estimating the size of major earthquakes (Bolt et al., 1975). In Australia the comparable record is only about 200 years long.

The earthquake which cost the greatest known loss of life anywhere in the world occurred in China near the city of Hsian in 1556. Dynastic records are available which give an estimate of 830 000 people who died from all causes in this earthquake. The loss of life was high because the earthquake occurred in a densely populated region where most of the population lived in caves in the loess hillsides. Since the earthquake occurred at about 5 a.m. local time, when the families were asleep, the caves collapsed and entombed the inhabitants. In addition, demoralization, famine, and disease which frequently follow such a great disaster would each no doubt have contributed to the death toll.

In this century, with the rapid growth of the world's population and the corresponding increase in area inhabited, the potential risk from earthquakes is continually increasing. On average about 10 000 people die each year from earthquakes. A UNESCO study gives 350 000 deaths from 1926 to 1950 from earthquakes, and damage losses amounting to $10 000 million (Bolt et al., 1975). Several towns, including Ashkhabad (1948), Agadir (1959), Skopje (1963), Yungay (1970), Managua (1972) and Guatemala (1976), and hundreds villages have been almost razed to the ground.

Fortunately the effects of earthquakes in Australia have not been so disastrous, but they are enough to be considered seriously. These effects will be discussed later but firstly I will consider matters relating to the earthquake source and the effects of earthquakes on the ground surface.

THE EARTHQUAKE SOURCE

Causes of earthquakes

There have been many theories to try and explain the causes of earthquakes. The most successful is the theory of Plate Tectonics. This regards the crust of the Earth as comprising several comparatively rigid plates, all moving relatively to each other. The plates can be several thousand kilometres across and are up to about 100 km thick. This upper 100 km layer is called the lithosphere and it rests on a plastic or partly melted zone (the asthenosphere) about 50 km thick which effectively decouples the plates from the more solid material deeper in the mantle of the Earth and enables them to move. Fig. 1 shows the locations of the major plates and the distribution of earthquakes. Notice that the plates do not coincide with either the continents or the individual ocean floors. Most of them include continental and oceanic crust welded together to form pieces of a global jigsaw puzzle. These are outlined by the Earth's seismically active zones because most earthquakes occur at the boundaries of the plates and are associated with the interactions taking place there.

Studies of the distribution of earthquakes enable these plate boundaries to be located accurately. These studies show that Australia is situated on the same plate as India, and is moving northward relative to the Antarctic Plate. The Australian Plate boundaries are well defined by: the narrow earthquake belts across the Indian and Southern oceans; the series of arc-like features extending from the Himalayas through Indonesia and New Guinea to Fiji; and the two edges delineated by the zones of earthquakes along the Kermadec-Tonga trench in the east and through Pakistan in the west (see Fig. 1).

While the distribution of earthquakes defines the plate boundaries, studies of the elastic radiation produced by the earthquakes provide information which enable the directions of plate movement to be determined. The relative motions between plates can be as high as 10 cm/yr; where these occur large amounts of strain are continuously stored in the crust near the plate boundaries and very large earthquakes occur frequently (about 50 years). Regions like New Guinea and Japan, where the Pacific Plate is moving rapidly with respect to the Australian and Eurasian Plates, are typical of this situation.

In general new crustal material is formed at the mid-ocean ridges and is consumed either at island arcs, where it sinks deep into the Earth, or in collision zones of mountain building such as the Himalayas. For example the mid-ocean ridge south of Australia (the southeast Indian rise) generates new crustal material at the southern edge of the Australian Plate. Along its northern boundary the crust is being consumed either in the zone associated with the deep sea trenches (e.g. the New Hebrides and Java trenches) or in regions of mountain building such as in New Guinea and the Himalayas.

As the strain increases, the crust usually bends and then, when the stress exceeds the strength of the rocks, the crust breaks and "snaps" into a new position. In the breaking process vibrations are generated at the fracture and if they are large enough can cause damage. These vibrations are recorded at seismograph stations throughout the world.

Although most of the world's earthquakes take place at the boundaries of the major plates, a small proportion (about 5%) occur within the plates. These intra-plate earthquakes pose several problems because they do not appear to lie in any well defined patterns that extend over long distances and hence they are difficult to explain and predict. Although comparatively infrequent they are important because they take place at shallow depth and can therefore cause much damage. Damaging intra-plate earthquakes have occasionally occurred in several parts of the world, for example:

U.S.A.	1811-12 New Madrid sequence which took place in the Mississippi Valley
India	1967 Koyna earthquake in the supposedly inactive Deccan Peninsula
Africa	1964 Kariba earthquake near the border of Southern Rhodesian and Zambia.

Australian earthquakes also fit into the intra-plate category (see Fig. 1).

Locating earthquakes

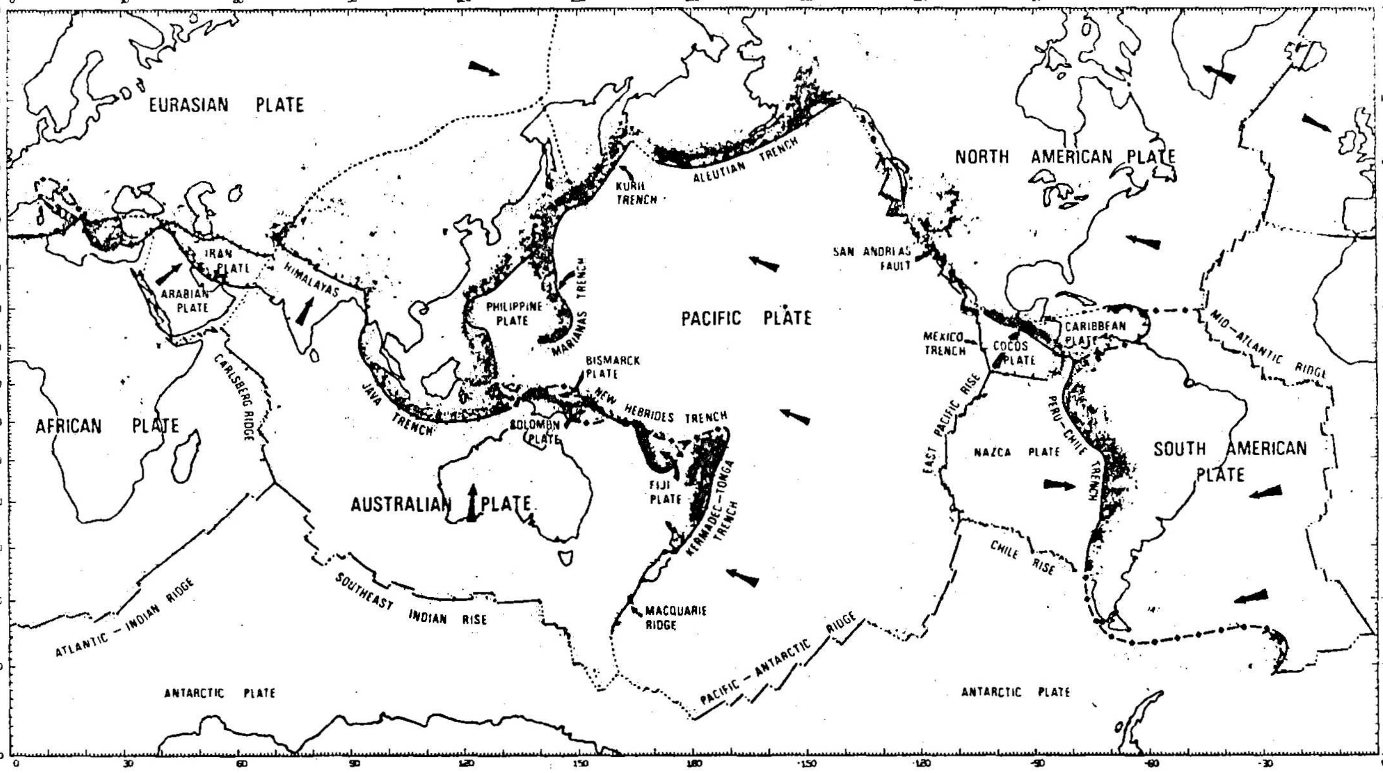
At this stage it is appropriate to mention how earthquakes are located. The focus or hypocentre of an earthquake is the place inside the Earth where the faulting, which is associated with the earthquake, commences. The epicentre of an earthquake is the place on the <u>surface</u> of the Earth situated directly above the hypocentre. To determine the hypocentre we need to know the latitude λ, and longitude ϕ, and the depth H. These parameters can be determined by using the arrival times of the waves from the earthquakes as recorded at seismograph stations around the world.

There are several types of waves generated by an earthquake but the P or primary waves are usually used to locate the hypocentre. The P wave is the fastest kind of wave and it causes the particles of rock through which it travels to vibrate to and fro along the direction in which the wave is travelling. Because it is the fastest kind of wave it arrives first at the seismograph and hence it can be readily identified. The velocity of P waves through the Earth varies from about 5 km/s at the top of the crust, through 8 km/s at the top of the mantle to about 14 km/s at the bottom of the mantle (roughly 3000 km from the surface).

Sometimes it is possible to use the S or secondary waves to determine the hypocentre. These waves cause the particles in the rock to vibrate at right angles to the direction in which the wave is travelling. They travel slower than the P waves (usually by a factor of about 0.6) and are not propagated through the Earth's core because it is liquid. Since the S waves travel slower than the P waves, the S arrival-time minus the P arrival-time is a function of the distance from the earthquake to the seismograph. If the distance from each station recording the earthquake can be calculated it is easy to estimate the source of the waves. However, since the S wave is not the first arrival its onset cannot be timed as accurately as the P wave's.

Tables have been drawn up to show how the travel-times of the P and S waves vary with the distance to the earthquake and its depth. These are used, together with the arrival times, to determine the hypocentre. Because there are four unknowns (T, λ, ϕ, and H) the arrival times are required from at least four seismographs to locate an earthquake using P waves. A large earthquake (magnitude 6 or greater) may be recorded at several hundred seismographs and will be easy to locate, but a small one (less than magnitude 4) could only be recorded by a few stations and may be difficult or impossible to locate. Earthquakes occur at depths ranging from about 1 km to 700 km; no deeper earthquakes have ever been recorded. Over 75 percent of the average annual seismic energy, however, is released by earthquakes with hypocentres less than about 60 km deep. These are the shallow-focus earthquakes which constitute the main hazard.

One important factor in obtaining a good solution is the distribution of the seismographs with respect to the earthquake. If they surround the earthquake in all quadrants it will be possible to obtain an accurate solution, but if they are all situated in only one quadrant - say to the north of the hypocentre - then it may be impossible to locate the earthquake accurately.



RIDGE AXIS
TRANSFORM
SUBDUCTION ZONE
UNCERTAIN PLATE BOUNDARY
EARTHQUAKE EPICENTRES
DIRECTION OF MOTION WITH RESPECT TO ANTARCTIC PLATE

Fig.1 LOCATION OF MAJOR PLATES AND DISTRIBUTION OF EARTHQUAKES

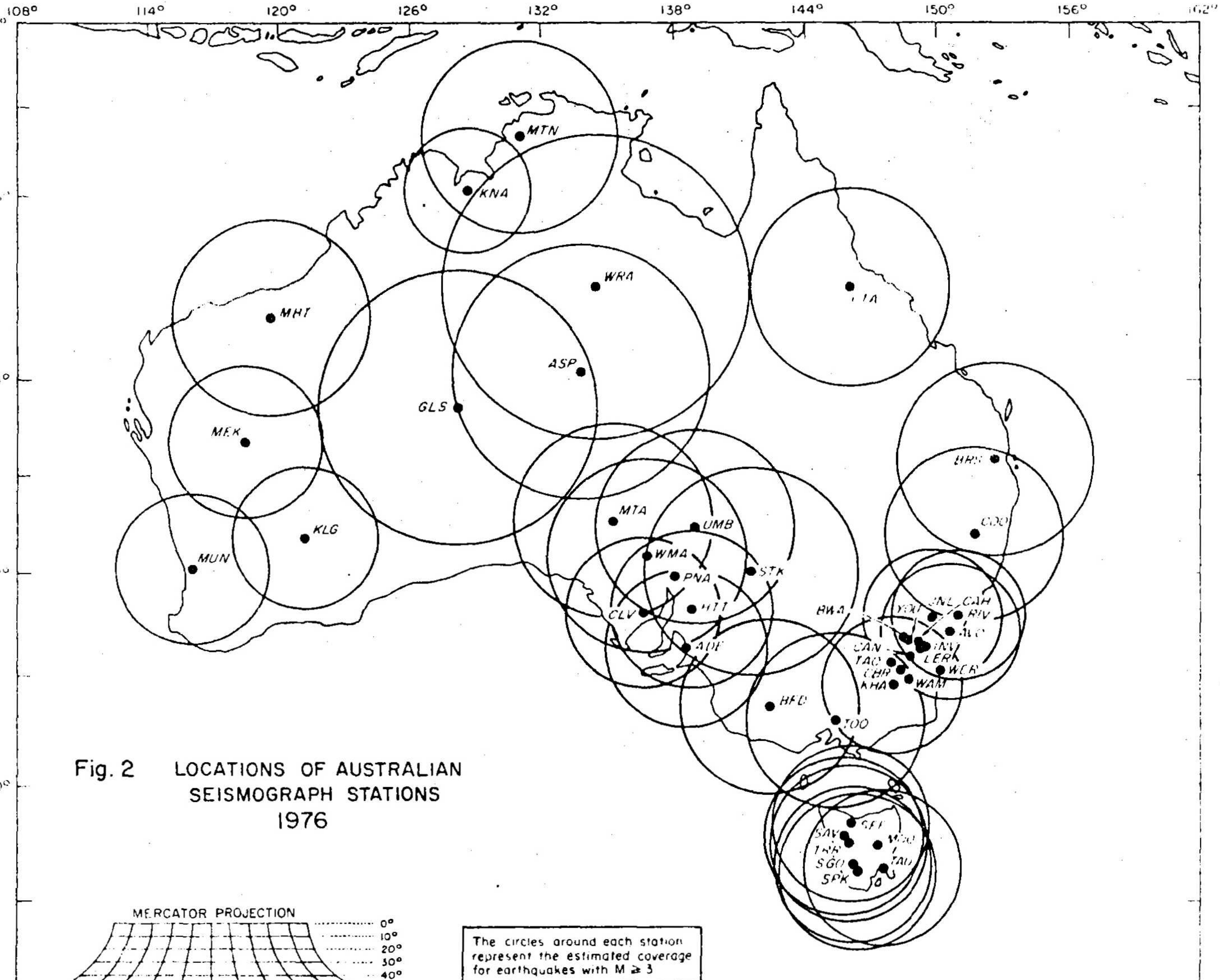


Fig. 2 LOCATIONS OF AUSTRALIAN SEISMOGRAPH STATIONS 1976

For small earthquakes surrounded by seismographs it is sometimes possible to locate the hypocentre to an accuracy of about 1 km but usually errors in the location will be of the order of 10 km. Surprisingly the hypocentres of some of the largest earthquakes are often difficult to locate. This is because the faulted area is very large (800 x 200 km for the 1964 Alaskan earthquake) and cannot be represented accurately as a point in space.

Fig. 2 shows the distribution of seismographs in Australia and their coverage for earthquakes of magnitude 3 and larger. The southeastern part of the continent is well covered, and all earthquakes occurring there larger than magnitude 3 are likely to be detected and located. But in Queensland and parts of Western Australia where there are very few stations there could be many earthquakes larger than magnitude 3 which taken place and are not located; however, it is thought that all earthquakes larger than 4 are located.

Source parameters

Earthquake types

An earthquake is a mechanical fracture of the Earth's crust or lithosphere. There are three basic types of fracture, each corresponding to a different faulting mechanism in different geological environments. The classification of faults is straightforward and depends on the geometry and direction of relative slips (see Fig. 3). The dip of a fault is the angle that the fault plane makes with the horizontal, and the strike is the direction of the fault line exposed at the ground surface relative to north.

(1) Strike-slip faults. These involve displacements of rock laterally, parallel to the strike. The displacements are either right-lateral or left-lateral depending on the relative movements along the fault. This type of faulting occurs at fracture zones that join spreading centres at mid-ocean ridges (the transform faults in Fig. 1), such as the fracture zones in the San Andreas Fault in California. Strike-slip faulting can also take place in regions dominated by compressive forces e.g. near the Anatolian fault in Turkey. Usually the stress which causes the faulting is near-horizontal.

(2) Thrust faults. These occur when the crust above the inclined fault plane moves upward relative to the block below the fault. Sometimes these are called reverse faults. They take place at island arcs and in zones of mountain building and crustal compression. The largest earthquakes such as the Chilean earthquake of 1960, the Alaskan earthquake of 1964, and the great Assam earthquake of 1897 have all been associated with thrust faulting. Like strike-slip earthquakes, the stresses causing thrust faults are usually near-horizontal.

(3) Normal faults. These occur when the rock above the inclined fault plane moves downward relative to the underlying crust. They occur at rift valleys, mid-ocean ridges, and areas of tension resulting from flexures in the crust or lithosphere. Usually these earthquakes are not as large as those associated with strike-slip and thrust faulting.

Fig. 4 depicts the pre-, during, and post-earthquake situations in diagrammatic form for thrust faulting at island arcs and at strike-slip faults. During very large earthquakes the faulting can extend over 100 km and the movement between the two sides of the fault can be up to several metres.

Magnitude, energy, and moment

Several methods of describing the size of an earthquake have been developed. The magnitude of an earthquake relates to the energy released, and is determined from the amplitude of the seismic waves recorded at seismograph stations at different parts of the Earth's surface. The best known scale for measuring magnitudes is the Richter Scale. On this the earthquake's magnitude is expressed in whole numbers and decimals. However, magnitude can be confusing unless the mathematical basis for the scale is understood. It is important to recognize that magnitude varies logarithmically with the amplitude of the earthquake recorded by the seismograph. Each whole number step on the magnitude scale represents an increase of 10 times in the measured wave amplitude of the earthquake. Thus a magnitude 6 earthquake causes ground motion amplitudes 10 times as large as those from a magnitude 5 earthquake, and a magnitude 8.5 earthquake produces amplitudes 10 000 times those from a magnitude 4.5 event.

A shock of magnitude 2 is the smallest normally felt by humans, and earthquakes with magnitudes of 6 or more can cause major damage if they are shallow and close to habitation. Although the scale is open ended, no earthquake greater than 9 has yet been recorded. The smallest earthquakes recorded are at about -2; these are about equivalent to a 3 kg weight falling from a height of one metre.

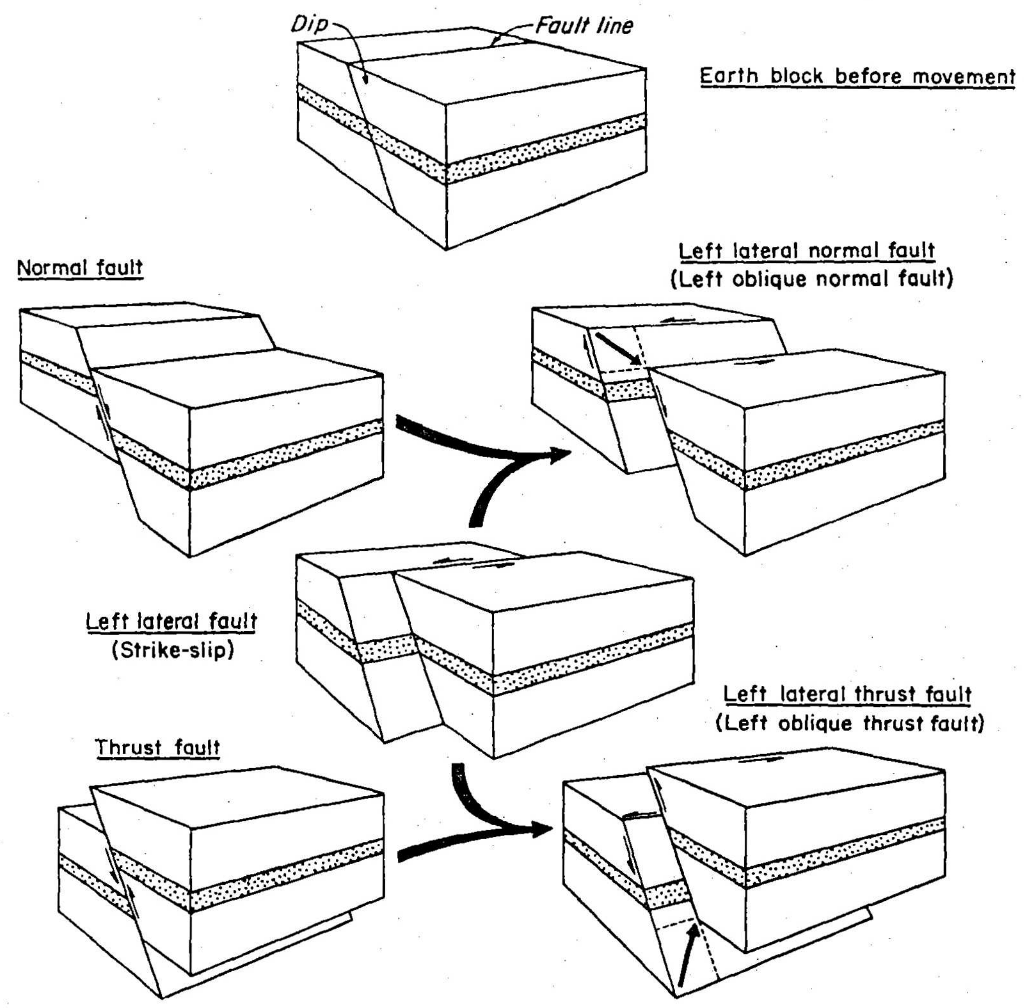


Fig.3 TYPES OF FAULTING ASSOCIATED WITH EARTHQUAKES

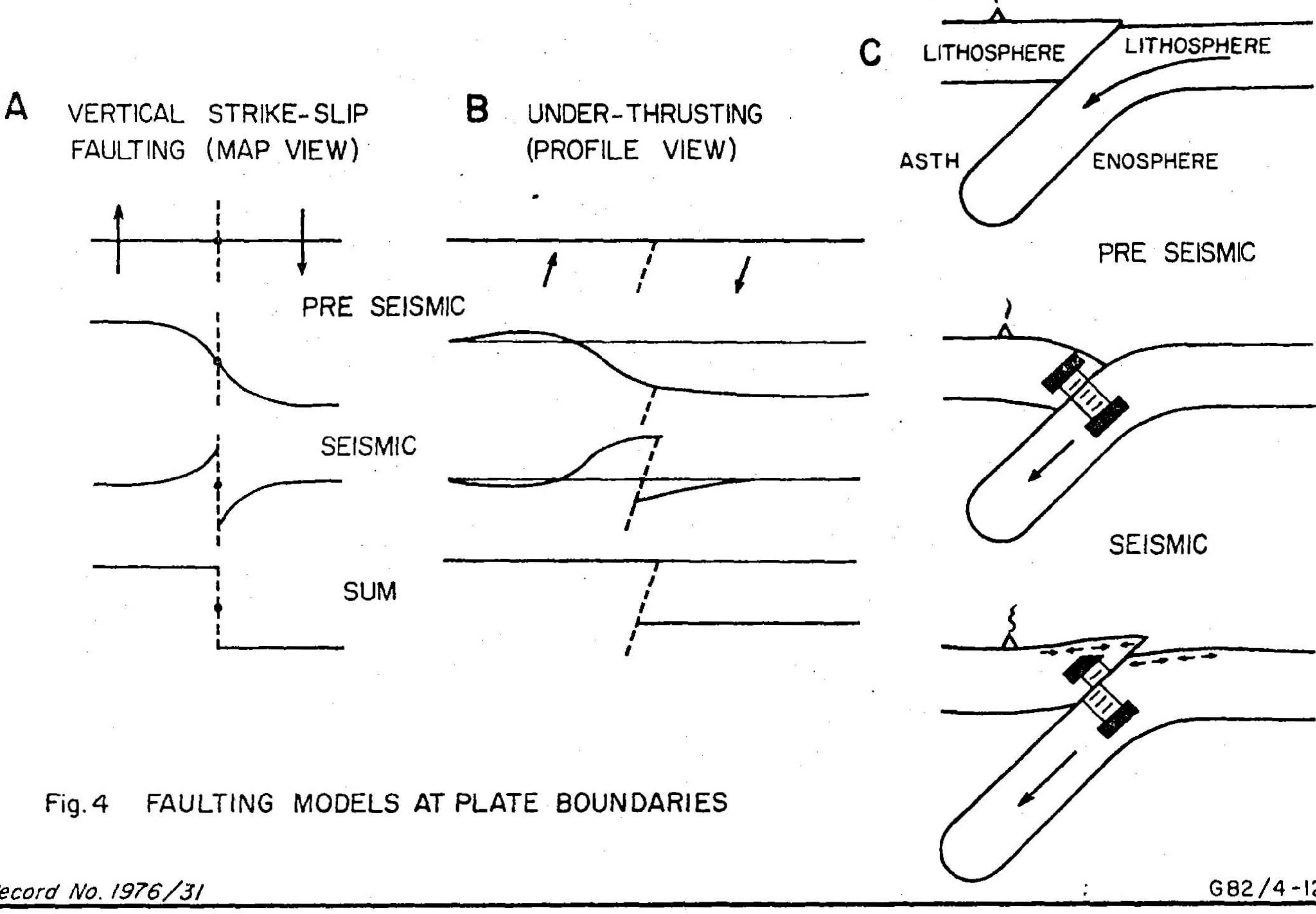


Fig. 4 FAULTING MODELS AT PLATE BOUNDARIES

The energy of shaking during an earthquake relates directly to the damage and hazard. However, this is practically impossible to measure because it is necessary to estimate the total energy flux radiating from the earthquake. An increase of one magnitude step corresponds to an increase of 30 times the amounts of energy released as seismic waves. Therefore, the energy released by a magnitude 6 earthquake will be 900 times that of a magnitude 4 earthquake.

The seismic moment (Mo) is another important parameter used to describe the size of an earthquake. If the earthquake is thought of as arising from the sudden relaxation of pairs of forces in the elastic rocks of the upper earth then the total moment of these forces is a measure of size. Mo is defined as:

$$Mo = \mu A \bar{u} \qquad (1)$$

where μ is the rigidity of the rock, A the fault plane area, and $\bar{u}$ the mean relative displacement between both sides.

Frequency distributions

It was soon recognized that the number of earthquakes occurring during a given time interval in a given area increases with decreasing magnitude. In most regions of the world the frequency of occurrence of earthquakes of different magnitudes is given by the relation

$$\log N = A - BM \qquad (2)$$

where N is the number of earthquakes of magnitude greater than or equal to M, and A and B are constants. This formula can be applied except for large values of M ($\geq$ 7). Where the relation ceases to be linear. In some regions this occurs at magnitudes as low as 6. It is evident that since there is a physical upper limit to the strength of the crustal rocks, in terms of the maximum strain which they are competent to support without yielding, there must be some upper limit to earthquake magnitude. Furthermore it is likely that this upper limit will vary from region to region as the type of rock varies. On a worldwide basis the upper limit is about 8.9 but in some areas, such as eastern Australia, it may be as low as about 6.5.

The constant A is a measure of the number of earthquakes that occur in a specific area during a specific time and the constant B determines the slope of the curve relating the number of earthquakes to their magnitudes. In most regions throughout the world B is of the order of 1, and considering all the world's earthquakes for one year A turns out to be about 8.

This gives about two earthquakes per year in magnitude range 7.7 to 8.6, and about 50 000 in the range 3.0 to 3.9, and shows there are many more earthquakes at the smaller magnitudes.

Unfortunately (from the prediction aspect) the larger earthquakes, which are the most damaging, are also the most infrequent, so it is difficult to obtain an accurate estimate of their frequency or their upper limits when data are available for only a few years. In Australia and throughout most of the world this amounts to only about 75 years of instrumental data, which is a very shore time span compared to the duration of geological processes.

EARTHQUAKE EFFECTS

Intensity scales

The severity of the effects on the ground due to an earthquake at any point are expressed on "intensity" scales. These describe earthquake effects and are subjective measures of the severity of an earthquake as experienced at particular places. The first scale was developed in the 1880s by de Rossi of Italy and Forel of Switzerland - hence the name Rossi-Forel scale. This scale, with values from I to X, was used for several years until in 1902 the Italian seismologist Mercalli devised a new scale on a I to XII range. This was modified by the American seismologists Wood and Neumann to become the well known Modified Mercalli or MM scale. In 1965 this was refined by Eiby for New Zealand conditions, and is listed in Table 1. It is probably the most appropriate scale available for Australian conditions. Naturally, large earthquakes can cause higher intensities than small ones; but the distance from the hypocentre and the properties of the ground surface in the epicentral regional are also significant parameters in determining the intensity. However, most of the potentially damaging earthquakes are those having magnitudes greater than 5.5 and occurring close to the Earth's surface (less than 30 km).

Strong ground motion

The intensity scales enable us to evaluate, albeit subjectively, the damage caused by earthquakes. What is really required is a quantitative estimate of the effect of earthquakes on the Earths' surface. If we can determine how the earth will move then it will be possible to calculate the response of buildings to earthquakes and hence to estimate the risk.

The usual first-order assumptions are that the maximum intensity, acceleration, velocity, or displacement Y is a function of: the source factors (S) which depend on the size of the earthquake and its radiation pattern; a propagation path factor R which depends mainly on the distance of the earthquake from the site under consideration and the attenuation of the energy along the propagation path; and a 'receiver' factor G which depends on the local site conditions. This can be written as:

$$Y = f\ (S,R,G) \qquad (3)$$

However, this formula is too general to have any practical application. It can be simplified by assuming that the site conditions are constant from site to site and that the source factor can be replaced by the magnitude of the earthquake (M), and then we get

$$Y = f\ (M,R) \qquad (4)$$

where R is the distance from the hypocentre to the site. Several attempts have been made to express (4) in analytical terms, and the most common type of expression used has been of the form

$$Y = ae^{bM}\ R^{-c} \qquad (5)$$

where e is the base of natural logarithms and a, b, and c are constants which vary according to whether Y represents the maximum intensity, acceleration, velocity, or displacement.

Unfortunately this formula is a very simplistic attempt to model the real situation. Firstly, because the maximum value Y does not necessarily relate to the damage caused by an earthquake; the duration of the shaking is an equally important factor, but gets no mention. Secondly, the site factors can change the amplitude of ground motion by a factor of at least 10 depending on whether the observations are made on unconsolidated material or hard competent rock. Thirdly, the source factor does not take into account the radiation pattern from the earthquake. This depends strongly on the azimuth between the source and the receiver, and the type of faulting associated with the earthquake. The source factor can vary by a factor of up to 5 for earthquakes of the same magnitude observed at different azimuths.

These large variations in the source and receiver parameters lead to extremely large scatters for the values of Y and large uncertainties in the values of a, b, and c. Fig. 5 illustrates the type of scatter observed in practice. These results were all obtained from one site - Yonki (6.24°S, 145.98°E) in Papua New Guinea - and since all the earthquakes occurred in the quadrant to the north of Yonki the variations in the site term are eliminated. However, the scatter is considerable and must arise solely from the source and distance parameters.

It appears therefore that the scatter of the observations simply reflects the facts of nature and although expressions like equation S do not give exact predictions they are reasonable approximations and probably the best currently available.

Seismic risk

The seismic risk of an area is represented by the danger of earthquake damage for which structures are subject. The risk is connected to the probable ground motion that may be recorded at a given locality with a given frequency.

It should always be kept in mind that the concept of risk is statistical in its nature and all estimates have the associated inherent uncertainties. Several methods of approach have been developed to estimate earthquake risk (see for example Lomnitz, 1974). I will outline briefly the extreme value methods which are commonly used.

These usually assume that the number of earthquakes taking place, say per year, is a Poisson random variable, and then use the extreme value theory developed by Gumbel (1958). Then if the time scale is divided into equally spaced intervals the extreme value y (the maximum value reached by the variable x within each interval) can be expressed in the form

$$G(y) = \exp\left(-\alpha e^{-\beta y}\right) \qquad (6)$$

Where G(y) is the cumulative probability that the variable x will exceed y. In order to estimate the parameters α and β one takes the largest yearly earthquake magnitudes $y_1, y_2, \ldots y_n$ is a sample of n consecutive years. These magnitudes are arranged in order of increasing size, so that $y_{(1)} \leqslant y_{(2)} \leq \ldots \leq y_{(n)}$ Then one estimates the values of G(y) from the formula:

$$G(y_j) = j/(n + 1) \qquad (7)$$

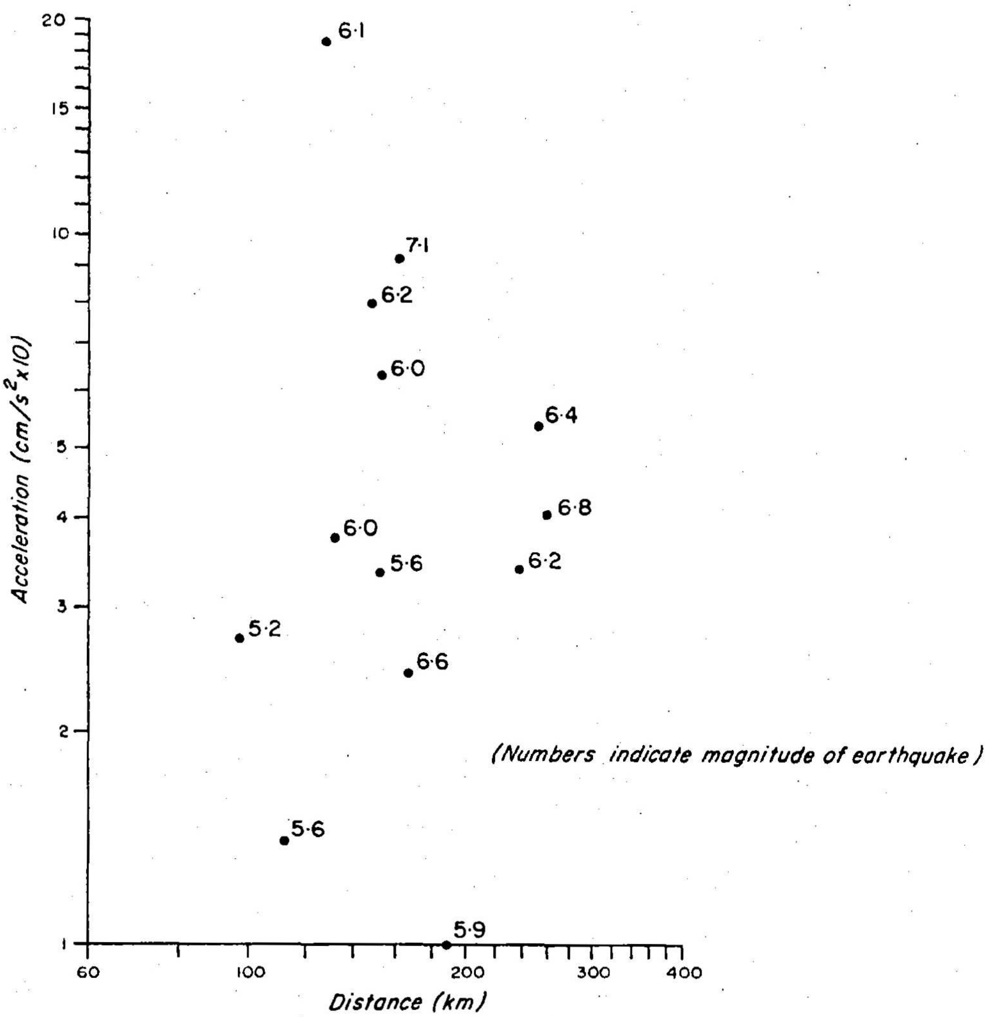


Fig. 5 MAXIMUM ACCELERATION AT YONKI, PAPUA NEW GUINEA

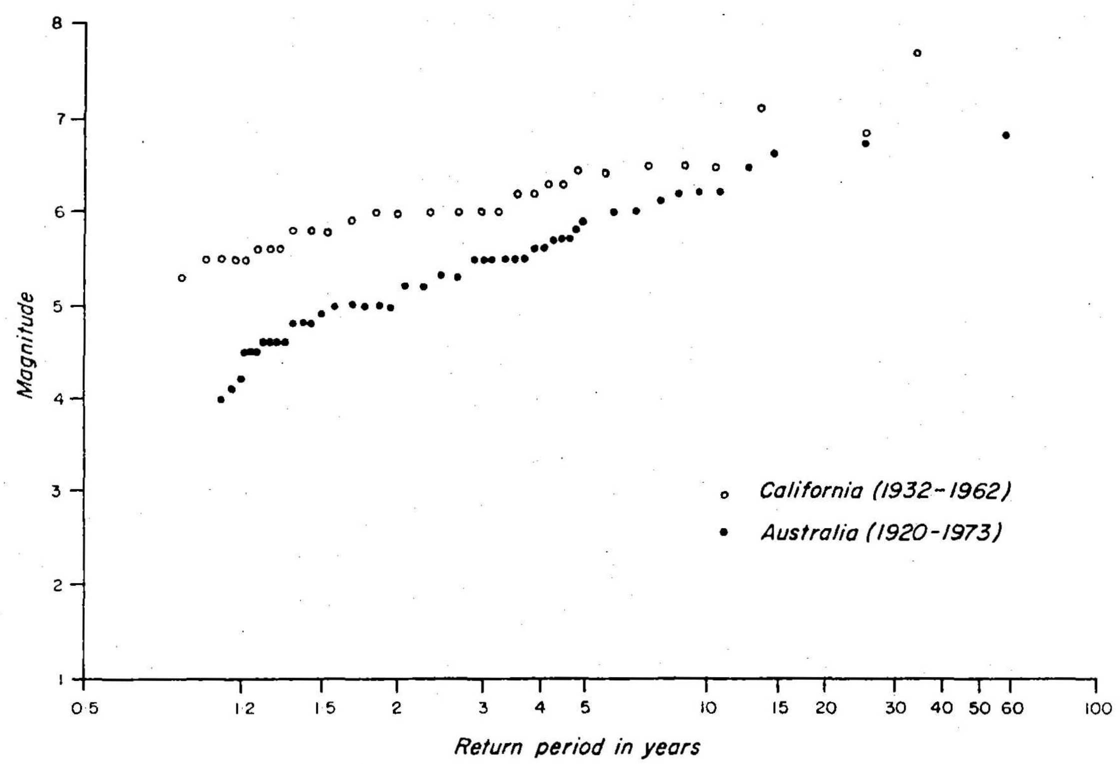


Fig. 6 EXTREME VALUE RESULTS FOR CALIFORNIA AND AUSTRALIA

Finally the values of α and β are estimated from a least-squares fit of equation 6.

$$\ln\left[-\ln G(y)\right] = \ln\alpha - \beta y \qquad (8)$$

We can then estimate the required probabilities for the occurrence of the earthquakes of interest or the return periods of earthquakes of various sizes. Fig. 6 shows a return-period/magnitude plot for Australia (1920-1973) and California (1932-1962) (from Epstein & Lomnitz, 1966). It shows that the California data fit equation (8) better than those from Australia.

There are probably two reasons why the Australian results do not fit a straight line. Firstly because before 1960 the station coverage was not sufficient to record the maximum earthquake for all the years in the sequence, and this results in the downward curve of the data for shorter return periods. Secondly, at the high end of the range it appears that there may be an upper limit of about magnitude 7 for the maximum earthquake that can occur.

One other observation is that the mean annual maximum earthquake is about half a magnitude larger in California (400 000 km^2) than it is in Australia (7.7 million km^2).

AUSTRALIAN EARTHQUAKES

Historical background

The historical record in Australia goes back only about 200 years. The first reported earthquake was felt at Port Jackson in June 1778 when "one evening this month a slight shock of an earthquake had been observed, which lasted two or three seconds, and was accompanied with a distant noise like the report of cannon coming from the southward; the shock however was local " (Jevons, 1859).

In 1837 the first settlers in South Australia were made aware of the existence of earthquakes when "There was a loud rumbling noise that lasted 20 seconds. The earth shook and trembled. It was an earthquake" (Blackett, 1907).

Similarly in the early histories of Melbourne (1841; Underwood, 1972) and Perth (1849; McCue, 1973) earthquakes were felt. Fortunately, as far as is known there have been no deaths caused by earthquakes in Australia and the damage caused during the last 200-year period has been very modest.

The reasons for the low damage rates are simply that the level of earthquake activity and the density of population are both very low. The low level of seismicity arises because the Australian continent is situated away from any active plate margins. Tables 2 and 3 list some of the largest earthquakes on a worldwide and Australia-wide basis. It is noteworthy that all earthquakes listed in Table 2 took place close to major plate boundaries. Furthermore although the largest Australian earthquakes have caused significant damage they are, on the whole, about an order of magnitude smaller than the world's most damaging shocks. This is also indicated in Fig. 6 where the data suggest a maximum magnitude of about 7.

In the last 75 years there have been 17 earthquakes of magnitude 6 or greater within the Australian continent. The rate of occurrence of about 1 every 5 years contrasts with a world average of about 140 per year.

Earthquake distribution

It is convenient to consider three major earthquake provinces - as shown in Fig. 7.

Eastern Region

Earthquakes occurring here tend to be associated with the Tasman Geosyncline. There are no significant major lineations of earthquakes in the region; rather a diffuse distribution of shocks over a wide area, with a few localized clusters of earthquakes where the activity rises above the regional level. One of the most consistently active areas is between Dalton and Gunning about 50 km north of Canberra, and several damaging earthquakes have taken place there in the last 50 years. No earthquake greater than magnitude 6 has been known to occur in the Eastern Region, but several medium sized earthquakes have caused significant damage. Since 1900 the Gayndah (Queensland), Robertson and Picton earthquakes (NSW) of 1935, 1961 and 1973 have probably caused the most damage.

The Robertson and Picton earthquakes had magnitudes of about 5½ and both occurred near the southern margin of the Sydney Basin. Cleary & Doyle (1962) described the effects of the Robertson earthquake, and Denham (1976) describes the effects of the Picton earthquake. The isoseismal maps are shown in Figs. 8 and 9 respectively. In both earthquakes the damage was confined to old buildings (some more than 100 years old).

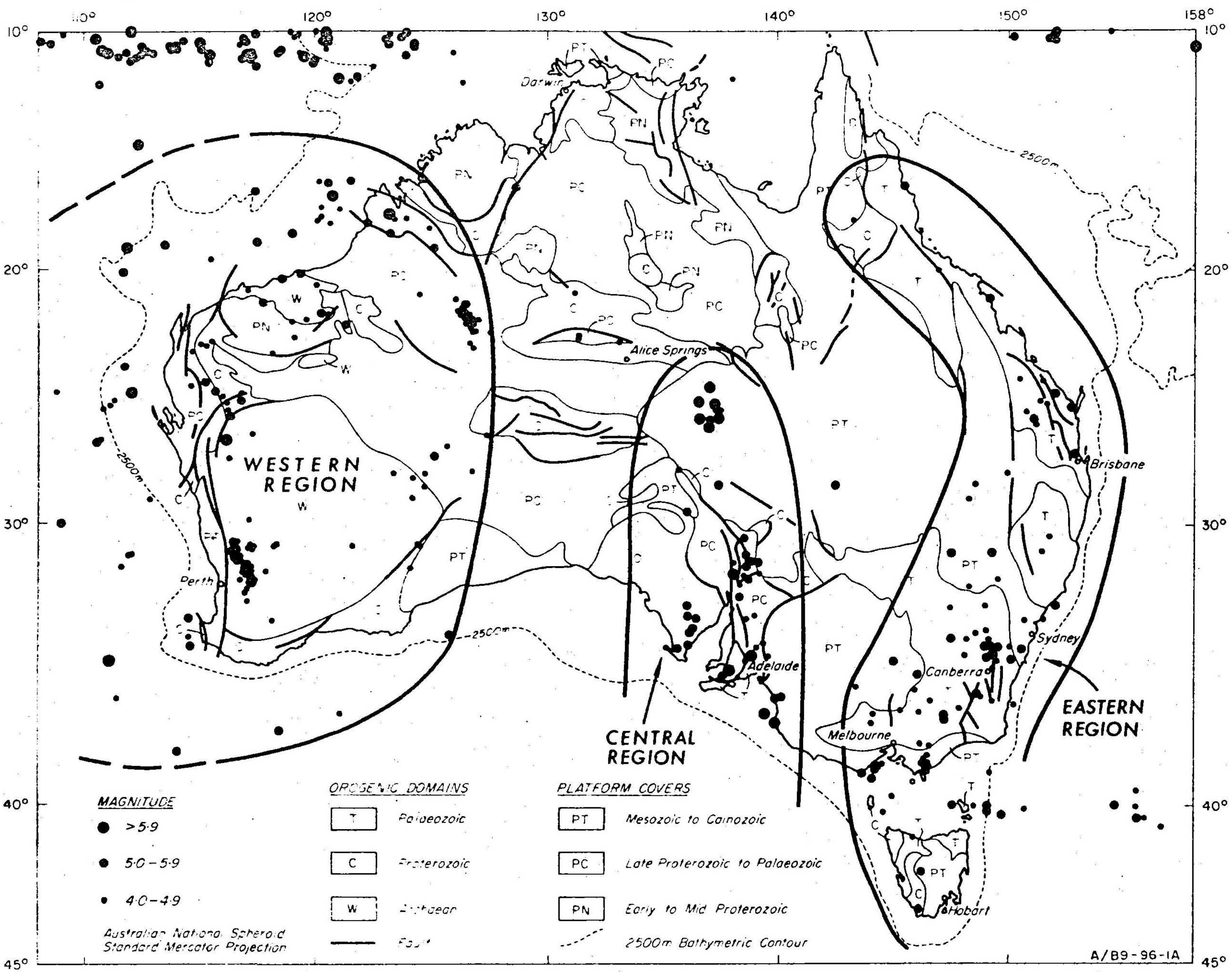


Fig. 7 LOCATION OF AUSTRALIAN EARTHQUAKES

ISOSEISMAL MAP OF THE ROBERTSON-BOWRAL EARTHQUAKE NEW SOUTH WALES NEAR EPICENTRE

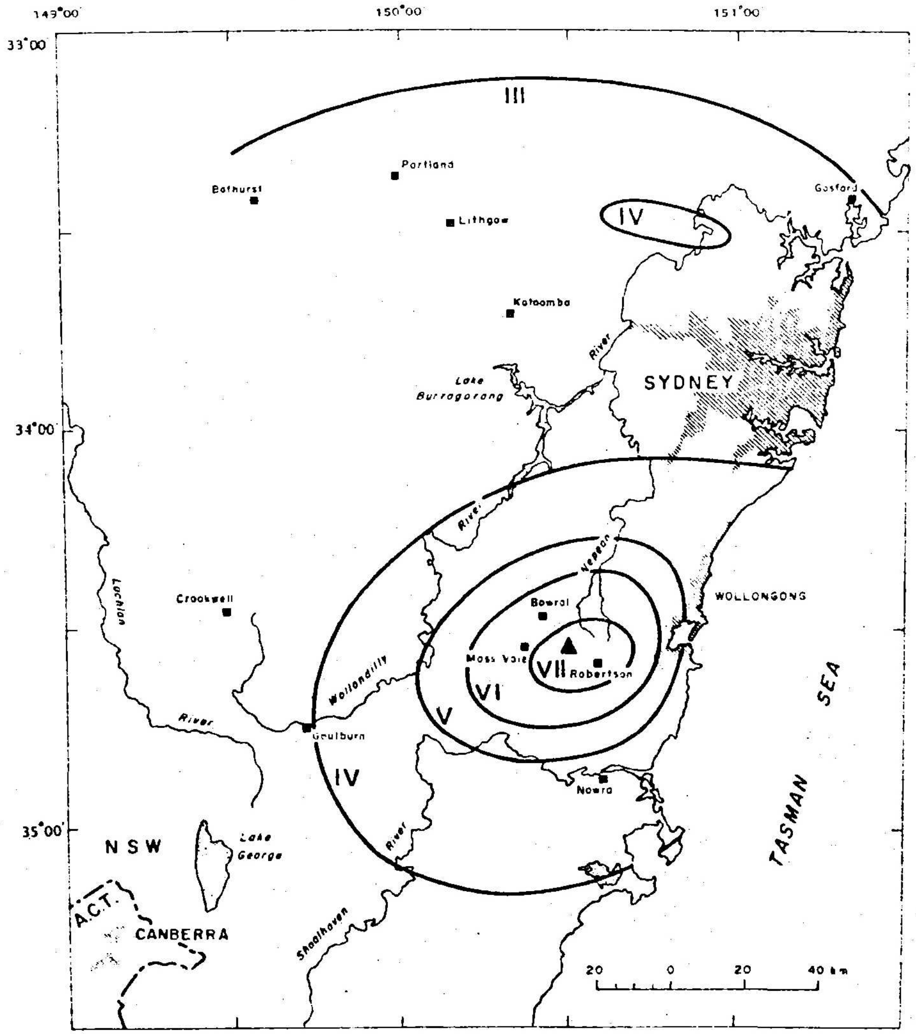


Fig.8

DATE: 21 MAY 1961
TIME 21:40 02·0 UT
MAGNITUDE: 5·8 MB, 5·6 ML
HYPOCENTRE 34·55°S 150·50°E
DEPTH 19 km

ISOSEISMAL MAP OF THE MEEBERRIE EARTHQUAKE W A

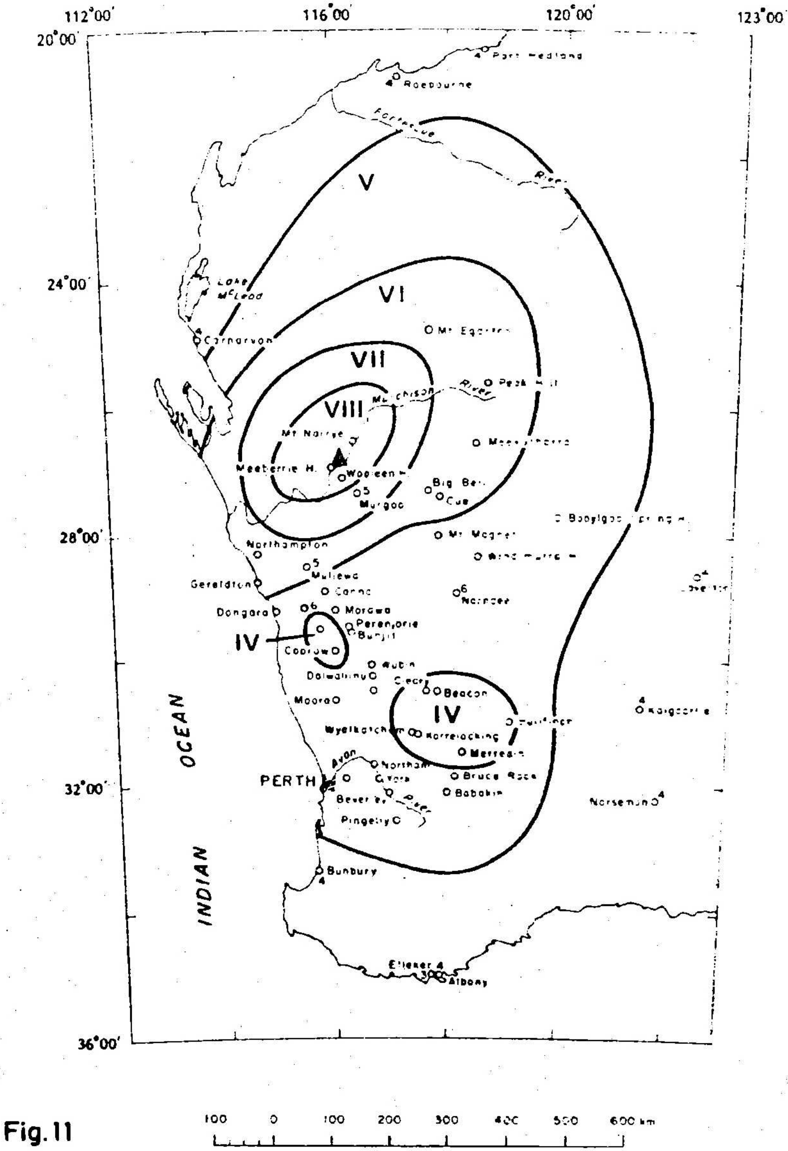
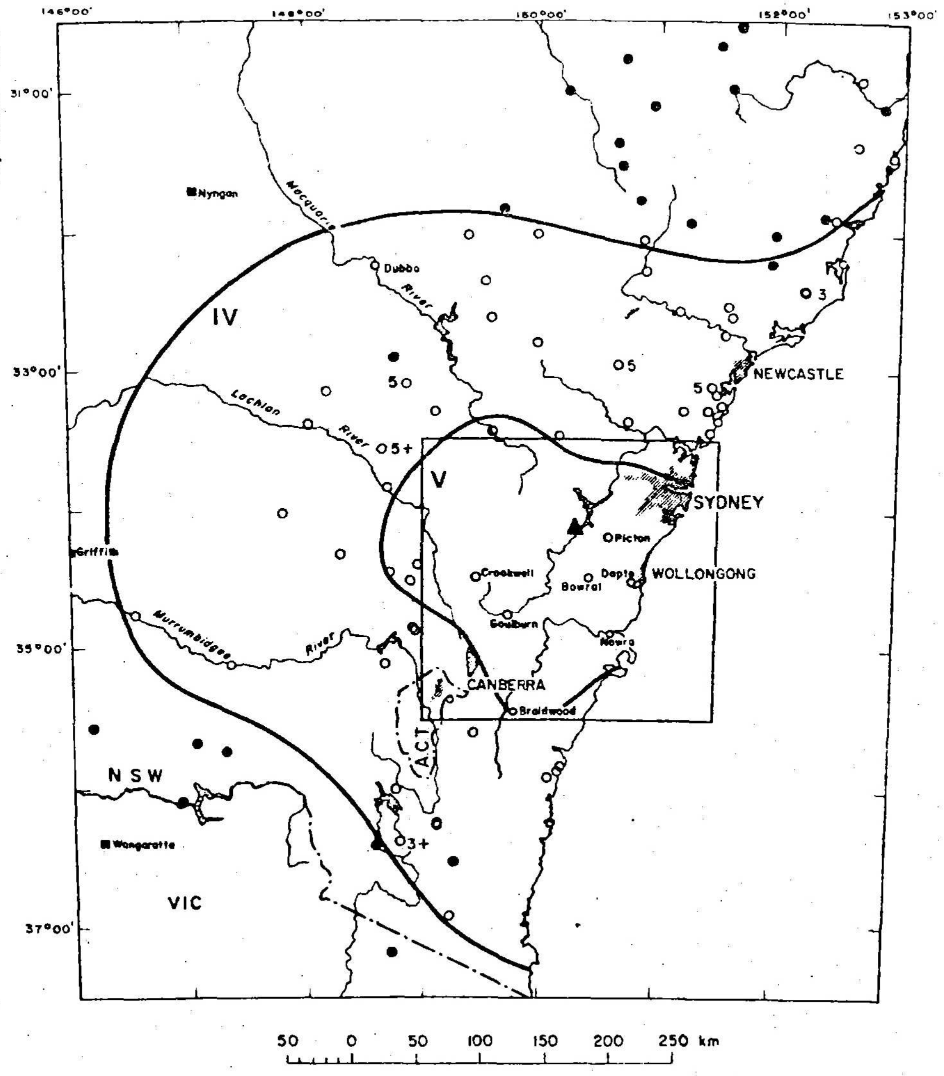


Fig.11

DATE 29 APRIL 1941
TIME 01 35 41 UT
MAGNITUDE 6 8MB, 6·8MS
HYPOCENTRE 26 8°S 116·1°E
DEPTH 33 km

▲ COMPUTED EPICENTRE
o EARTHQUAKE WAS FELT
IV ZONE INTENSITY DESIGNATION (MM)

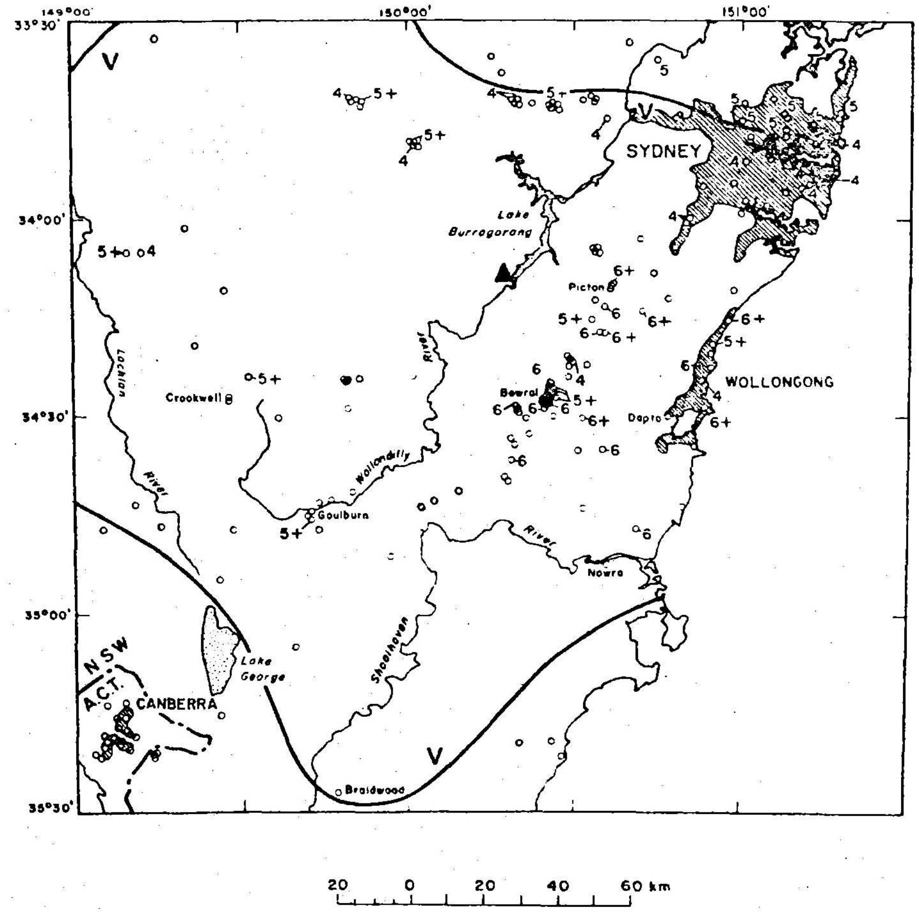
Small figure beside open circle indicates intensity is different from zone designation



DATE: 9 MARCH 1973
TIME: 19:09:14 UT
MAGNITUDE: 5.5 ML
HYPOCENTRE: 34.14°S 150.29°E
DEPTH: 20 km

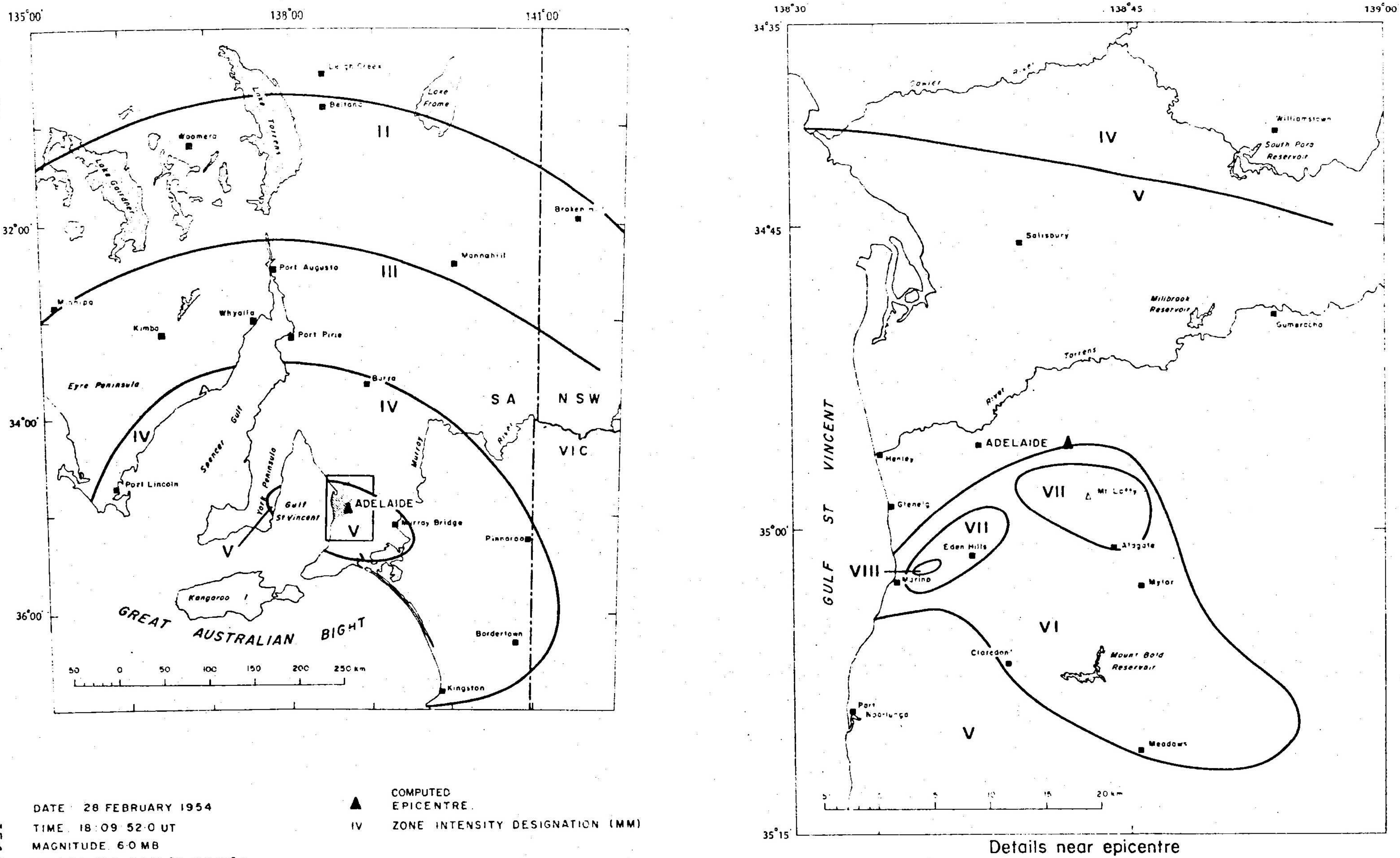
▲ COMPUTED EPICENTRE
○ EARTHQUAKE WAS FELT
● EARTHQUAKE WAS NOT FELT
IV ZONE INTENSITY DESIGNATION (M M)

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



DATE: 9 MARCH 1973
TIME: 19:09:14 UT
MAGNITUDE: 5.5 ML
HYPOCENTRE: 34.14°S 150.29°E
DEPTH: 20 km

Fig. 9 ISOSEISMAL MAPS OF 1973 PICTON EARTHQUAKE



DATE 28 FEBRUARY 1954
TIME 18:09 52.0 UT
MAGNITUDE 6.0 MB
HYPOCENTRE. 34.93 °S 138.69°E
DEPTH 10 km

▲ COMPUTED EPICENTRE.
IV ZONE INTENSITY DESIGNATION (MM)

Fig.10 ISOSEISMAL MAPS OF 1954 ADELAIDE EARTHQUAKE

For the Picton shock, which was felt over an area of about 60 000 km^2, light damage was experienced over a wide area (about 4000 km^2). This consisted of damage to plaster, brickwork, and the tops of chimneys where the heat from the fires had destroyed the adhesive properties of the mortar. No reports were received of complete chimneys breaking at roof level, and only one instance is known (at a glass works in Wollongong) of significant damage to goods or stores. The earthquake occurred deep in the crust (about 25 km) so the areas experiencing higher than normal intensities are scattered over a wide area and not localized in one region as would have happened if the earthquake had been very shallow. 483 claims were received by the Fire and Underwriters Association of NSW of which 423 were admitted at a total cost of $196,400. The total damage is estimated to be about $500 000 and a similar amount was probably caused by the 1961 earthquake.

Central Region

The central Australian seismic zone extends from the Victorian/ South Australian border to the Simpson Desert. Most of the earthquakes occurring in this region can be explained by postulating a regional stress field resulting from a predominantly north-south pressure axis. Although the Simpson Desert region is probably the most active in Australia, it is uninhabited and no damage has been reported there. August 1972 was the last time a large earthquake took place there; it had a magnitude of 6.2 and generated a series of aftershocks extending ENE-WSW for about 120 km. Focal-mechanism studies indicated a horizontal north-south pressure axis with a left-lateral strike-slip fault associated with the earthquake.

The most important earthquakes in the Central Region were the Beachport earthquake of 1897, the Warooka earthquake of 1902, and the Adelaide earthquake of 1954. The Beachport earthquake was the largest of the three and many buildings in Kingston, Robe, and Beachport were damaged. The 1954 Adelaide earthquake was probably the most damaging to have occurred in Australia. Although of only moderate size (M about 5½) it caused widespread damage, mainly to old domestic dwellings, and no less than 30 000 insurance claims were filled (Botta, 1974). The total amount paid out by insurance companies was about £4½ million and although some of the cracks claimed for may not have been caused by the earthquake the amount is still large. Fig. 10 shows the isoseismal maps taken from Kerr Grant (1956).

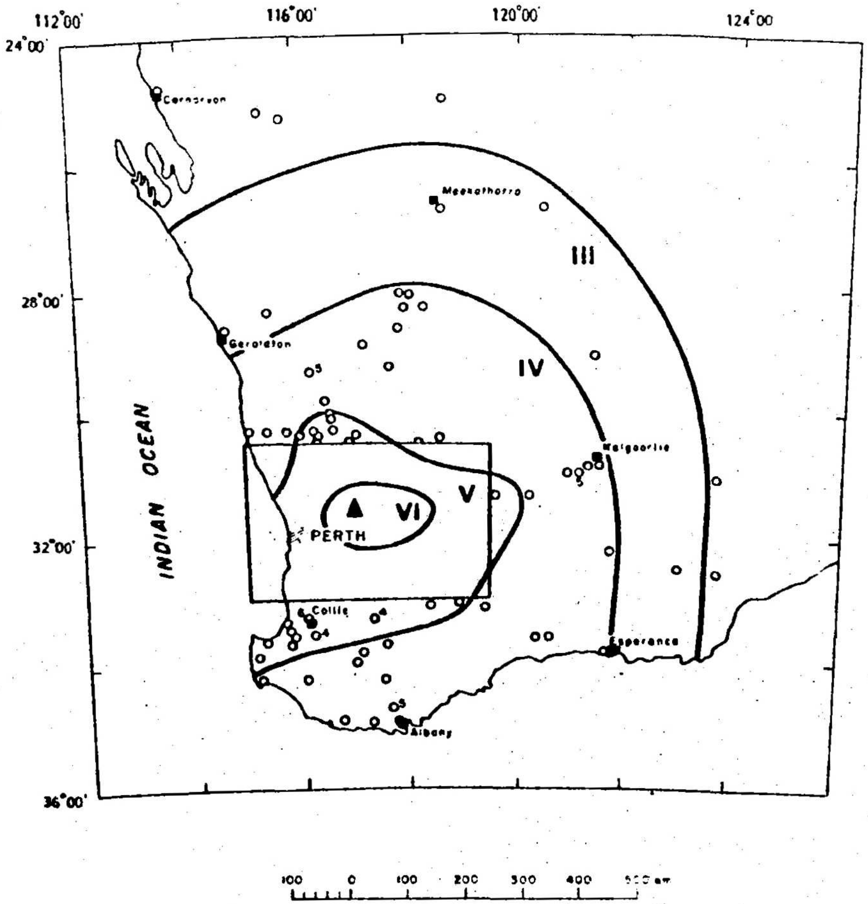
Western Region

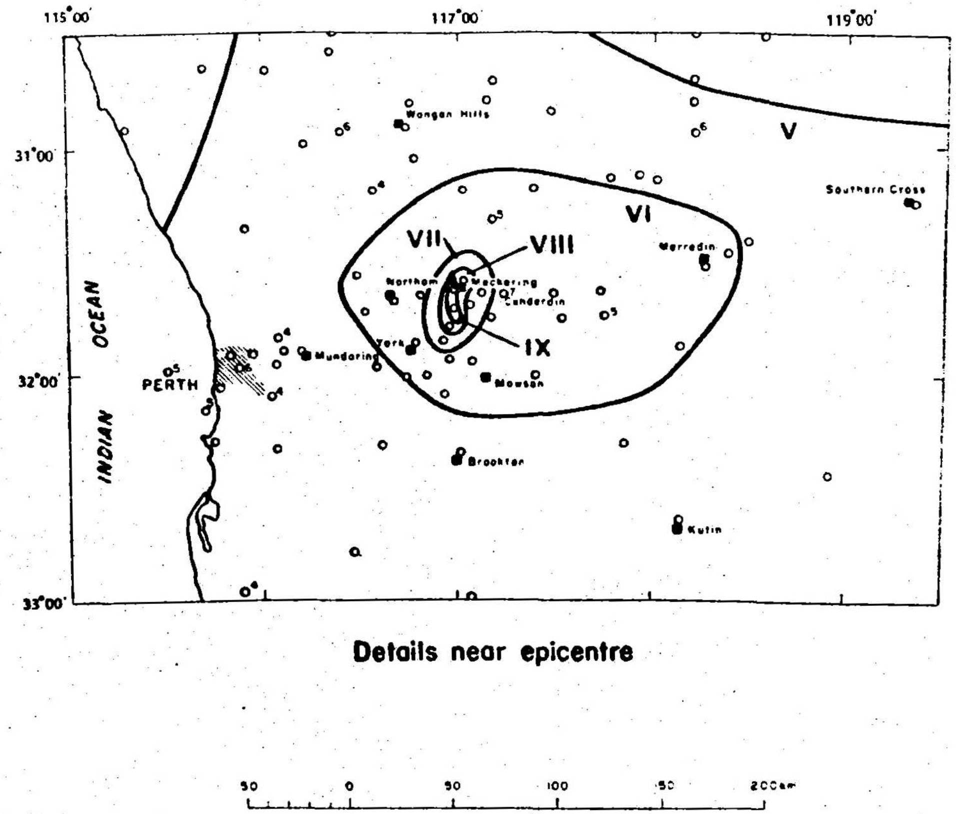
In Western Australia the stress patterns appear to produce several separate zones of seismic activity, each a few hundred kilometres long. Examples are in the Great Sandy Desert, the Southwest Seismic Zone to the east of Perth, and the Meeberrie-Onslow zone east of Carnarvon. There is also considerable activity offshore, and the largest known Australian earthquake of magnitude 7.4 occurred there at 19°S, 112°E in 1906. However, none of the offshore activity appears to follow any well defined lineament. Apart from the 1906 earthquake the largest earthquakes known to have occurred in the Australian continent took place in Western Australia. They were the 1941 Meeberrie earthquake and the 1968 Meckering earthquake.

The Meeberrie earthquake was one of the largest to have occurred in Australia. Its magnitude was about 6.8 and it was felt over a wide area of Western Australia. Fig. 11 shows the isoseismal map, which indicates the extent and severity of the shaking. The original isoseismal map by Clarke et al. (1955) was based on only 13 points and is significantly different from the one shown here, which was compiled in the BMR from about 50 observations.

Damage from the earthquake was small because of the low population in the epicentral region, but the shaking at Meeberrie was very severe; all the walls in the homestead were cracked, several rainwater tanks burst, and widespread cracking of the ground occurred. Although questionnaires were distributed by the WA government astronomer these cannot be traced now and consequently our knowledge of this earthquake is restricted to reports in local newspapers and to a report from Meeberrie station.

The most spectacular earthquake in recent years was the 1968 Meckering event. It occurred in a supposedly stable part of the Archaean shield and produced an arcuate fault zone about 35 km long and with a maximum throw of about 2 m. The zone trended approximately north-south, and convex westwards. Most of the movement along the fault was overthrust with a smaller component of right-lateral movement. A complete account of the damage caused by this earthquake has not been published but the Tariff Insurers met 7706 claims totalling $1 340 763 (Botta, 1974). To this must be added the cost of repairing the public buildings, roads, railways, and water pipes that were damaged and the other private costs would therefore be of the order of $3 million.





Details near epicentre

DATE: 14 OCTOBER 1968
TIME: 02 58 50.6 UT
MAGNITUDE: 6.0 MB, 6.9 ML, 6.8 MS
HYPOCENTRE 31.62°S 116.98°E
DEPTH 10 km

▲ COMPUTED EPICENTRE
o EARTHQUAKE WAS FELT
IV ZONE INTENSITY DESIGNATION (MM)

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

Fig.12 ISOSEISMAL MAPS OF 1968 MECKERING EARTHQUAKE

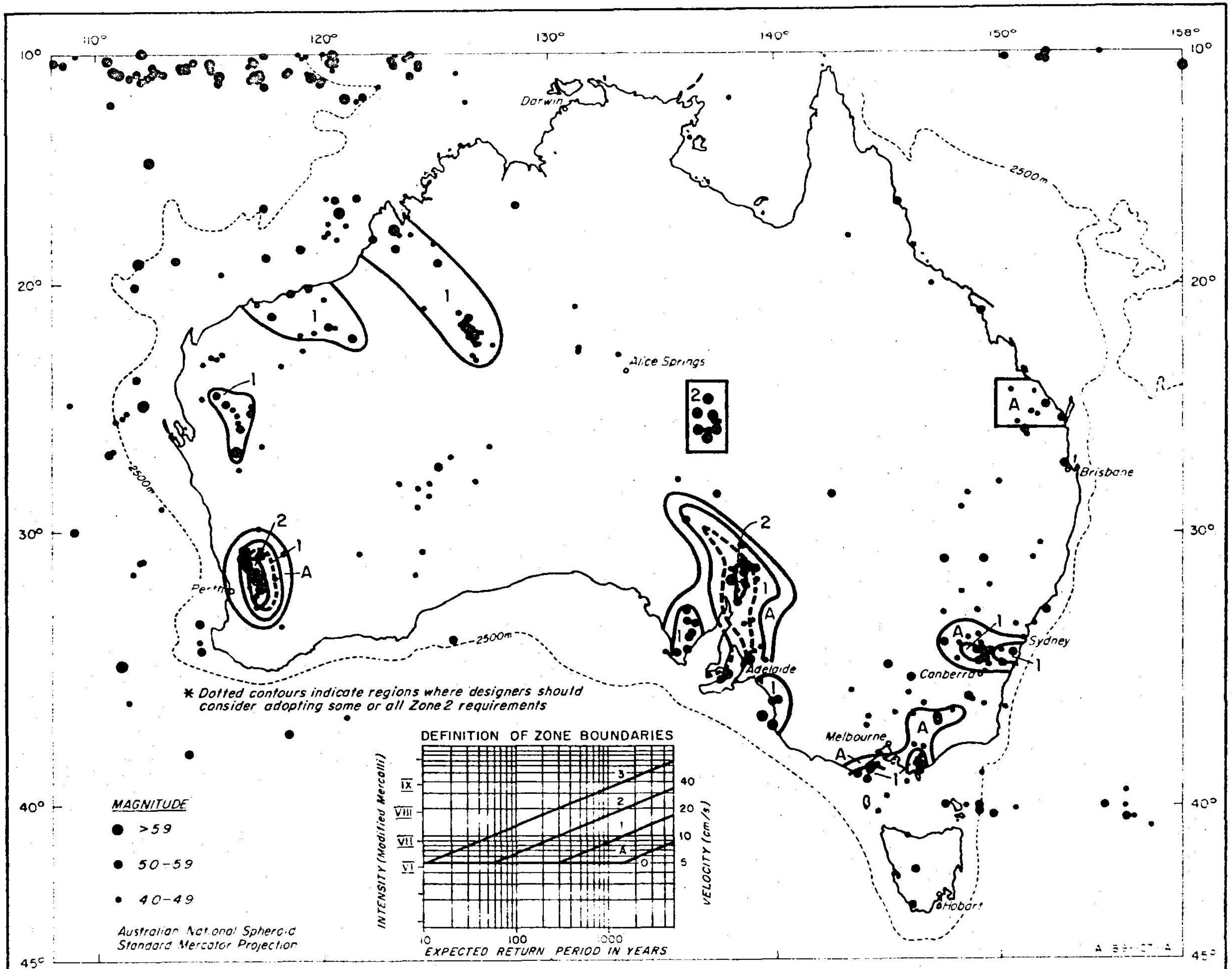


Fig.13 EARTHQUAKE RISK MAP OF AUSTRALIA

Seismic Zoning

For consideration and evaluation of earthquake hazard it is desirable to create maps which indicate the degree of seismic danger. Such maps are also used by engineers in conjunction with building codes which frequently contain chapters on earthquake regulations. In general the higher cost of earthquake resistant construction should balance the seismic risk in such areas. Hence it is important to determine the earthquake risk as accurately as possible so that adequate precautions are taken when designing and constructing buildings. It is also important not to overdesign the buildings so that unnecessary additional costs are incurred.

Most countries have adopted some form of earthquake zoning maps but each country seems to have chosen a different method of presenting and defining the zones.

In Australia the National Committee for Earthquake Engineering has been preparing a zone map for the continent, and a preliminary version is shown in Fig. 13. This map is based on the instrumental data from 1960 and the historical information from about 1900. The basis for the map is described by McEwin et al. (1976). In essence the method uses the scaling formula given by equation 5 (with values of a, b, and c as per Esteva & Rosenblueth, 1964), and determines the values of acceleration, velocity, and intensity at the nodes of a half-degree grid over the entire continent. The values of the appropriate ground motion parameters (acceleration, velocity, or intensity) are then ranked in order and extrapolated as per Gumbel's extreme value theory to obtain the required contours and risk maps.

MAN-MADE EARTHQUAKES

As well as typical tectonic earthquakes it appears that some earthquakes are triggered by man's activity. These man-made earthquakes fall into two categories.

Earthquakes Induced by Large Earthquakes

Until Lake Mead on the Colorado River was filled in 1935, there was no historical record of earthquake activity in the area; afterwards small earthquakes became frequent. This was the first occasion when the filling of a large dam appeared to produce earthquakes. Since then at least a dozen documented cases have been reported where large reservoirs have probably triggered earthquakes.

The more significant have been the Hsinfenkiang dam in China, the Kariba dam in Rhodesia, the Kremasta dam in Greece, and the Koyna dam in India. While each of these dams was filling, earthquakes of magnitude close to six were generated, and surprisingly all the dams are situated in regions where previous earthquake activity was rare or unknown.

There appears to be no rule of thumb which enables one to predict whether a particular dam, when filled, will generate earthquakes. The only single factor in common seems to be the dam height. In all instances (except for the Grandval dam in France h = 78 m) only the dams with a wall height of over 100 m have triggered earthquakes. However, there are many dams throughout the world with heights above 100 m that have not triggered earthquakes. The most likely mechanism for earthquake generation may be reservoir water penetrating through fractures below the newly filled reservoir. The head of groundwater would increase the pore pressure in the rocks sufficiently to reduce the effective frictional resistance along fractures and lines of weakness, thus allowing sudden slips to take place.

This model presumes that considerable tectonic stress is present in the crust before the dam was filled.

In Australia thousands of very small earthquakes ($M \leqslant 3.5$) have been generated by the filling of the Talbingo dam (height 176 m). Some of these were large enough to be felt, but no damage has yet been caused.

Both the Dartmouth (Victoria) and Gordon (Tasmania) reservoirs appear to have the capacity for generating earthquakes and seismic activity in their vicinities should be closely monitored.

When earthquakes are generated by reservoirs the only effective way to reduce the hazard is to lower the reservoir level.

Fluid injection

Since Griggs suggested in 1965 (Press, 1965), that fluid injection into a fault might control the earthquakes associated with it at least two examples of earthquakes generated in this way have been reported.

The first was by Evans (1966), and showed that the rate of fluid injection by the US Army into a well near Denver, Colorado, was linked directly to the level of earthquake activity close by.

The second was in the Rangely oilfield in Colorado (Raleigh et al., 1972
In this instance water was injected by the field's producers into the reservoir rock for the secondary recovery of oil. This had raised the fluid pressures in the vicinity of the field and generated earthquakes along pre-existing faults.

In both these examples it appears that the crustal rocks were already stressed before the fluid was injected, and the earthquake activity was simply triggered by the change in pore pressure near the faults.

It is not thought that similar situations occur within Australia.

The list of references contains items cited in the text and also some general references that have been used to compile this article. Those asterisked would form a valuable background reading list for studies in earthquake risk and the seismicity of Australia.

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TABLE 1

MODIFIED MERCALLI SCALE
(N.Z. Version, 1965, after Eiby 1965)

MM 1 Not felt by humans, except in especially favourable circumstances, but birds and animals may be disturbed.
Reported mainly from the upper floors of buildings more than 10 storeys high.
Dizziness or nausea may be experienced.

Branches of trees, chandeliers, doors and other suspended systems of long natural period may be seen to move slowly.
Water in ponds, lakes, reservoirs, etc., may be set into seiche oscillation.

MM 2 Felt by a few persons at rest indoors, especially by those on upper floors or otherwise favourably placed.

The long-period effects listed under MM 1 may be more noticeable.

MM 3 Felt indoors, but not identified as an earthquake by everyone.
Vibration may be likened to the passing of light traffic.

It may be possible to estimate the duration, but not the direction.
Hanging objects may swing slightly.
Standing motorcars may rock slightly.

MM 4 Generally noticed indoors, but not outside.
Very light sleepers may be wakened.
Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building.

Walls and frame of buildings are heard to creak.
Doors and windows rattle.
Glassware and crockery rattles.
Liquids in open vessels may be slightly disturbed.
Standing motorcars may rock, and the shock can be felt by their occupants.

MM 5 Generally felt outside, and by almost everyone indoors.
Most sleepers awakened.
A few people frightened.

Direction of motion can be estimated.
Small unstable objects are displaced or upset.
Some glassware and crockery may be broken.
Some windows cracked.
A few earthenware toilet fixtures cracked.
Hanging pictures move.
Doors and shutters swing.
Pendulum clocks stop, start, or change rate.

MM 6 Felt by all.
People and animals alarmed.
Many ran outside.
Difficulty experienced in walking steadily.

Slight damage to Masonry D.
Some plaster cracks or falls.
Isolated cases of chimney damage.

Windows, glassware, and crockery broken.
Objects fall from shelves, and pictures from walls.
Heavy furniture moved. Unstable furniture overturned.

Small church and school bells ring.
Trees and bushes shake, or are heard to rustle.
Loose material may be dislodged from existing slips, talus slopes, or shingle slides.

MM 7 General alarm.
Difficulty experienced in standing.
Noticed by drivers of motorcars.
Trees and bushes strongly shaken.
Large bells ring.

Masonry D cracked and damaged.
A few instances of damage to Masonry C.

Loose brickwork and tiles dislodged.
Unbraced parapets and architectural ornaments may fall.
Stone walls cracked.
Weak chimneys broken, usually at the roof-line.
Domestic water tanks burst.
Concrete irrigation ditches damaged.

Waves seen on ponds and lakes.
Water made turbid by stirred-up mud.
Small slips, and caving-in of sand and gravel banks.

MM 8 Alarm may approach panic.
Steering of motorcars affected.

Masonry C damaged, with partial collapse.
Masonry B damaged in some cases.
Masonry A undamaged.

Chimneys, factory stacks, monuments, towers, and elevated tanks twisted or brought down.
Panel walls thrown out of frame structures.
Some brick veneers damaged.
Decay wooden piles broken.
Frame houses not secured to the foundation may move.

Cracks appear on steep slopes and in wet ground.
Landslips in roadside cuttings and unsupported excavations.
Some tree branches may be broken off.

Changes in the flow or temperature of springs and wells may occur.
Small earthquake fountains.

MM 9 General panic.

Masonry D destroyed.
Masonry C heavily damaged, sometimes collapsing completely.
Masonry B seriously damaged.
Frame structures racked and distorted.

Damage to foundations general.
Frame houses not secured to the foundations shifted off.
Brick veneers fall and expose frames.

Cracking of the ground conspicuous.
Minor damage to paths and roadways.
Sand and mud ejected in alluviated areas, with the formation of earthquake fountains and sand craters.
Underground pipes broken.
Serious damage to reservoirs.

MM 10 Most masonry structures destroyed, together with their foundations.
Some well built wooden buildings and bridges seriously damaged.
Dams, dykes and embankments seriously damaged.
Railway lines slightly bent.
Cement and asphalt roads and pavements badly cracked or thrown into waves.

Large landslides on river banks and steep coasts.

Sand and mud on beaches and flat land moved horizontally.
Large and spectacular sand and mud fountains.
Water from rivers, lakes, and canals thrown up on the banks.

MM 11 Wooden frame structures destroyed.
Great damage to railway lines.
Great damage to underground pipes.

MM 12 Damage virtually total. Practically all works of construction destroyed or greatly damaged.

Large rock masses displaced.
Lines of slight and level distorted.
Visible wave-motion of the ground surface reported.
Objects thrown upwards into the air.

Categories of Non-wooden Construction

Masonry A. Structures designed to resist lateral forces of about 0.1 g, such as those satisfying the New Zealand Model Building Bylaw, 1955. Typical buildings of this kind are well reinforced by means of steel or ferro-concrete bands, or are wholly of ferro-concrete construction. All mortar is of good quality and the design and workman is good. Few buildings erected prior to 1935 can be regarded as in category A.

Masonry B. Reinforced buildings of good workmanship and with sound mortar, but not designed in detail to resist lateral forces.

Masonry C. Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Masonry D. Building with low standards of workmanship, poor mortar or constructed of weak materials like mud brick and rammed earth. Weak horizontally.

Windows

Window breakage depends greatly upon the nature of the frame and its orientation with respect to the earthquake source. Windows cracked at MM 5 are usually either large display windows, or windows tightly fitted to metal frames.

Chimneys

The "weak chimneys" listed under MM 7 are unreinforced domestic chimneys of brick, concrete block, or poured concrete.

Water tanks

The "domestic water tanks" listed under MM 7 are of they cylindrical corrugated-iron type common in New Zealand rural areas. If these are only partly full, movement of the water may burst soldered and riveted seams. HA-water cylinders constrained only by supply and delivery pipes may move sufficiently to break pipes at about the same intensity.

Table 2. Some major earthquakes - Worldwide

Date	Place	M	Dead	Damage $\$ \times 10^6$	Houses destroyed
1905	Kangra (India)	8.6	20 000		
1906	San Francisco (US)	8.3	700	800	
1908	Messina (Italy)	7.5	75 000		
1920	Kansu (China)	8.6	180 000		
1923	Tokyo (Japan)	8.3	143 000		
1935	Quetta (Pakistan)	7.6	60 000		
1960	Agadir (Morocco)	5.7	12 000		100% at Kasbah
1960	Chile	8.4	1 000		
1962	Iran	7.5	12 000		21 000
1964	Skopje (Yugoslavia)	5.4	1 000		37%
1964	Alaska (US)	8.4	125	311	
1964	Niigata (Japan)	7.5	25	800	
1968	Iran	6.3	11 588		
1968	Tokachi-Oki (Japan)	7.9	47	131	
1970	Peru	7.8	50 000	250	
1971	San Fernando (US)	6.6	65	700	
1972	Managua (Nic.)	6.2	10 000		city of 400 000 abandoned
1975	Lice, Turkey	6.7	1 900		
1976	Guatemala	7.5	22 000		