EARTHQUAKES 12

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Australian Seismological Report, 1991

Kevin McCue and Peter Gregson

Record 1994/10

Geophysical Observatories and Mapping

Department of Primary Industries and Energy

AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

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AUSTRALIAN SEISMOLOGICAL REPORT, 1991

compiled by
Kevin McCue & Peter Gregson
(Australian Seismological Centre)

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EARTHQUAKE EPICENTRE MAP

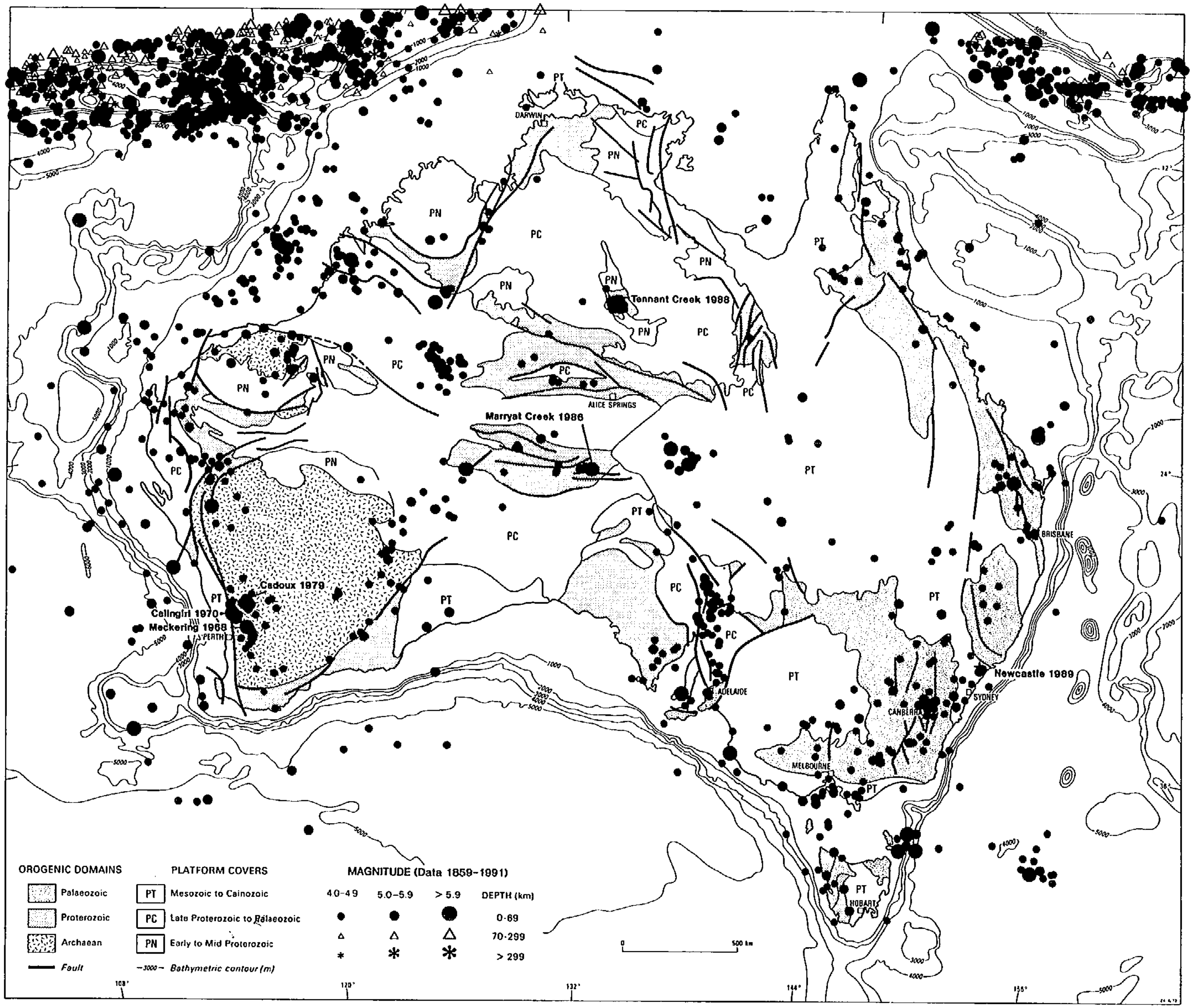

Figure 1 Epicentres of Australian earthquakes, 1873-1991, magnitude ML ≥ 4.0.

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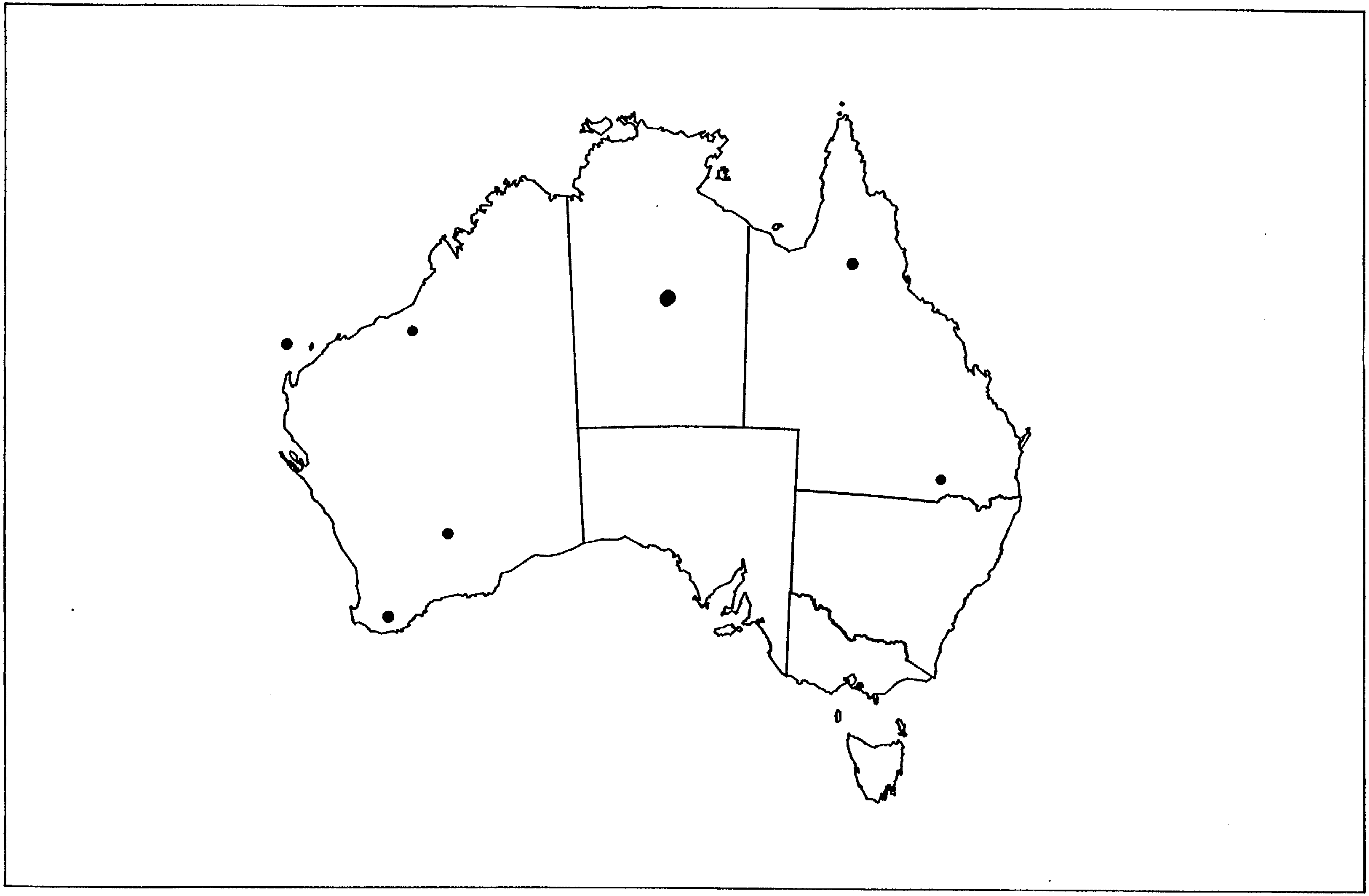


Figure 2 Epicentres of Australian earthquakes, 1991, magnitude ML ≥ 4.0.

SUMMARY

The year was an unusually quiet one as measured by the size and frequency of Australian earthquakes. The largest earthquakes and the only two of magnitude 5 or more were at Tennant Creek NT, both aftershocks of the 22 January 1988 mainshocks. The largest earthquake outside the Tennant Creek area and the first of magnitude 4 or more was at Georgetown Qld., on 7 August. Minor damage was reported at Georgetown and Forsayth, but there was no significant earthquake damage in 1991.

The Georgetown earthquake triggered a recently installed digital accelerograph on the proposed Tully-Millstream Damsite near Cairns, 206 km from the epicentre, the first accelerogram recorded in Queensland.

An event of some interest was a magnitude ML 4.2 rockburst at Kalgoorlie WA on 9 March. Damage occurred in underground stopes but no miners were injured in this, the largest rockburst ever recorded in Australia.

Fifteen earthquakes and the rockburst were felt by sufficient people that intensity questionnaires were distributed and isoseismal maps compiled. The average magnitude of these events was only ML 3.3. Of these, five were in WA, at Kalgoorlie, Karratha, Albany, Shay Gap and Cranbrook. Four others were in SA, at Maitland, Willalooka, Truro and Tumby Bay and there were seven in Queensland; near Mundubbera, Georgetown, St George, Bajool south of Rockhampton, Proston and Borumba Reservoir.

Worldwide there were 8 major earthquakes, the largest with a magnitude of 7.4 was in Costa Rica on 22 April. At least 2000 people died in a major earthquake in Northern India on 19 October which accounted for most of the 2800 killed in 1991, far fewer than the average number of earthquake fatalities of 10 000 per year since 1900.

During 1991, 14 presumed underground nuclear explosions were detonated. This compares with 16 in 1990, 26 in 1989 and 38 in 1988. Neither China nor Russia tested weapons whilst the USA detonated 7, France 6 and the UK 1 (at the US test site in Nevada).

INTRODUCTION

Earthquakes are not uncommon in Australia and are occasionally a threat to life and property as so tragically demonstrated by the Newcastle earthquake. This report contains information on earthquakes of Richter magnitude 3 or greater that were reported in the Australian region during 1991. An annual report has been compiled since 1980 by the Australian Geological Survey Organisation, using data from AGSO and contributing seismological agencies in Australia. Its purposes are to aid the study of earthquake risk in Australia, and to provide information on Australian and world earthquakes for scientists, engineers and the general public.

The report has six main sections: **Australian region earthquakes** which contains a summary of the 1991 seismicity with a State by State breakdown and a brief descriptions of the more important earthquakes; **Isoseismal maps** describing those that were widely felt; **Network operations** which gives details of the seismographs that operated in Australia during the year; **Accelerograph data** which tabulates recordings from the accelerograph network; **Principal world earthquakes** which lists the largest and most damaging earthquakes that took place world-wide during 1991; and **Monitoring of nuclear explosions** which describes the operation of the Nuclear Monitoring Section and lists known underground nuclear explosions.

In the report we refer to the *magnitude* of an earthquake and *intensity* caused by an earthquake. These terms are defined below.

Magnitude

The magnitude of an earthquake is a measure of its size and is related to the energy released at its focus. It is calculated from the amplitude and period of seismic waves recorded on seismograms. The magnitude scale is logarithmic: a magnitude 6 earthquake produces ground amplitudes 10 times as large as a magnitude 5 earthquake, but an energy release about 30 times greater.

A rule of thumb relation between magnitude M and energy E (joules) is

$$\log E = 4.8 + 1.5M$$

A shock of magnitude 2 is the smallest normally felt by humans, whereas earthquakes of magnitude 5 or more can cause significant damage if they are shallow and close to buildings. *Great, major, large,* and *moderate* are terms used to describe earthquakes above magnitude 8, 7, 6 and 5 respectively whilst *small* and *micro-earthquake* are for magnitudes below 4 and 3 respectively. The following magnitude scales are in common use.

Richter magnitude (ML)

Richter (1958) defined a scale to determine the relative size of local earthquakes in California

$$ML = \log A - \log A_0$$

where A is the maximum trace amplitude (zero-to-peak) in millimetres on a standard Wood-Anderson seismogram, and A_0 is the attenuation of amplitude with distance out to 600 km. In California, Richter's reference earthquake, magnitude ML 3.0, causes a trace amplitude of 1 mm on the Wood-Anderson seismogram, 100 km from the epicentre.

If standard, Wood-Anderson instruments (Anderson & Wood, 1925) are not available, an equivalent Richter magnitude can be determined by correcting for the difference in magnification (see Willmore, 1979, para. 3.1.1) between the seismometer used and the Wood-Anderson, and for a seismometer mounted vertically, rather than horizontally. Allowance must also be made for differences in attenuation from that in California.

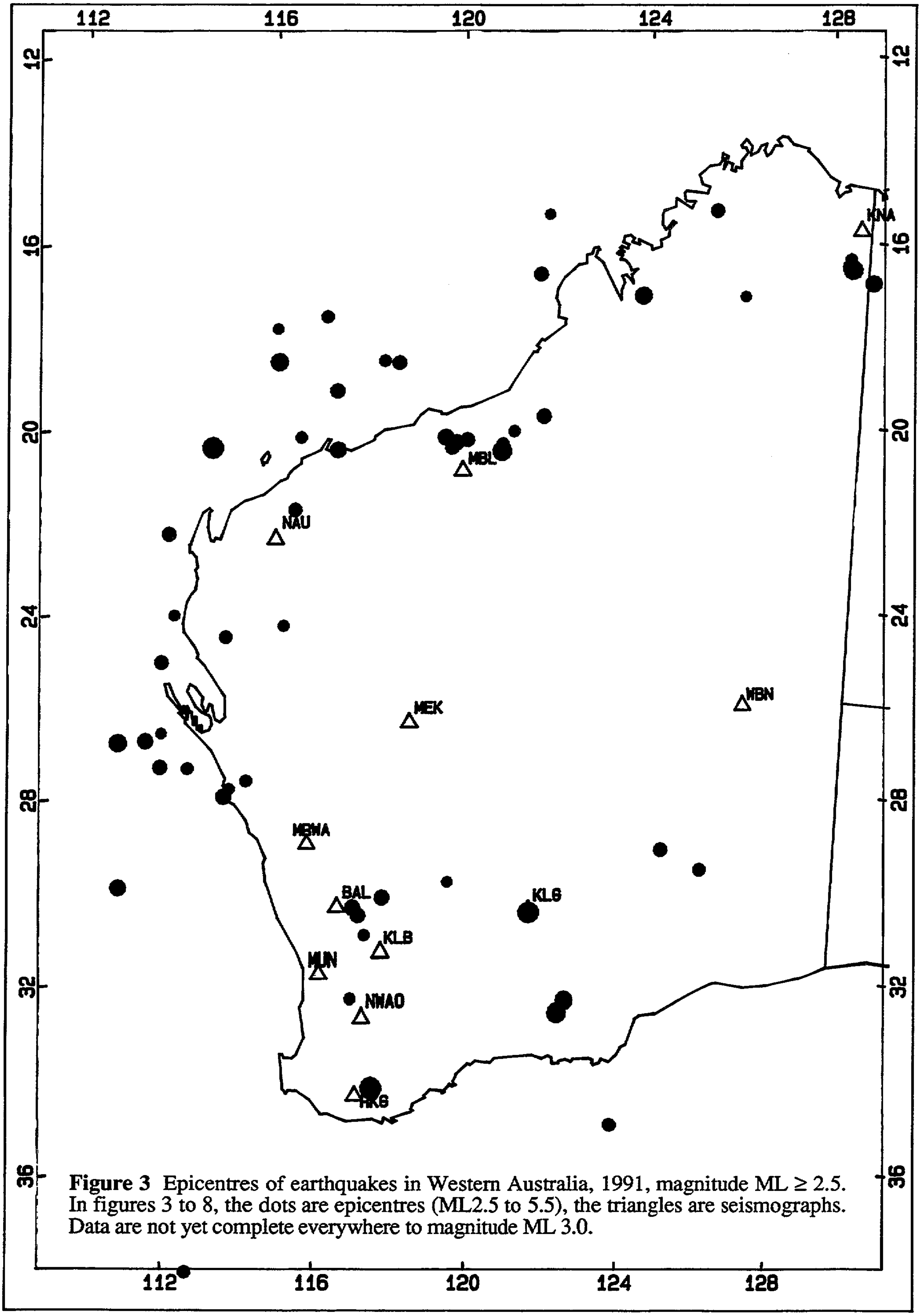


Figure 3 Epicentres of earthquakes in Western Australia, 1991, magnitude ML ≥ 2.5. In figures 3 to 8, the dots are epicentres (ML2.5 to 5.5), the triangles are seismographs. Data are not yet complete everywhere to magnitude ML 3.0.

Surface-wave magnitude (Ms)

The surface-wave magnitude was originally defined for shallow earthquakes in the distance range 20–160°, and in the period range $T = 17–23$ s. When these conditions hold, Ms values are calculated from the 1967 IASPEI formula (see Båth, 1981)

$$Ms = \log A/T + 1.66 \log \Delta + 3.3$$

where A is the ground amplitude in micrometers (10^{-6} m), T is in seconds and Δ is the epicentral distance in degrees. Marshall & Basham (1973) extended this formula to distances as close as 1°, and periods as short as 10 s.

Body-wave magnitude (mb)

For deeper earthquakes with negligible surface waves, or shallow earthquakes outside the distance range defined for ML or Ms, Gutenberg (1945) defined a body-wave scale

$$mb = \log A/T + Q\ (\Delta, h)$$

where A is the maximum mean-to-peak ground amplitude in microns of the P, PP, or S-wave train, T is the corresponding wave-period (seconds), and Q is a function of focal depth h and distance Δ. The Q factors were derived by Gutenberg (1945) and are listed in Richter (1958). This definition was subsequently modified to limit the amplitude measurement to the first 20 s of the P or S phase for moderate sized earthquakes and the first 60 s for large earthquakes.

Duration magnitude (MD)

When an earthquake is close to the seismograph, the wave amplitude on the seismogram may be clipped, in which case no measure of magnitude is possible. To counteract this, another scale was devised (Bisztricsany, 1958), based on the recorded duration of the seismic wave train on short-period seismograms

$$MD = a \log t + b\,\Delta + c$$

where t is the length of the earthquake coda in seconds (usually from the initial P onset), Δ is the distance from the epicentre, and a, b, and c are constants for a particular recording station. Many other forms of this equation have been used.

Seismic moment magnitude (Mw)

Kanamori (1978) defined another magnitude scale from the seismic moment M_o

$$Mw = (\log M_o) / 1.5 - 6.0$$

and $$M_o = \mu A d$$

where μ is the rigidity of the bedrock, A the fault area displaced, and d the average slip on the fault. M_o is the amplitude of the force couple across the fault and is proportional to the amplitude of the far-field ground displacement at low frequencies.

Magnitude from isoseismals

In some cases, where reliable magnitudes or moments cannot be determined from seismograms, it is possible to estimate magnitudes from macroseismic data. In this report, the formula of McCue (1980) is used

$$M(Rp) = 1.01 \ln(Rp) + 0.13$$

where Rp is the radius of perceptibility (km), the distance equal to the radius of a circle with an area equal to that enclosed by the MM(III) isoseismal, and ln is the natural logarithm. $M(Rp)$ is approximately equivalent to ML below magnitude 6, and to Ms above magnitude 6. Greenhalgh & others (1989) modified the equation using a larger data set and extended the method to other intensities, but at the expense of simplicity in application:

$$M(Rp) = 0.35\ (\pm 0.12)(\log Rp)^2 + 0.63\ (\pm 0.41)(\log Rp) + 1.87\ (\pm 0.36)$$

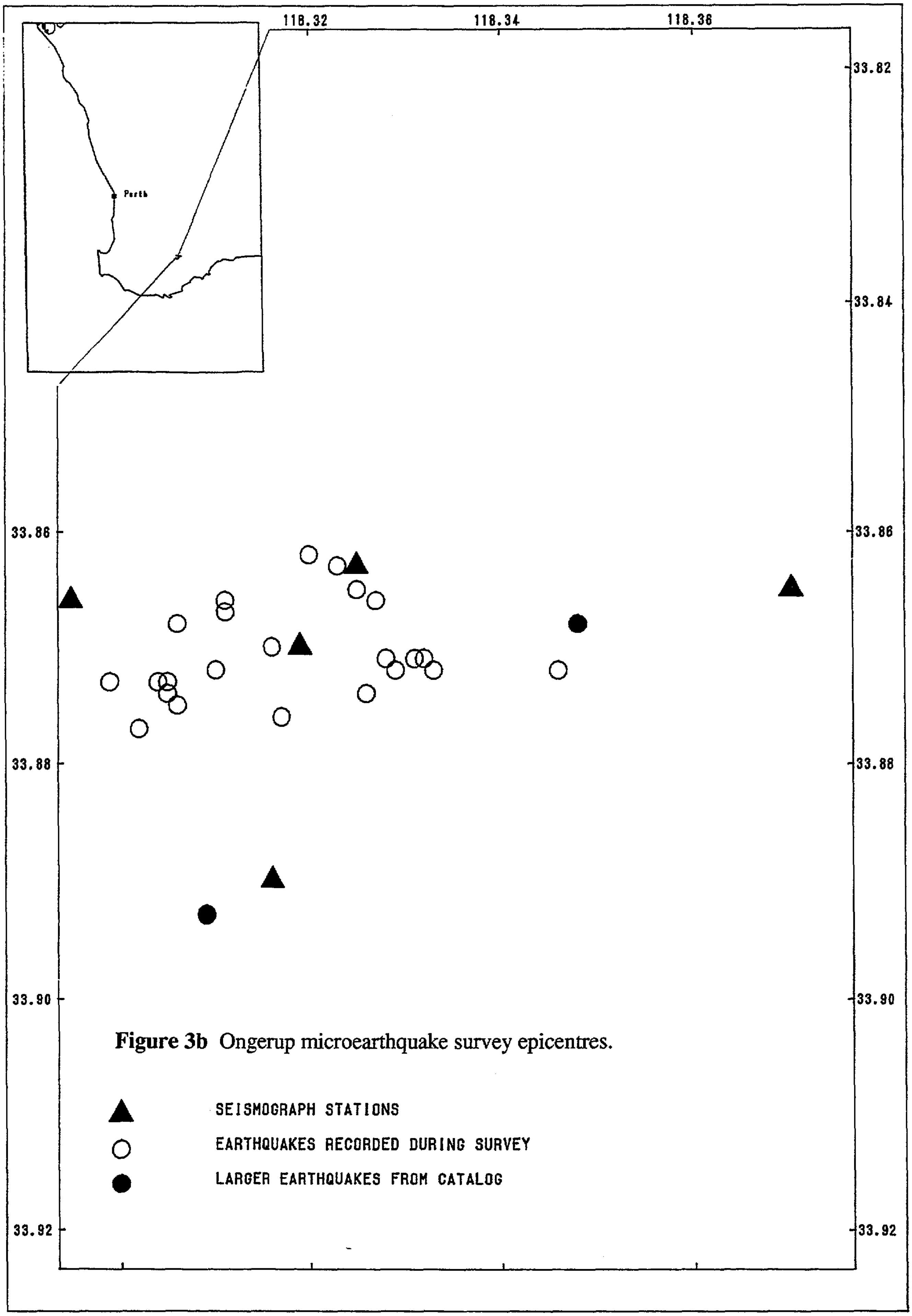


Figure 3b Ongerup microearthquake survey epicentres.

Additional information on magnitudes is available in McGregor & Ripper (1976), Bâth (1981), and Denham (1982).

Intensity

The intensity of an earthquake is a measure of its effects on people and buildings and should not be confused with magnitude which is a measure of the energy release. In this report we use the modified Mercalli (MM) scale as presented by Eiby (1966) for New Zealand The scale is listed in the Appendix. Essentially the MM scale is an assessment of how severely the earthquake was felt and of the degree of damage caused at a particular place. Some earthquakes are felt over a sufficiently wide area that an isoseismal map can be prepared using information compiled from questionnaires, newspaper reports, and personal interviews and inspections.

David Denham, Peter Gregson & Kevin McCue

AUSTRALIAN REGION EARTHQUAKES, 1991

For the first year since 1960, the largest earthquake in Australia, excluding aftershocks, was smaller than magnitude 5. The earthquake at Georgetown, Qld on 7 August at magnitude ML 4.4 was not only the largest but the first non-aftershock of magnitude 4 or more for the year. There were no magnitude 5+ earthquakes outside the Tennant Creek area though the average frequency since 1960 is 3.5, and there were far fewer earthquakes of magnitude 4 or more, only 5, compared with a post-1980 average of 21 per year. The year was a very quiet one as far as earthquakes are concerned.

The Tennant Creek aftershock sequence continued and magnitude ML 5.1 (Mb 5.2, ISC) and 5.0 aftershocks occurred in June and July. These were felt in the town of Tennant Creek but caused no damage.

Kevin McCue

Western Australia (Figure 3)

Four earthquakes of magnitude ML 4 or greater occurred in Western Australia; one less than in 1990. The two largest, ML 4.3 occurred on 18 October, 158 km north of Exmouth and 13 December, 20 km south-west of Cranbrook in the South-west Seismic Zone. The other 2 occurred on 3 March, 5 km south of Kalgoorlie (ML 4.2) and on 23 September, 111 km north-east of Marble Bar. Of the 217 earthquakes recorded in WA, the majority of activity occurred within, or close to the defined zones.

One hundred and twenty three earthquakes were located in the South-west Seismic Zone, compared with 78 in 1990. The most significant activity occurred near Cadoux (27 events) where the largest earthquake (ML 3.3) was recorded on 8 January. Other areas of activity were Meckering (18); Nyabing (12); Quairading (9); Brookton (6); Wyalkatchem (6). Minor activity occurred near Burakin (5); 2 each at Merredin, Ongerup, Beacon, Pingrup, Wooroloo, Cranbrook and Gnowangerup, with single earthquakes at Wubin, York, Wongan Hills, Darkan, Katanning, Tambellup, Ballidu, Dumbleyung, Calingiri, Pingelly, Kirup and Mingenew. The latter two are of paticular interest as they are very close to the Darling Fault where no previous activity has been recorded.

Isoseismal maps were prepared for earthquakes that occurred at Kalgoorlie, Albany, Shay Gap and Cranbrook.

Peter Gregson

<u>Micro-earthquakes near Ongerup, February - April 1991</u>. A temporary network of 4 digital seismographs and 1 analogue seismograph was set up following reports of frequent small tremors near Ongerup WA, a wheatbelt town in the South-West Seismic Zone. More than 20 earthquakes per night were reported felt. The survey continued for 10 weeks, and 31 locatable events were recorded, 16 of which occurred between 22

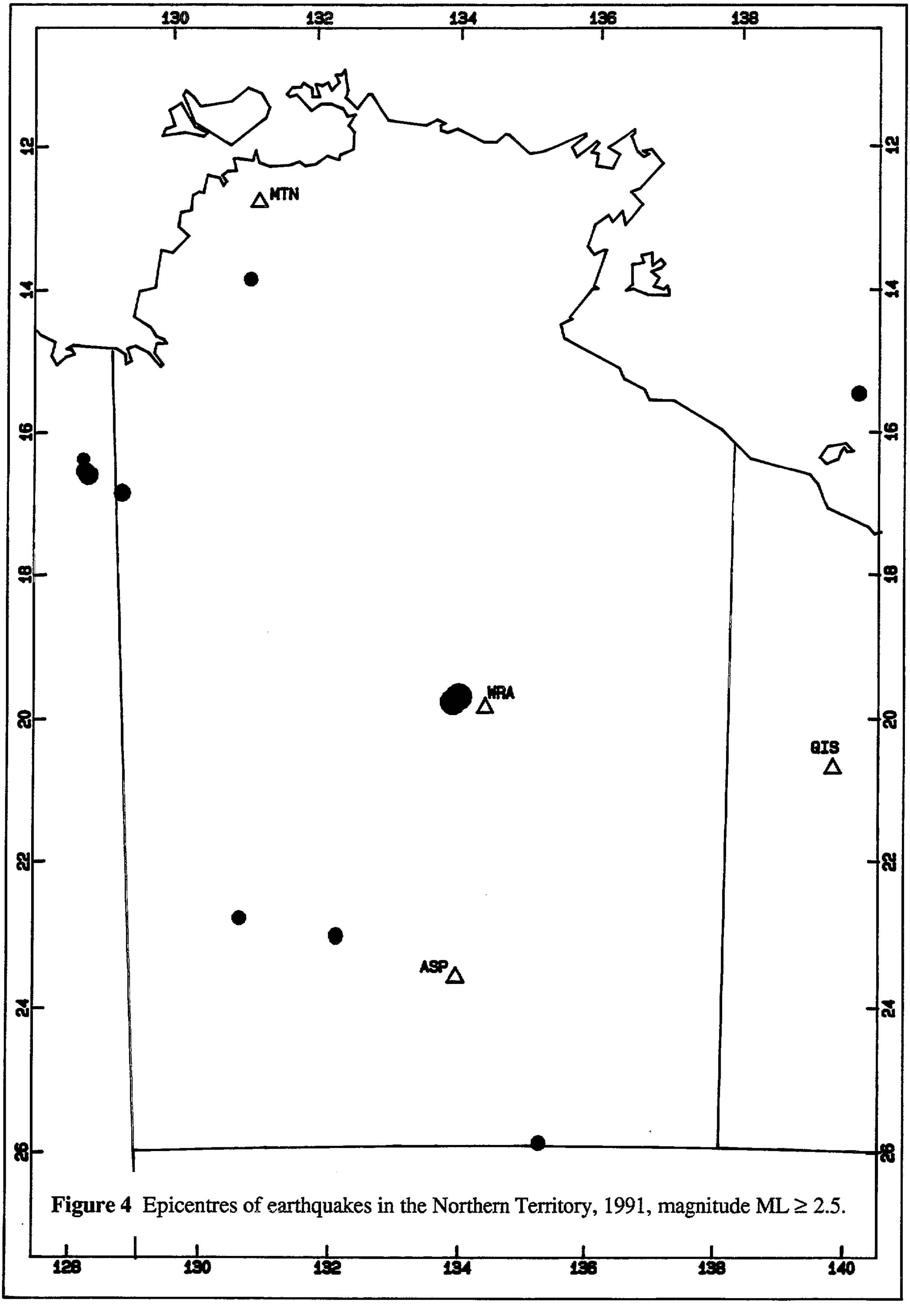


Figure 4 Epicentres of earthquakes in the Northern Territory, 1991, magnitude ML ≥ 2.5.

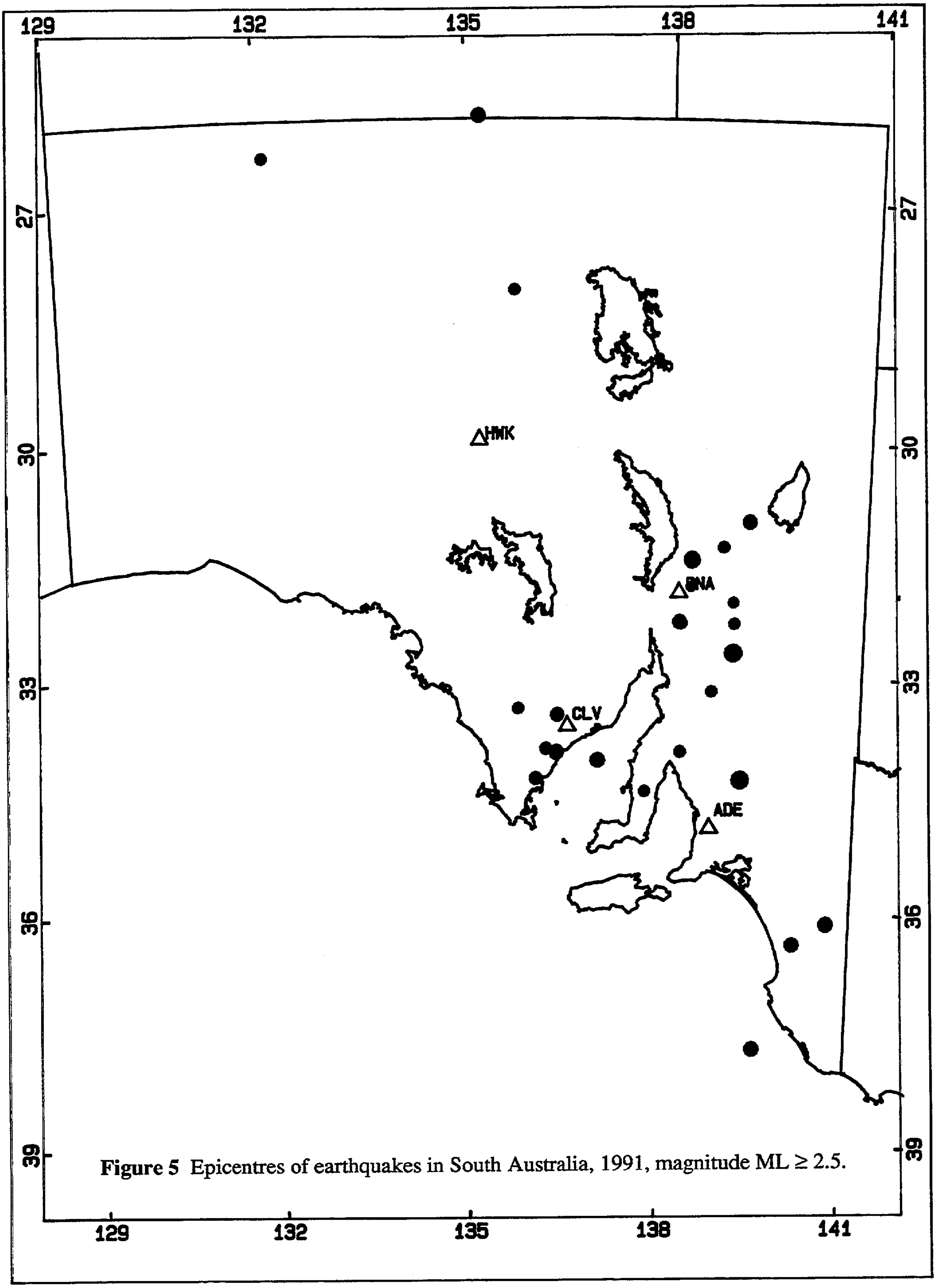


Figure 5 Epicentres of earthquakes in South Australia, 1991, magnitude ML ≥ 2.5.

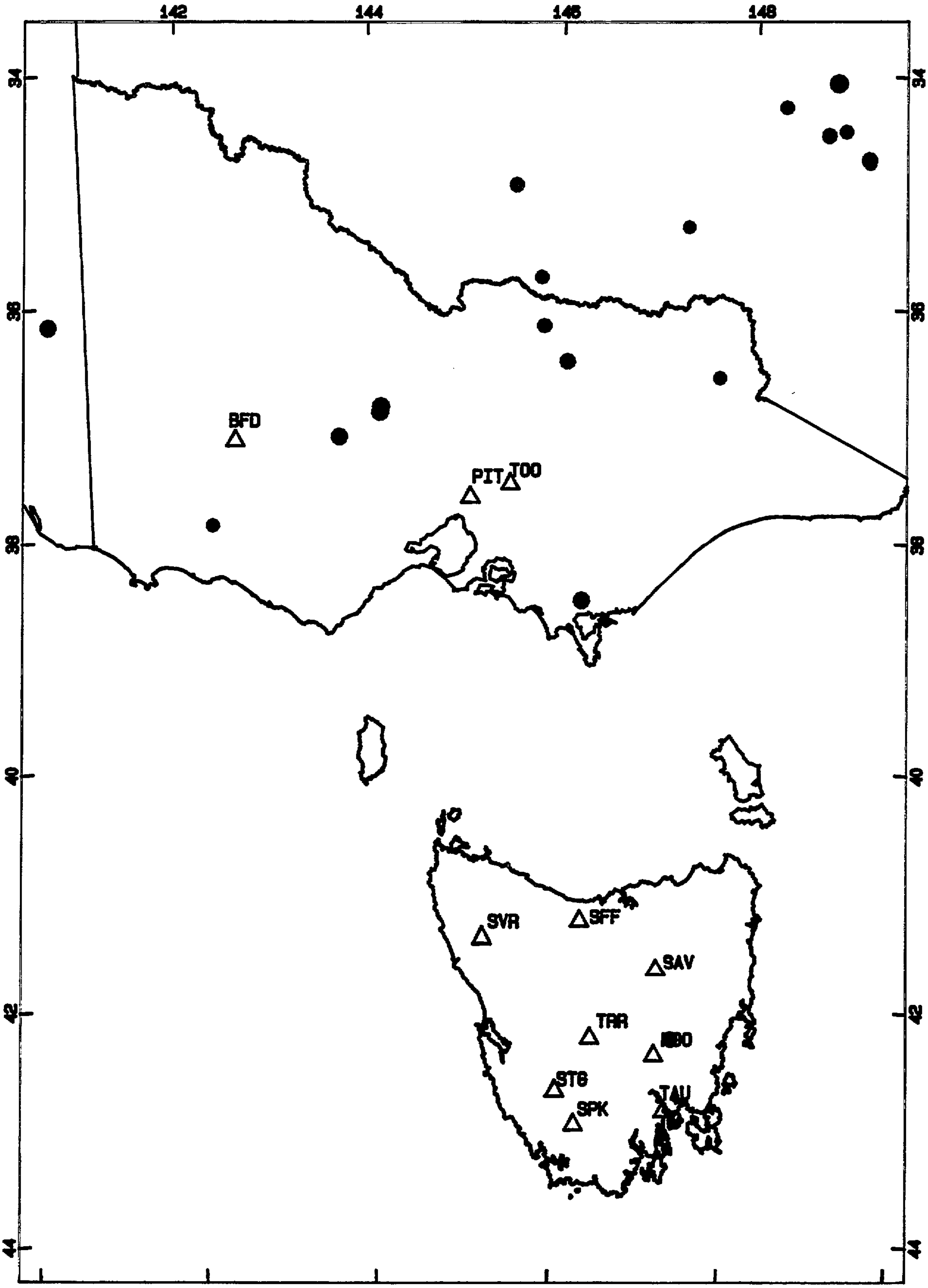


Figure 6 Epicentres of earthquakes in Victoria & Tasmania, 1991, magnitude ML ≥ 2.5.

Isoseismal maps were prepared for earthquakes that occurred at Kalgoorlie, Albany, Shay Gap and Cranbrook.

Peter Gregson

Micro-earthquakes near Ongerup, February - April 1991. A temporary network of 4 digital seismographs and 1 analogue seismograph was set up following reports of frequent small tremors near Ongerup WA, a wheatbelt town in the South-West Seismic Zone. More than 20 earthquakes per night were reported felt. The survey continued for 10 weeks, and 31 locatable events were recorded, 16 of which occurred between 22 and 26 March 1991. The largest, on 10 March, had a magnitude of approximately ML 1.0. All of the other recorded microearthquakes were significantly smaller than this. The earthquakes were very shallow, all focal depths were between 0 and 2 km.

The location errors are estimated to be at best ± 0.5 km because of timing and azimuth considerations. The epicentres (Figure 3b) form a NE trending zone over a distance of about 3km. It is thought that had more stations been available, the zone would have been seen to extend over a greater distance. This seismic episode commenced in November 1990 when three earthquakes up to magnitude ML 2.2 occurred in the area.

Vic Dent

Northern Territory (Figure 4)

The 3 largest earthquakes in Australia during 1991 were at Tennant Creek, all after-shocks of the 22 January 1988 mainshock series (Jones & others, 1991). Aftershocks continued throughout the year, those on 19 June and 8 July at magnitude ML 5.1 and ML 5.0 (Table 1) were the largest.

The June earthquake was felt at intensity MMV in Tennant Creek. A depth phase pPKP, of opposite polarity to P, was recorded at Wattenberg (WTTA), 0.9 s after the PKP which is diagnostic of a focal depth of 2.6 (±0.3) km. This earthquake was relocated with this fixed depth and using P arrival times at each element of the Warramunga array and other Australian station times. The relocated epicentres have errors in latitide and longitude of about ±10 km because the P waves saturated the array seismographs and no S phases could be distinguished. The large error ellipse includes the Kunayungku fault but the epicentres are on the western branch of the Lake Surpise Fault. No further movement was noticed on the fault scarps formed in 1988 and no damage was reported.

Another 5 small earthquakes were located outside the Tenant Creek area, one of them 140 km south of Darwin.

Kevin McCue

South Australia (Figure 5)

Earthquake activity during 1991 was at about the average level of recent years, with 334 events located by the network. Activity was spread through all the usual areas, with a higher level than normal only on Eyre Peninsula. There were 12 events over magnitude 3, with the largest near Truro on 17 August (ML 3.7). Four isoseismal maps were prepared.

Besides some swarm-like activity on Eyre Peninsula, there were two other notable sites of activity in the year. On July 16 and 17 there was a serious of 6 felt events at Ernabella in the far North-West of the State which were heard as very loud bangs, frightening local residents, but none were large enough to record on the Alice Springs array. There were two events of magnitude 3.3 and 3.5 on 27 November just east of Lake Torrens, which were followed by a long sequence of aftershocks.

David Love

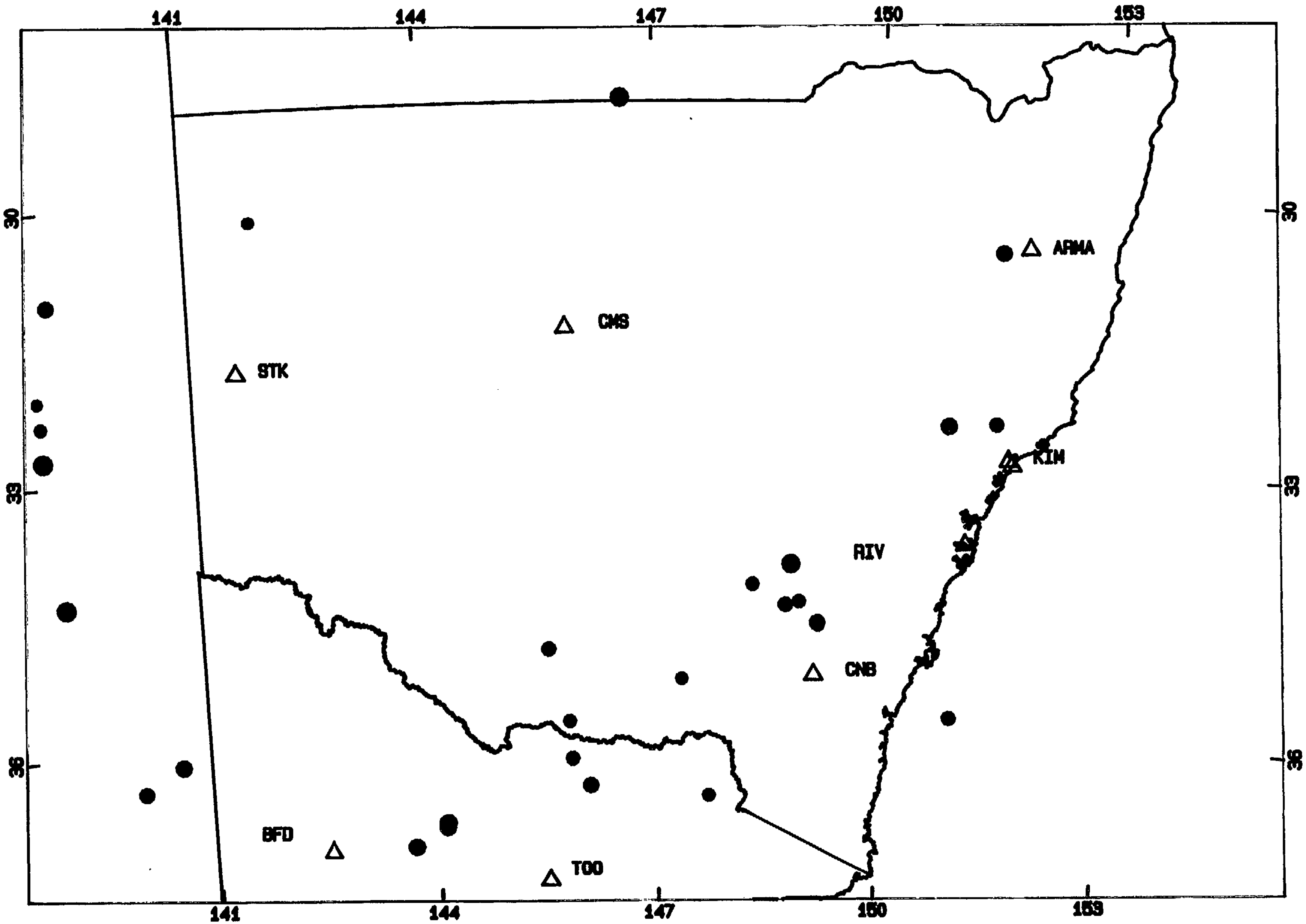


Figure 7 Epicentres of earthquakes in New South Wales 1991, magnitude ML ≥ 2.5.

Victoria & Tasmania (Figure 6)

A single microearthquake near the Moorlands station (MOO) was the extent of onshore activity in Tasmania during 1991 and there were no earthquakes in either the east or west Bass Strait zones.

The largest earthquake to occur within Victoria in 1991 was of magnitude ML 3.6 near Boolarra South in West Gippsland on March 28 at 21:26 UTC. The depth of this event was 21 kilometres. This is the deepest well constrained earthquake that we have ever located in Victoria. As is characteristic of deeper earthquakes this event was felt with a fairly low epicentral intensity of MM 4 at Morwell River. It was felt at low intensities at scattered locations as far away as Sale and Emerald. An aftershock of magnitude ML 1.7 followed at 21:50 UTC.

On April 16 at 16:08 UT (02:09 am EST) a magnitude ML 2.8 event occurred just off the coast of south Gippsland near Seaspray. That night a substantial fish kill was reported washed up on the Ninety Mile beach adjacent to Rotomah Island, some 65 kilometres northeast of the earthquake epicentre. It has been suggested that fish are sensitive to vibrations and that the tremor may have disoriented the fish causing them to strand. Alternatively, there may have been a release of natural gas associated with the earthquake and this may have bubbled into the water causing the fish to die. Either way no direct link has been proven between these two events.

On June 23 at 08:30 UTC (06:30 pm EST) an earthquake was felt with a Modified Mercalli Intensity of 3 in the township of Dartmouth. The earthquake occurred at a depth of 16 kilometres, about 3 kilometres east of the dam. The magnitude was ML 2.7. Because of the depth, it was probably not a reservoir induced event.

The nearby DTM seismograph was driven to full scale. Full scale for this recorder is about 32 768 counts which corresponds to a velocity (v) of 0.184 mm/s. The peak motion occurred during a short duration S wave coda, with a frequency (f) of 15 Hz. The acceleration at DTM must therefore have exceeded $2\pi fv = 17.34$ mm/s^2 (or 0.00177 g). Note that this is the maximum acceleration that can be recorded by this seismograph for this frequency of motion, and not the peak motion which actually occurred.

On November 22 at 07:11 UTC a magnitude ML 3.1 event occurred about 16 kilometres east of Benalla. This event was not reported felt, possibly because it was located at a depth of 7 kilometres.

<u>The 1991 Bradford Hills Earthquake Swarm</u> The first of a swarm of nearly two hundred shallow local earthquakes occurred on April 27. The epicentres were on the Bradford Hills property about 12 kilometres north of Maldon and 25 kilometres southwest of Bendigo. Most of the swarm earthquakes occurred during May, but activity continued at a decreasing rate into 1992.

The first events were of magnitude less than ML 1.1, but they were followed by eight events with magnitudes up to ML 2.0 on April 30. On May 1 at 22:39 UTC there was an event of magnitude ML 2.7, and this was followed by more smaller earthquakes, and another magnitude 2.7 on May 2 at 00:13 UTC.

The largest earthquake in the swarm occurred on May 3 at 17:28 UTC (Saturday morning at 03:28 am EST). This had a magnitude of ML 3.5, and was felt throughout the district, particularly in Maldon and Bendigo. It was followed by another six events between ML 1.0 and ML 2.4 that day and another eight larger than ML 1.0 on the next day.

The level of seismic activity then began to diminish to the rate of a couple of small events every few days with an occasional larger event. On June 8 at 19:55 UTC another magnitude ML 3.0 event occurred.

The earthquakes all occurred at a very shallow depth, most less than 3 kilometres from the surface. Very small events were felt at the Bradford Hills property, even some with magnitude less than ML 1. This means that the largest event, with magnitude almost three units higher, would have given ground motion almost 10^3 or 1000 times higher than that felt from the small events. Magnitude ML 3.5 is still a small earthquake so the duration of motion would have been quite short, but peak

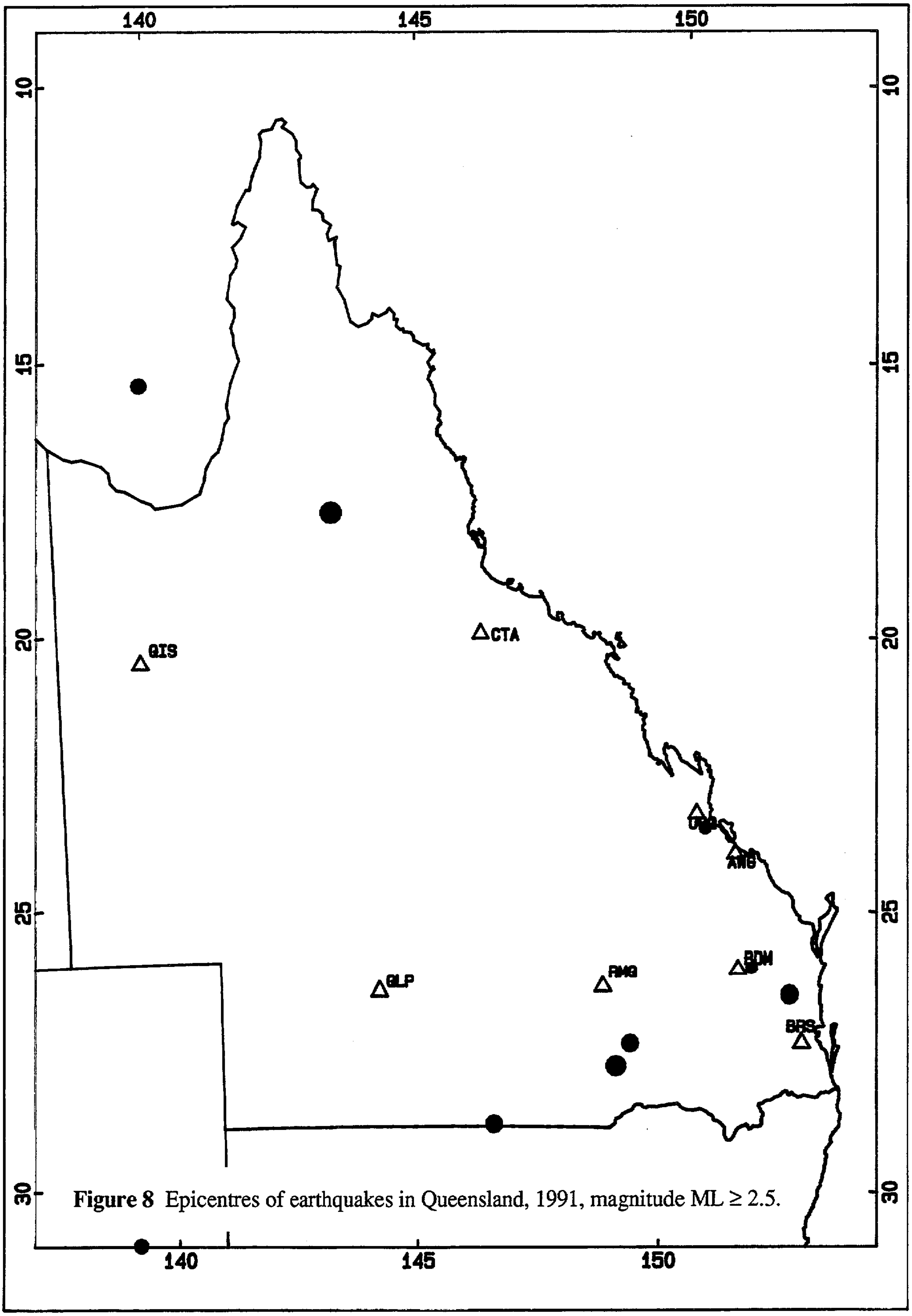


Figure 8 Epicentres of earthquakes in Queensland, 1991, magnitude ML ≥ 2.5.

ISOSEISMAL MAP OF THE MAITLAND EARTHQUAKE, SOUTH AUSTRALIA
12 FEBRUARY 1991

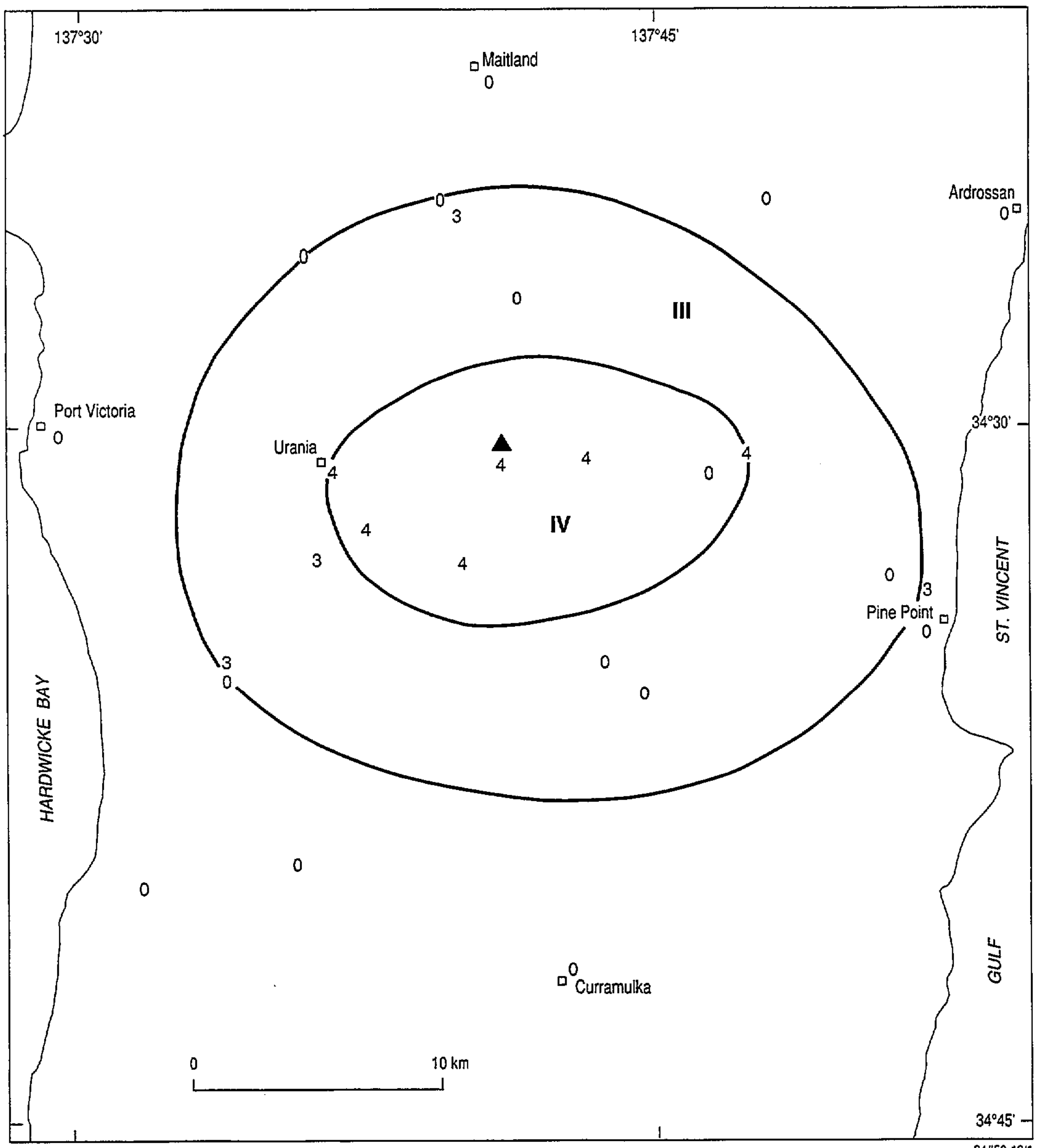
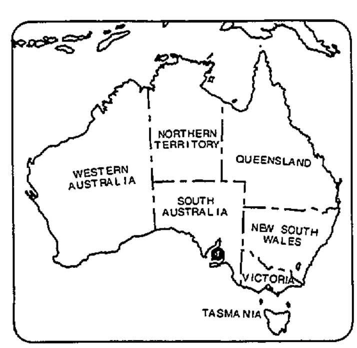


Figure 9

DATE: 12 FEBRUARY 1991
TIME: 18:18:44.2 UTC
MAGNITUDE: 2.6 ML (ADE)
EPICENTRE: 34.51°S,137.69°E

▲	*Epicentre*
IV	*Zone intensity designation*
4	*Earthquake felt (MM)*
0	*Earthquake not felt*



ISOSEISMAL MAP OF THE KALGOORLIE ROCKBURST, WESTERN AUSTRALIA 9 MARCH 1991

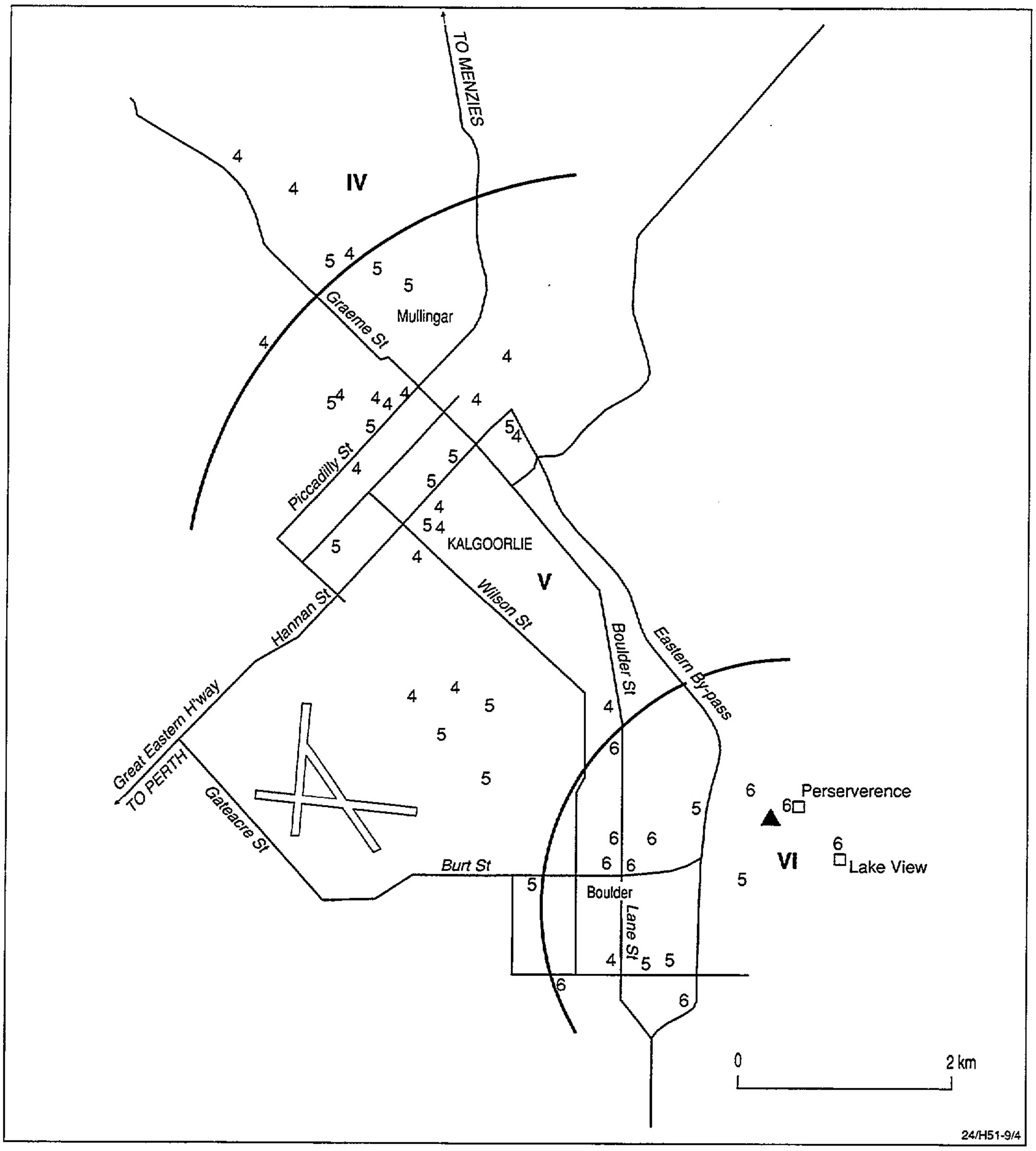
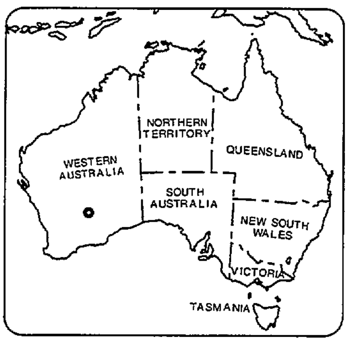


Figure 10

DATE: 9 MARCH 1991
TIME: 01:36:30.4 UTC
MAGNITUDE: 4.2 ML (MUN)
EPICENTRE: 30.78°S, 121.50°E
DEPTH 1 km

▲ *Epicentre*
IV *Zone intensity designation*
6 *Earthquake felt (MM)*
0 *Earthquake not felt*



motion at the Bradford Hills property probably exceeded values that would normally give damage. The house and buildings are well-constructed framed structures in good condition, so are less likely to suffer earthquake damage than most structures.

The Seismology Research Centre installed a network of six seismographs in the area by the evening of the day before the largest event occurred. Good seismograph coverage enabled this event and the following earthquakes to be located to a high degree of accuracy, with most epicentres having an uncertainty of less than one kilometre. Another seismograph was installed at the epicentre, so many later events were located with an uncertainty of less than a half kilometre in both epicentre and depth. This is very much more precise than the normal uncertainty of two to ten kilometres for local earthquakes. It required very precise seismograph timing, to an accuracy of 0.01 seconds or better.

The earthquake swarm was in an area where granite outcrops at the surface. It is just to the west of the surface outcrop of the Muckleford Fault, a major north-south reverse fault.

This is the largest earthquake swarm in Victoria since detailed seismograph coverage started in 1976. More common patterns of earthquake activity in Victoria have been a larger event followed by a diminishing series of aftershocks, single isolated events, or small swarms with no more than about ten events. The character of the Bradford Hills swarm was probably related to the shallow depth of the earthquakes.

Gary Gibson, Wayne Peck & Kevin McCue

New South Wales and ACT (Figure 7)

The ML 3.5 and 3.6 earthquakes near Cowra (20 May) and west of Hebel on the NSW/Qld border (4 January) were the largest in the State. A magnitude ML 3.1 earthquake in the Dalton-Gunning Seismic Zone on 24 November was the expected largest (most frequent annual maximum magnitude) earthquake there, based on the history of the last 30 years (McCue & others, 1989). No significant damage resulted from these earthquakes.

There were no notable earthquakes in the ACT in 1991.

Kevin McCue

Queensland (Figure 8)

An earthquake which was located near Georgetown in north Queensland has provided the first recorded acceleration data from an earthquake in that State. The earthquake which had a magnitude of 4.5 occurred at 14:11 UTC on 6 August. Residents of the townships of Georgetown and Forsayth were awoken and while there were isolated reports of minor damage the maximum intensity was assigned as MMIV.

The was also a magnitude ML 4.1 earthquake near St George on 24 September with an ML 3.6 aftershock on 28 September. No damage was reported after these earthquakes.

A doublet of ML 2.9 earthquakes excited considerable public interest at Bajool, 30 km south of Rockhampton, shortly after installation of a network of seismographs around Rockhampton by the University of Central Queensland (McKavanagh and others, 1993). Minor damage was reported and an average intensity of V was assigned on the felt reports from in and around Bajool.

R Cuthbertson, B McKavanagh, B Boreham & W Cooper

ISOSEISMAL MAPS

Despite the low seismicity, eleven small earthquakes and one WA rockburst were sufficiently widely felt that questionnaires were distributed and the returned forms collated to draw up isoseismal maps, 5 in WA, 4 in SA and 2 in Qld.

ISOSEISMAL MAP OF THE KARRATHA EARTHQUAKE, WESTERN AUSTRALIA
9 APRIL 1991

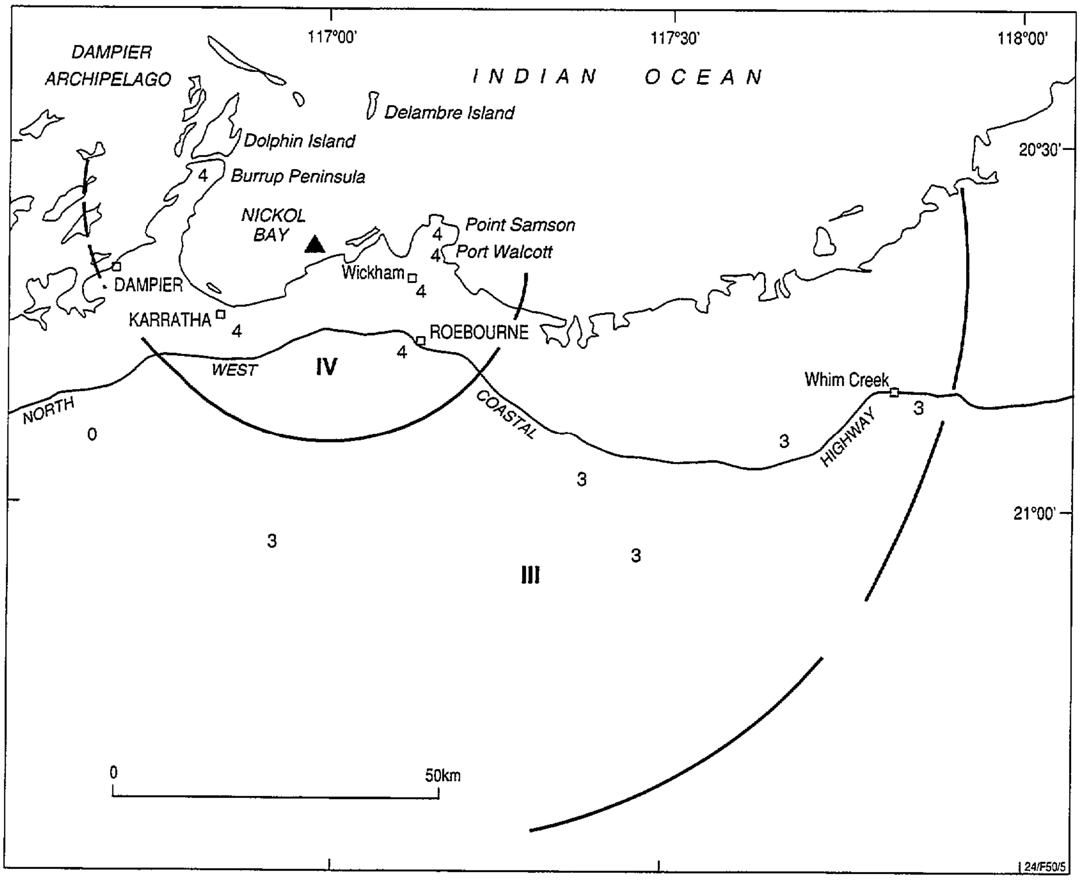
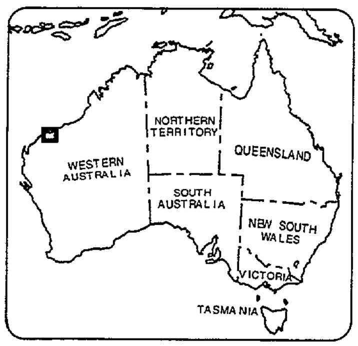


Figure 11

DATE: 9 APRIL 1991
TIME: 14:00:08.0 UTC
MAGNITUDE: 3.5 ML (MUN)
EPICENTRE: 20.65°S, 116.99°E

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*



Maitland SA, 12 Feb

A small earthquake of magnitude ML 2.6 occurred south of Maitland at 04:48 am (Wednesday 13 February Central Standard Time). It was heard and felt over a small area of central Yorke Peninsula, rattling doors and ornaments. A few people woke to the sound of a loud explosion, but many did not wake at all. A small aftershock was reported felt at Urania but was not recorded by the seismograph network. Following the earthquake the South Australian Department of Mines and Energy telephoned people in the area and the isoseismal map was produced from their brief descriptions.

Kalgoorlie WA, 9 March

Kalgoorlie-Boulder is the centre of gold mining on the Golden Mile. Eastern Goldfields residents are familiar with frequent mine explosions. On 9 March 1991 at 9.36 a.m. (WST), they were shaken much more severely than usual (Gregson, 1992). The computed epicentre of this magnitude ML 4.2 event was 5 km SSE of Kalgoorlie which is consistent with reports of maximum intensity.

The maximum intensity at the surface was MM VI in Boulder up to 3 km from the epicentre. The radius of the MM V was 7 km. Population in the region outside Kalgoorlie-Boulder is sparse and only scattered reports were received. The maximum intensity reported outside the town was MM IV at a distance of 30 km to the east.

The Kalgoorlie Prison in South Boulder suffered damage valued at $30 000 (personal communication). Severe damage (MM VIII) occurred in the underground mine workings near the Perseverance and Lake View shafts between the 500 m and 600 m levels. Stope pillars creaked, timbers fell and rails lifted from the floor of the drives. In some areas at about 500 m, the floor heaved, water flow increased and drives disappeared as a result of collapse. The Perseverance shaft was stripped of timbers below 500 m by falling rock. One "crib" room was damaged by dislodgment of rocks.

A phone conversation between two people 7 km apart in Boulder (S) and Kalgoorlie (N) lends support to the epicentre determination closer to Boulder.

S: "Did you feel that?"
N: "No .... yes I did!".

Aftershocks occurred as follows:

Date 1991	*Time UTC*	*Latitude °S*	*Longitude °E*	*ML*
Mar 09	0318	30.76	121.42	0.5
Mar 09	0405	30.76	121.42	0.8
Mar 09	0821	30.76	121.42	0.7
Mar 09	1629	30.76	121.42	1.4
Mar 10	0552	30.76	121.42	1.5
Apr 10	0606	30.76	121.42	3.1
Apr 10	0635	30.76	121.42	2.5
Apr 11	0205	30.76	121.42	1.5
Apr 12	0137	30.76	121.42	1.5

Karratha WA, 9 April

A magnitude ML 3.5 earthquake located just offshore between Karratha and Wickham occurred at 10:00 p.m. (14:00 UTC) on 9 April 1991 (Gregson, 1992). The region is sparsely populated and the maximum intensity experienced was MM IV in the Karratha - Roebourne region. The radius of the MM IV isoseismal was 30 km and the earthquake was felt over an area of 5000 sq km.

The region has economic significance because of the North-west gas facilities at Burrup Peninsula, the gas pipeline, the iron ore port facilities at Dampier and the town of Karratha (population 11 000). Other earthquakes within 50 km include:

ISOSEISMAL MAP OF THE WILLALOOKA EARTHQUAKE, SOUTH AUSTRALIA
11 MAY 1991

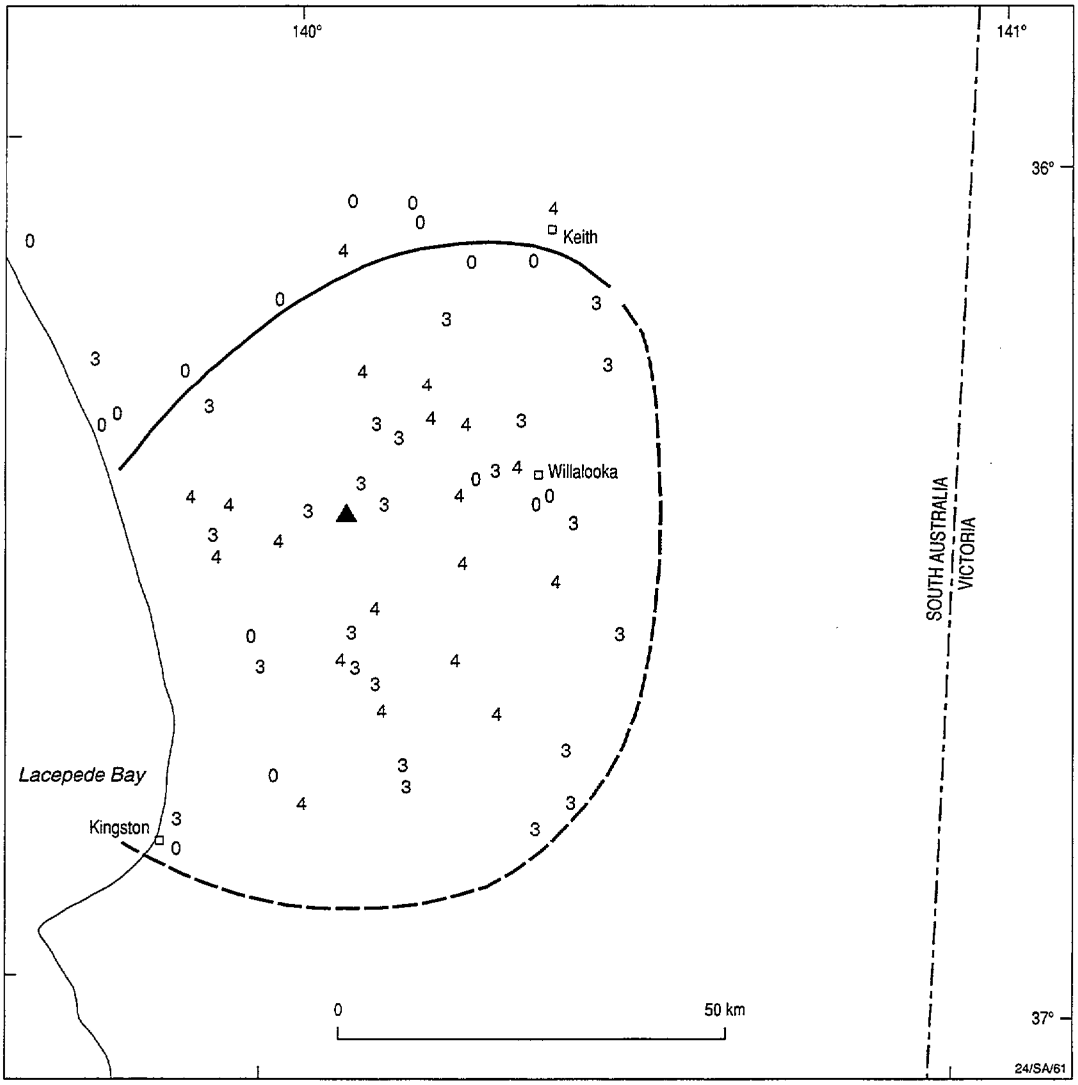
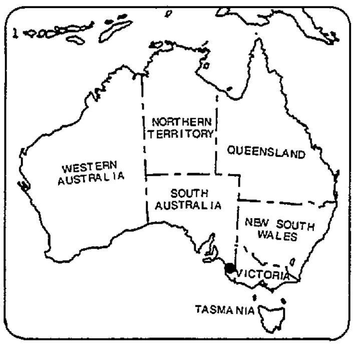


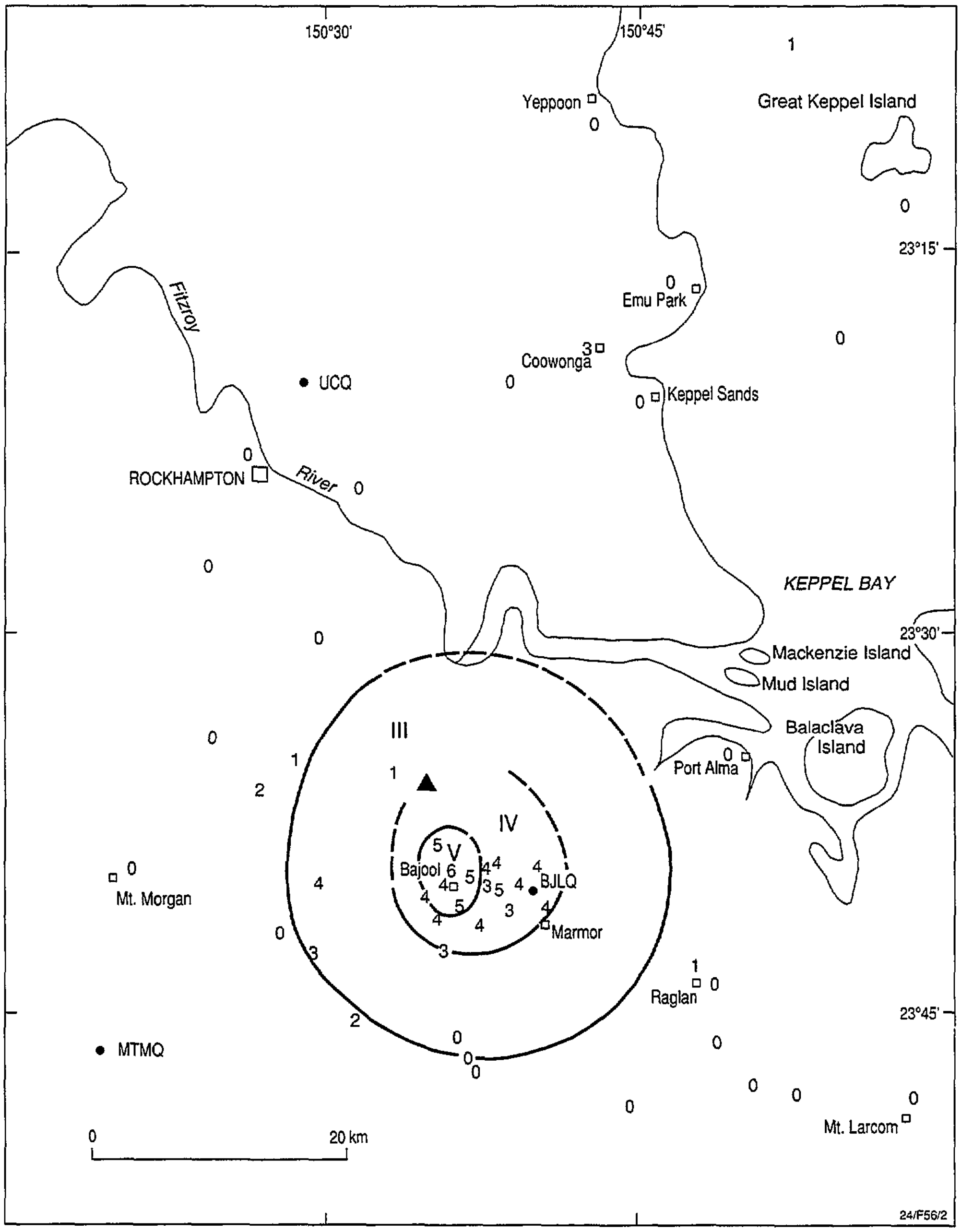
Figure 12

DATE:	11 MAY1991
TIME:	090:04:10.6 UTC
MAGNITUDE:	3.0 ML (ADE)
EPICENTRE:	36.43°S, 140.05°E
DEPTH:	10 km

▲	*Epicentre*
IV	*Zone intensity designation*
4	*Earthquake felt (MM)*
0	*Earthquake not felt*



ISOSEISMAL MAP OF THE BAJOOL EARTHQUAKES, QUEENSLAND
10 JUNE 1991



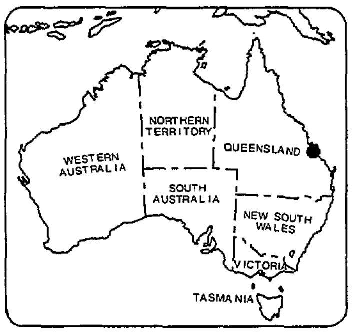


Figure 13

DATE: 10 JUNE 1991
TIME: 12:00:23 & 13:00:44 UTC
MAGNITUDE: 2.9 ML
EPICENTRE: 23.59°S, 150.60°E

▲	*Epicentre*
IV	*Zone intensity designation*
4	*Earthquake felt (MM)*
0	*Earthquake not felt*
●UCQ	*Seismographs*

ISOSESMAL MAP OF THE MUNDUBBERA EARTHQUAKE, QUEENSLAND 13 JULY 1991

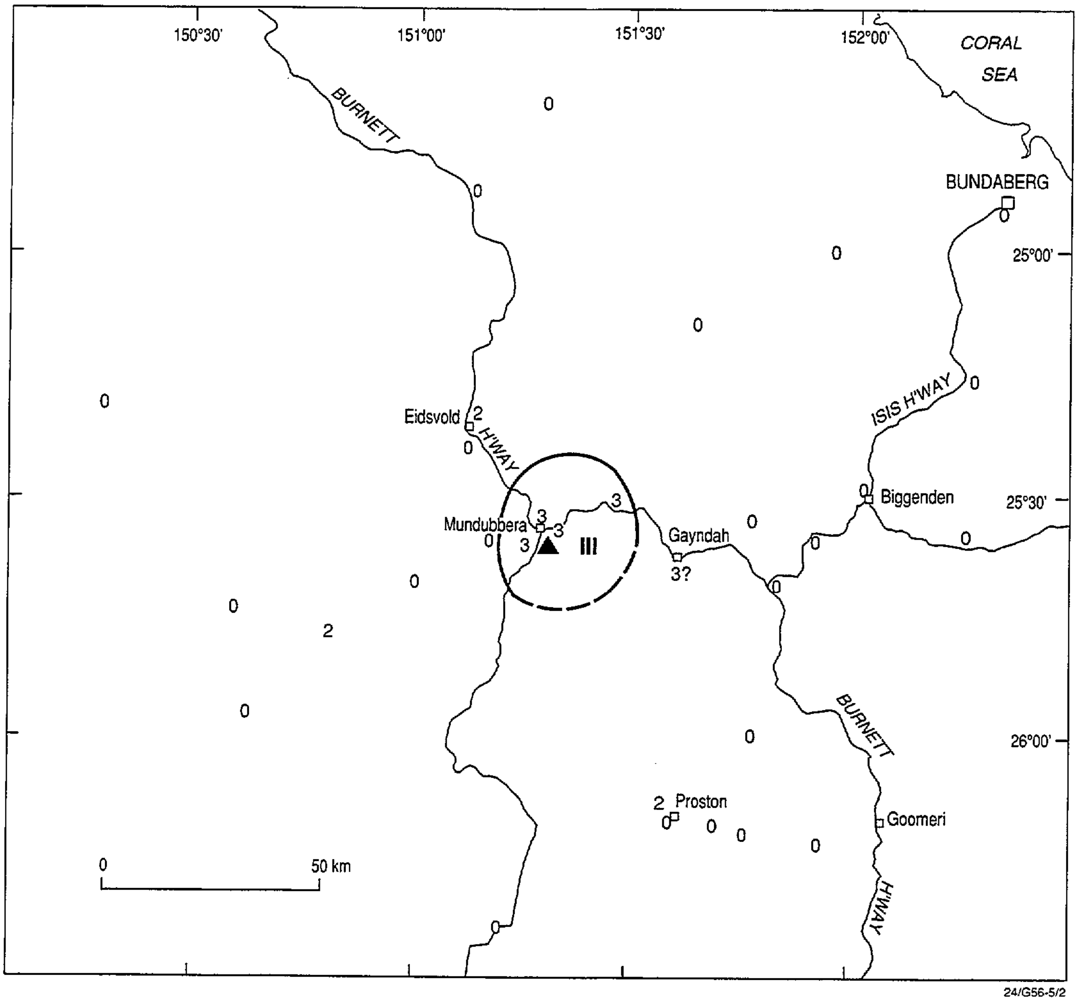
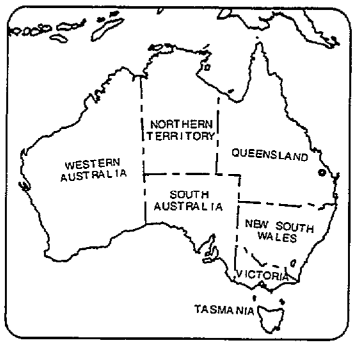


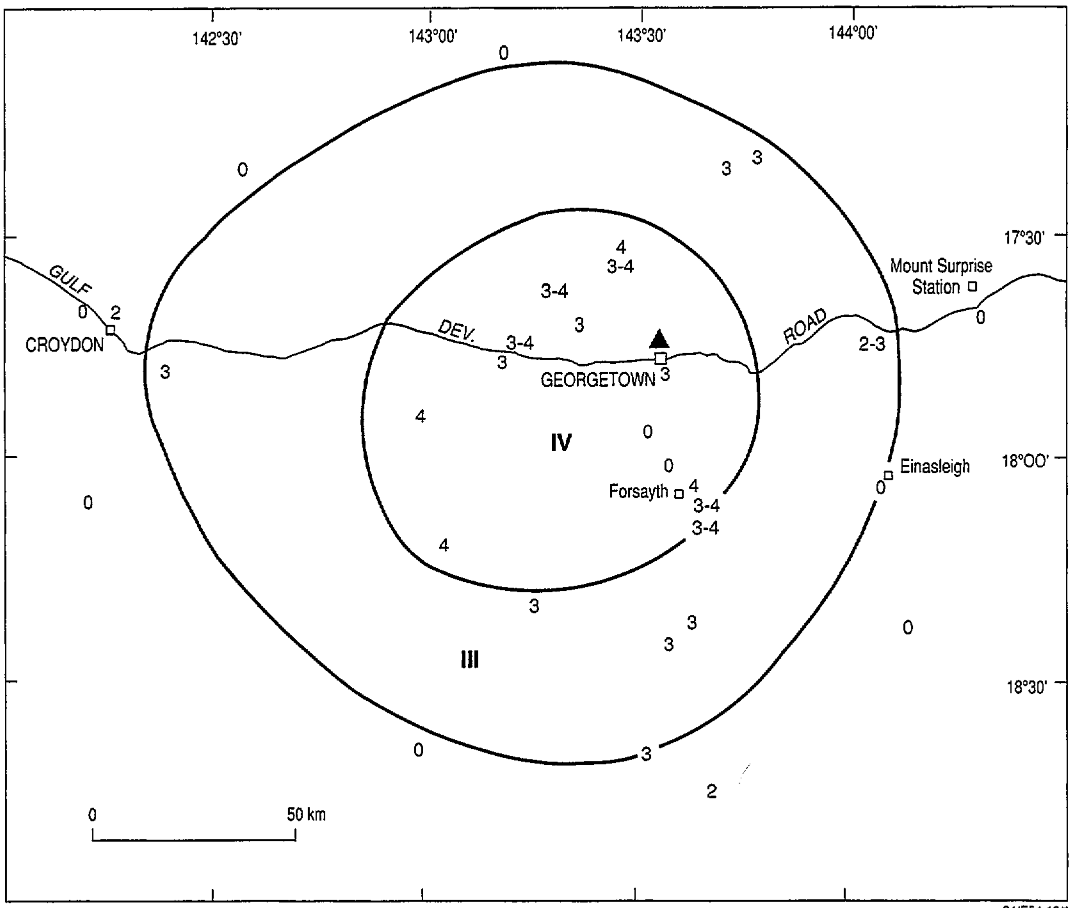
Figure 14

DATE: 13 JULY 1991
TIME: 19:35:01
MAGNITUDE: 2.3 ML (GSQ)
EPICENTRE: 25.62°S, 151.31°E
DEPTH: 3 km

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*



ISOSEISMAL MAP OF THE GEORGETOWN EARTHQUAKE, QUEENSLAND
6 AUGUST 1991

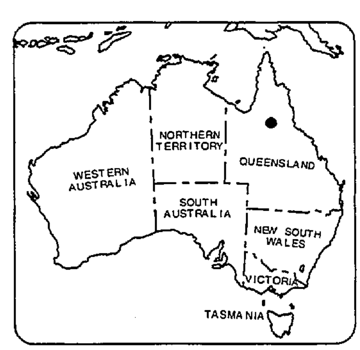


24/E54-12/1

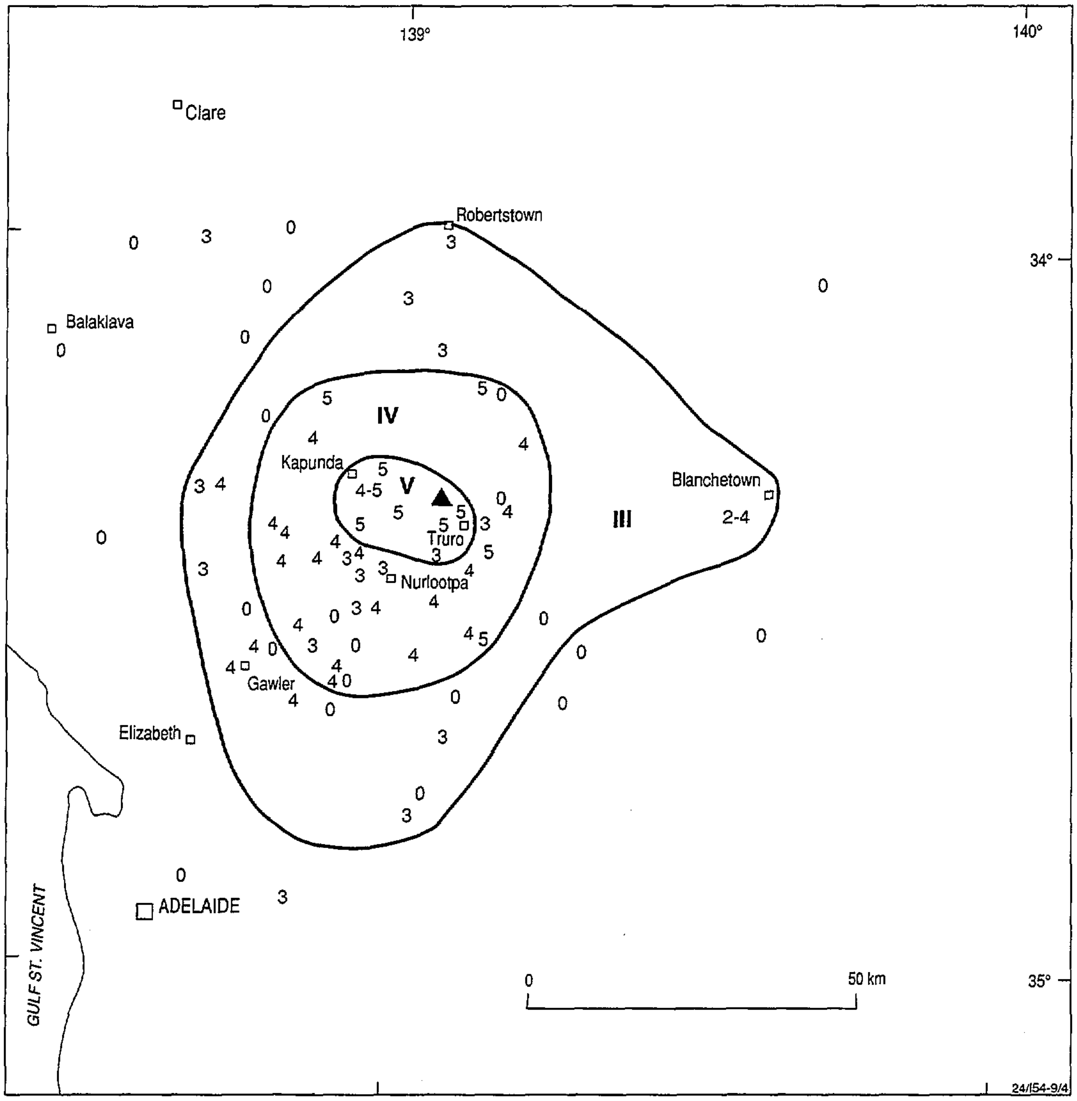
Figure 15

DATE: 6 AUGUST 1991
TIME: 14:11:48
MAGNITUDE: 4.4 ML
EPICENTRE: 18.22°S, 143.51°E
DEPTH: 5 km

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*



ISOSEISMAL MAP OF THE TRURO EARTHQUAKE, SOUTH AUSTRALIA
17 AUGUST 1991



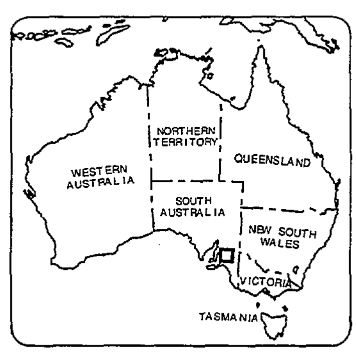


Figure 16

DATE: 17 AUGUST 1991
TIME: 06:28:56.2 UTC
MAGNITUDE: MD 3.4 (ADE)
EPICENTRE: 34.36°S, 139.08°E
DEPTH 13 KM

▲ *Epicentre*
IV *Zone intensity designation*
5 *Earthquake felt (MM)*
0 *Earthquake not felt*

Date	*Time UT*	*Lat °S*	*Long °E*	*Magnitude*
1968 Jul 04	0648	20.80	117.10	4.8 MB
1987 Jun 19	1332	20.56	116.69	3.7 ML
1989 Apr 30	1616	20.52	117.26	2.5 ML
1990 Oct 29	0452	20.71	116.82	2.8 ML

Willalooka SA, 11 May

On Saturday evening at 6:34 pm there was an earthquake in the South East between Kingston and Keith. The shock was heard and felt by many people in the area, surprising some with a loud bang, and also moving a few pictures and shaking ornaments.

A quick phone survey suggested that the felt area was limited to about 15 km radius, but an article in the local paper brought many replies. In all, 76 questionnaires were distributed and the replies, together with the phone calls, were used to produce a map (Figure 12). The felt radius is not clearly defined to the east and south, and there is no clear intensity increase at the epicentre.

The high gain station at Willalooka 24 km east recorded only 3 aftershocks, the largest of which was felt by a few people (ML 1.4, 15th May at 2:30 am).

Bajool Qld, 10 June

The village of Bajool, 30 km south of Rockhampton Qld, was shaken by two earthquakes almost exactly an hour apart, on 10 June at 12:00 and 13:00 UTC. But for the time of day (10 and 11 pm local time) most people would have attributed the loud explosion and brief shake to blasts at the local Marmor Quarry. Minor damage was reported in one house and fresh cracks were later found in 2 concrete water tanks (Figure 13, McKavanagh & others, 1993).

Four small foreshocks and 4 equally small aftershocks were recorded, one on the digital recorder set up at Bajool by the UCQ field team. The recorded S-P time of 0.72s, corresponding to a focal distance of less than 4 km, so the focal depth must have been quite shallow.

Mundubbera Qld 13 July

A magnitude ML 2.3 microearthquake at 5:35 am AEST (14 July) was located 3 km south of the town of Mundubbera. Investigations by seismologists at the University of Queensland and Department of Resource Industries indicated that the tremor was felt within a radius of about 17 km with isolated reports of intensity MM II from as far as 60 km (Figure 14).

Georgetown Qld 6 August

People in the north Queensland towns of Georgetown and Forsayth were woken at 12:11 am AEST (7 August) by a magnitude 4.4 earthquake that caused minor damage in the towns. A survey of effects was conducted by seismologists from the University of Queensland and Department of Resource Industries with the assistance of the local shire council and the isoseismal map was drawn (Figure 15).

Truro SA, 17 August

At 3.58 pm (local time) during a popular Barossa festival, many people were shaken by a small earthquake. Residents near the epicentre described a loud explosion, and others reported ornaments upset, pictures askew and tinkling of wine glasses. A total of 100 questionnaires were returned to produce the isoseismal map (Figure 16). Although 2

ISOSEISMAL MAP OF THE TUMBY BAY EARTHQUAKE, SOUTH AUSTRALIA
19 AUGUST 1991

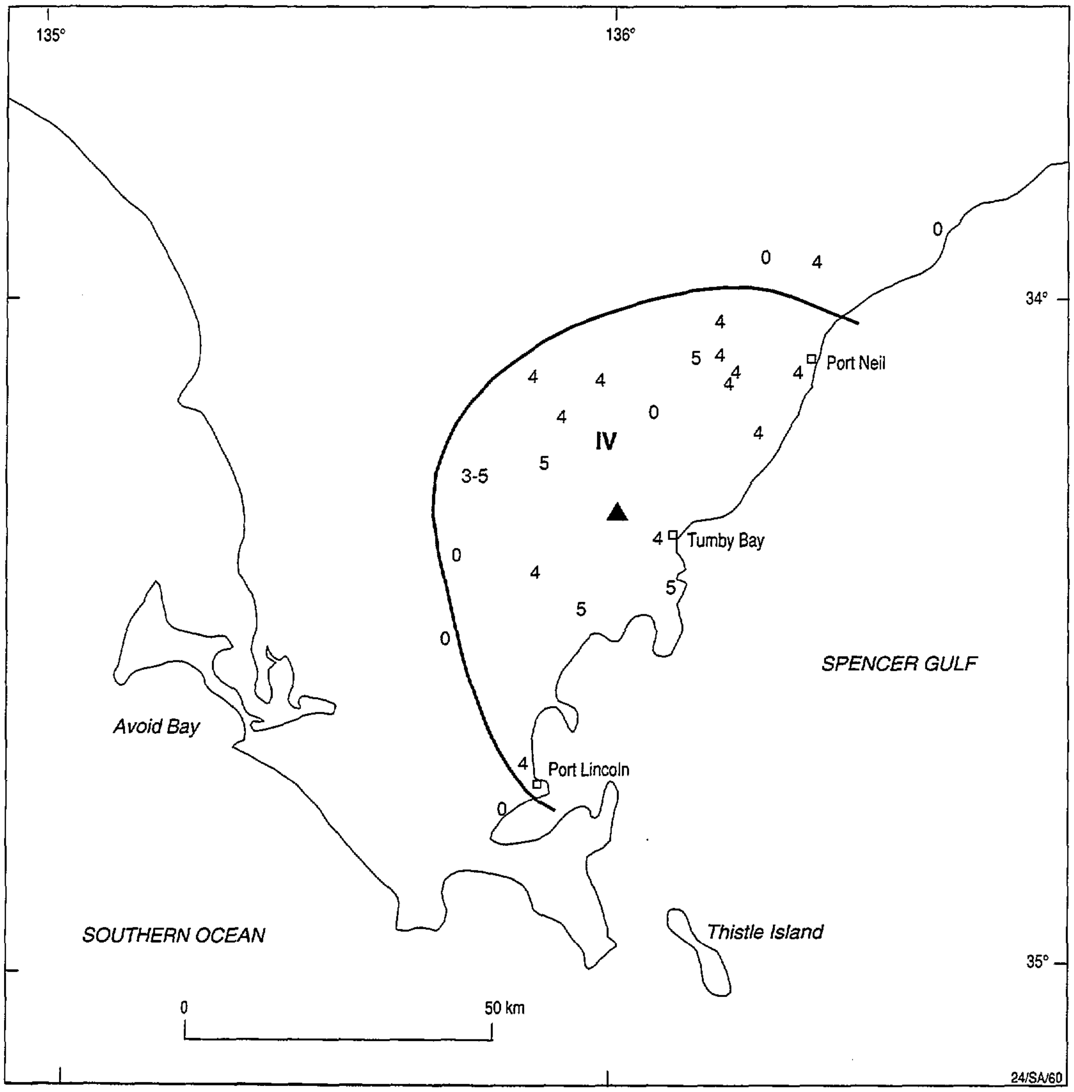
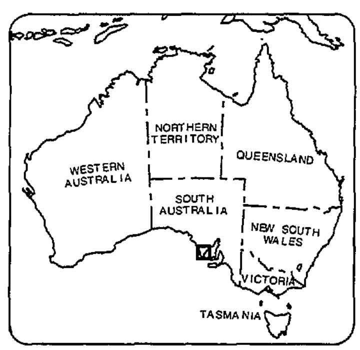


Figure 17

DATE: 19 AUGUST 1991
TIME: 18:58:14.0 UTC
MAGNITUDE: 2.9 ML (ADE)
EPICENTRE: 34.35°S, 136.00°E
DEPTH: 25 km

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*



ISOSEISMAL MAP OF THE ALBANY EARTHQUAKE, WESTERN AUSTRALIA 22 SEPTEMBER 1991

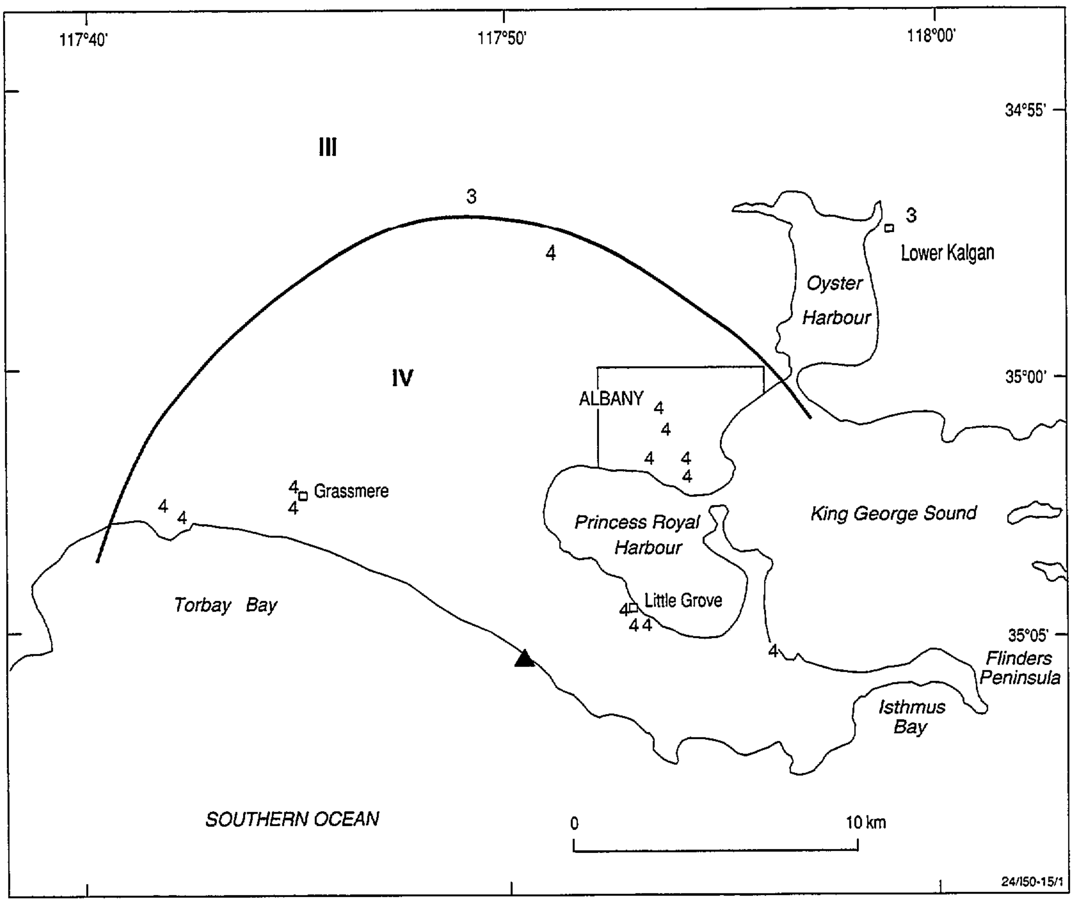
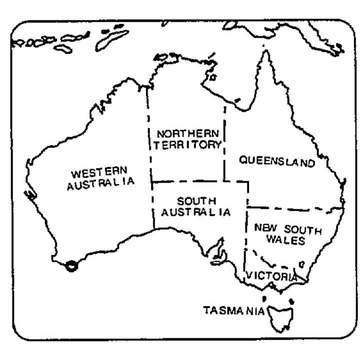


Figure 18

DATE: 22 SEPTEMBER 1991
TIME: 17:01:36.9 UTC
MAGNITUDE: 2.4 ML (MUN)
EPICENTRE: 35.09°S, 117.83°E

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*



ISOSEISMAL MAP OF THE SHAY GAP EARTHQUAKE, WESTERN AUSTRALIA 23 SEPTEMBER 1991

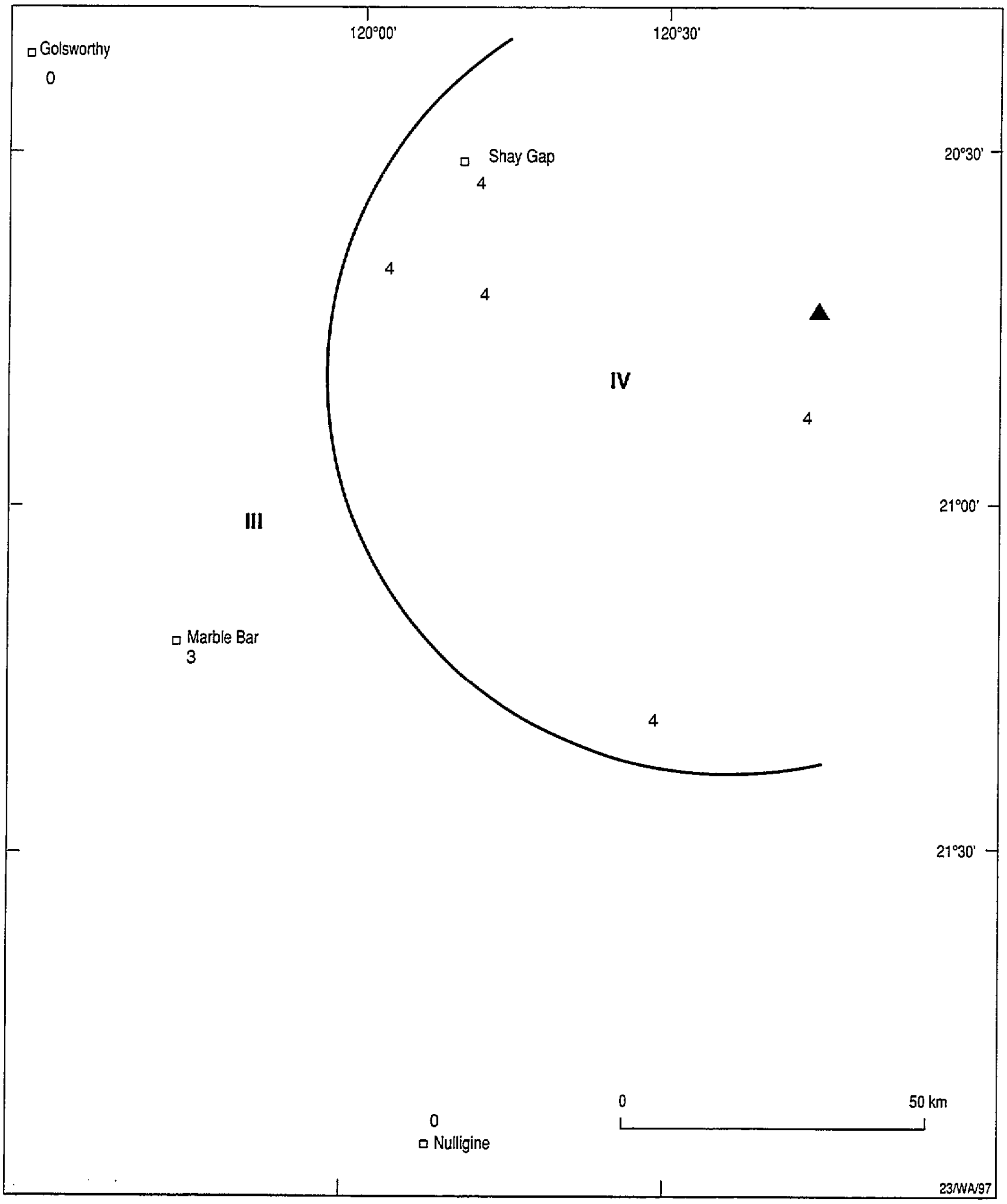
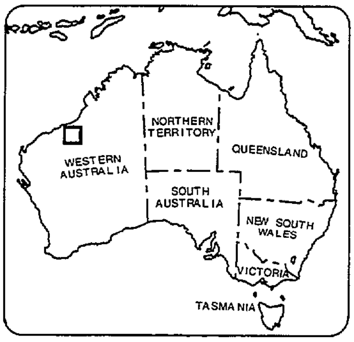


Figure 19

DATE: 23 SEPTEMBER 1991
TIME: 21:19:58.1 UTC
MAGNITUDE: 4.0 ML (MUN)
EPICENTRE: 20.72°S, 120.71°E

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*



replies reported cracked windows and a further 8 reported minor plaster cracking, a maximum intensity of V was assigned.

With all nearby stations saturated, a duration magnitude of 3.4 was assigned though the Richter magnitude from CLV was greater than 3.6. A similar sized earthquake occurred near Truro in 1979 (4 July, ML 3.5).

Tumby Bay/Port Lincoln SA, 19 August

At 4:38 am on Tuesday morning (20 August) many people from Port Lincoln to Port Neill were woken by an earthquake. In the dark it was difficult to determine other effects, and the worst appeared to be a cracked window and ornaments upset. One couple had to get up to calm a whining dog five minutes before the earthquake.

In all 32 questionnaires were distributed and the map was compiled from 23 replies and a few phone calls (Figure 17). A number of respondents reported noticing other tremors in previous months.

Albany WA, 22 September 1991

A magnitude ML 2.5 seismic event occurred at 1.01 a.m. (local time) on 23 September about 10 km south-west of the Albany townsite. The maximum MM intensity experienced was MM IV with ground vibrations and windows rattling. Where it was possible to determine the direction from which the ground vibrations came at Grassmere and Albany, they were consistent with the epicentre (Figure 18).

There were several reports of explosion like sounds and flashes of light, coincident with the time of the seismic event. It is possible that a meteorite sighting occurred simultaneously.

A series of 14 earthquake ranging from magnitude 1.2 to 4.5 occurred 15 km to the east in May 1977. The details of the largest are shown below.

Date	*Time*	*Lat°S*	*Long°E*	*Depth (km)*	*Mag*
1977 May 05	19 16 07.6	35.00	117.95	10	ML 4.5

Shay Gap WA, 23 September 1991

At 5.20 a.m. (24 September local time) a magnitude ML 4 earthquake occurred 60 km south-east of Shay Gap. The region is sparsely populated with the closest report being about 15 km from the epicentre. MM intensities of IV were reported up to 75 km from the epicentre (Figure 19).

Six earthquake of magnitude 4.0 or greater have been recorded within 50 km of the epicentre of this earthquake.

Date	*Time*	*Lat °S*	*Long°E*	*Depth*	*Mag*	*Place*
1975 Jul 25	222341.7	21.09	120.47	10 N	MB 5.0	90 km E Shay Gap
1982 Nov 03	024032.0	20.53	120.48	37	ML 5.2	Shay Gap, WA
1985 Apr 09	071804.8	29.49	120.52	10 N	ML 3.0	100 km NE Marble Bar
1988 Jan 28	014630.0	21.05	120.60	5 N	ML 4.8	90 km E Marble Bar
1988 Jan 28	014934.0	21.05	120.60	5 N	ML 4.6	90 km E Marble Bar
1988 Jan 28	015617.5	21.05	120.60	5 N	ML 5.0	90 km E Marble Bar
1988 May 16	181600.5	21.42	120.19	5 N	ML 3.0	55 km SE Marble Bar

St George Qld, 24 & 28 September

A series of earthquakes in September was felt by residents of St George and surrounding areas within a radius of nearly 90 km (Figure 20). The largest earthquake, magnitude ML 4.3, occurred at 2:36 pm AEST on 24 September. Far fewer reports were received following the magnitude ML 3.6 earthquake at the same epicentre on 29 September at

ISOSEISMAL MAP OF THE ST. GEORGE EARTHQUAKES, QUEENSLAND
24 AND 28 SEPTEMBER 1991

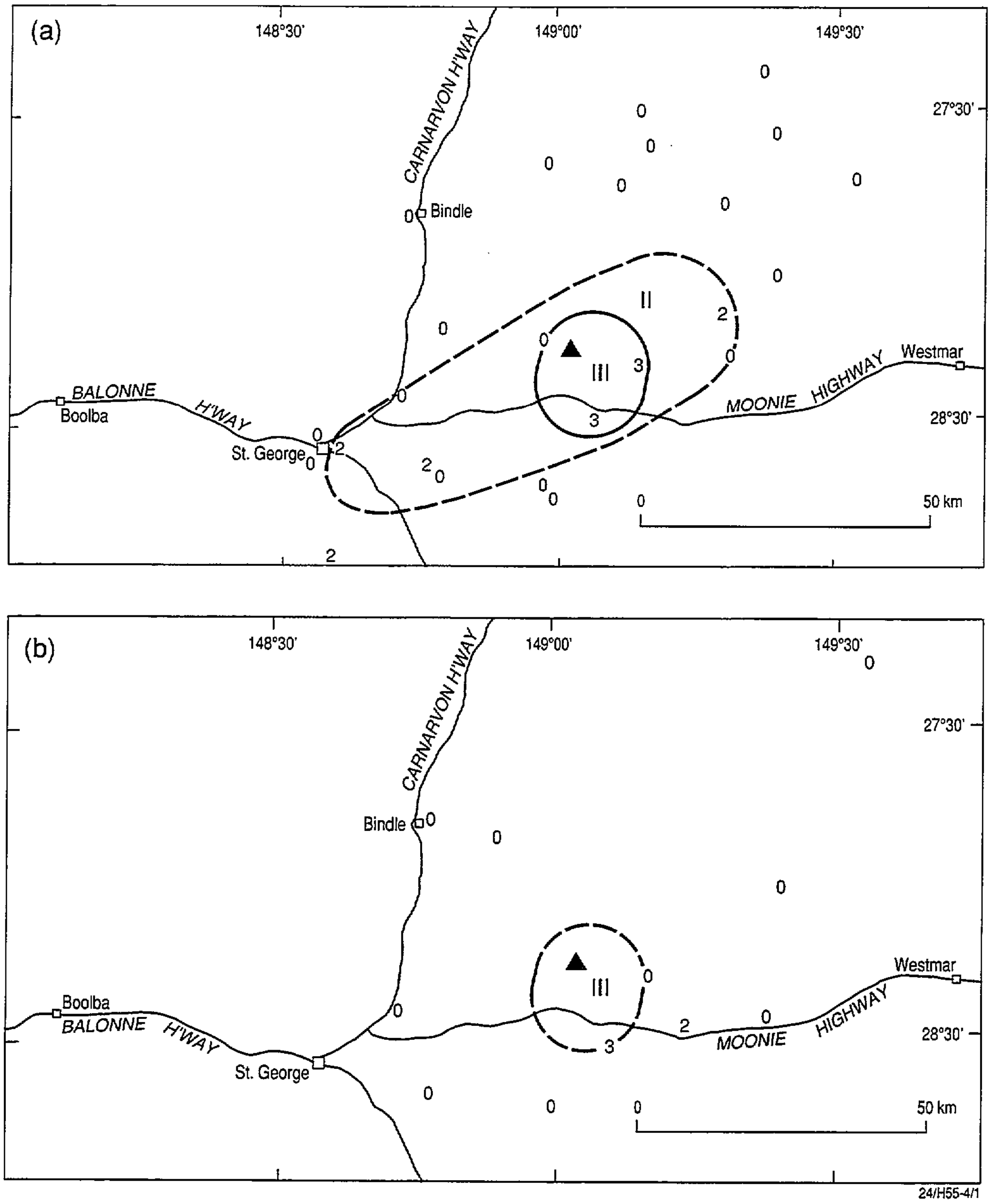


Figure 20

DATE:	(a)	24 SEPT 1991	(b)	28 SEPT 1991
TIME:		04:36:53		15:05:34
MAGNITUDE:		4.1 ML (GSQ)		3.6 ML (GSQ)
EPICENTRE:		27.89°S, 149.05°E		27.87°S, 149.04°E
DEPTH:		8 km		4 km

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*

ISOSEISMAL MAP OF THE PROSTON EARTHQUAKE, QUEENSLAND
22 NOVEMBER 1991

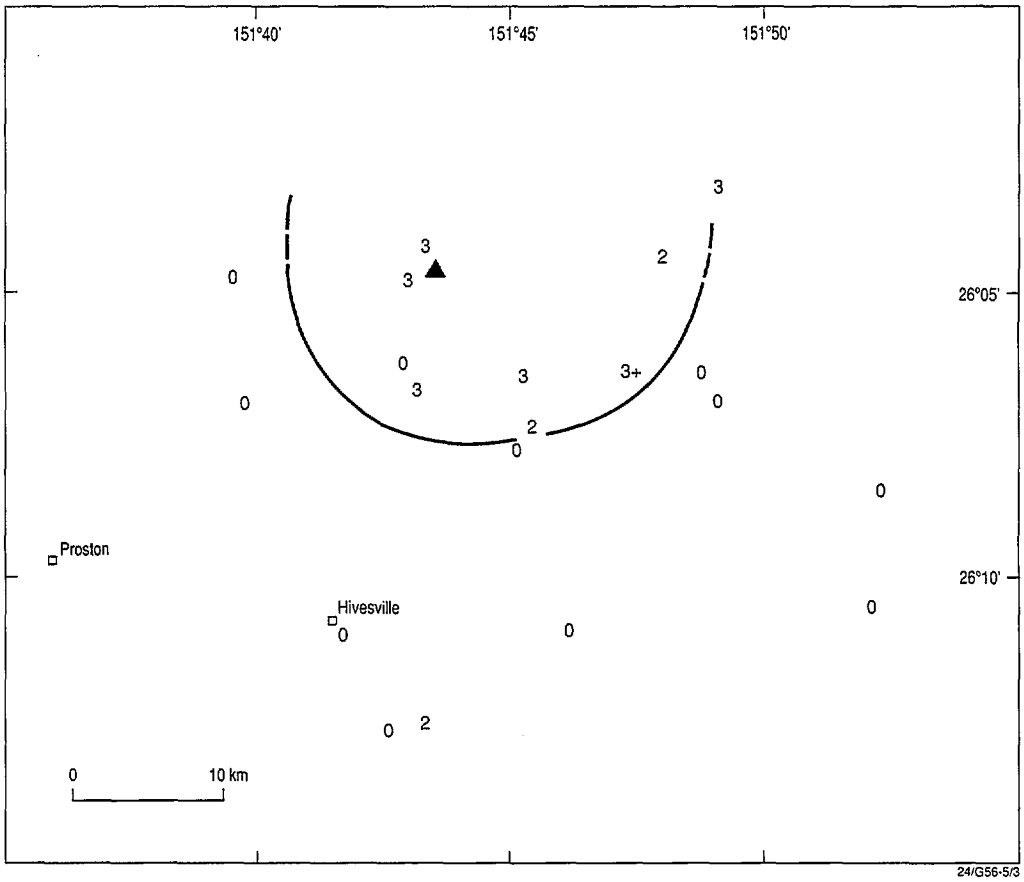
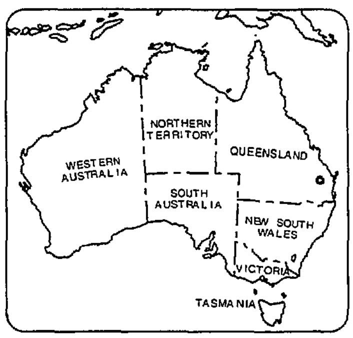


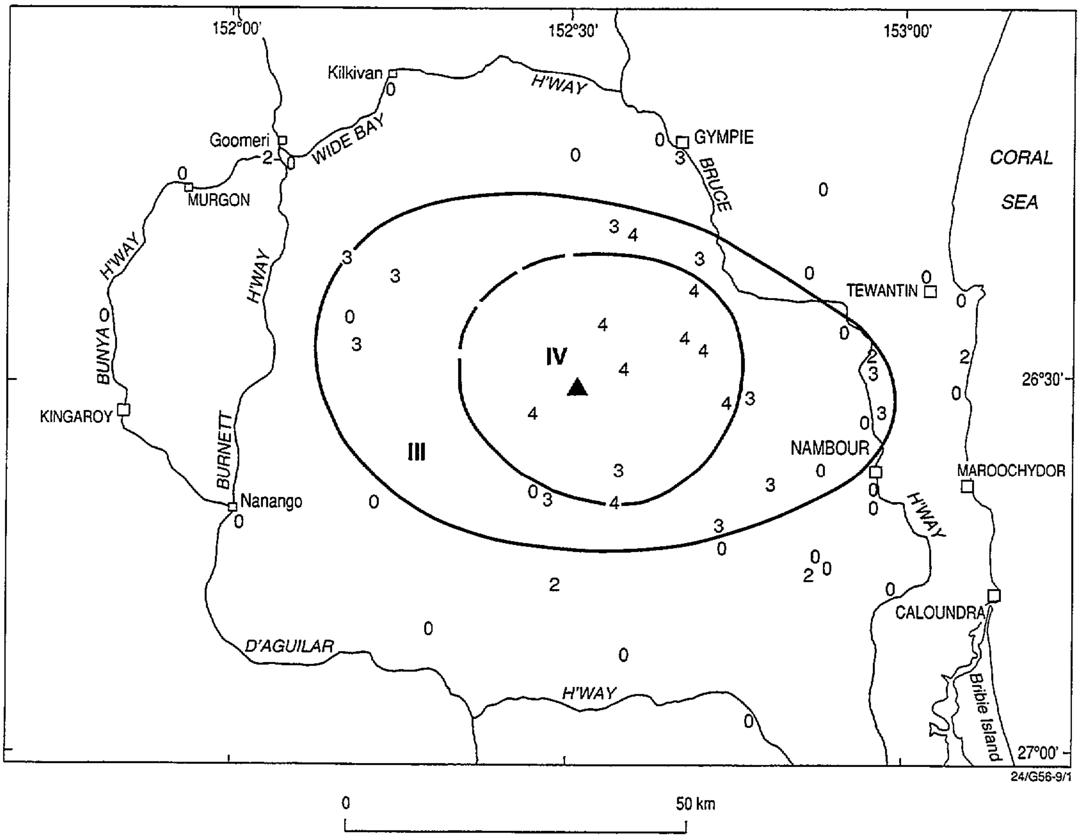
Figure 21

DATE: 22 NOVEMBER 1991
TIME: 17:39:14
MAGNITUDE: 2.7 ML (GSQ)
EPICENTRE: 26.07°S, 151.72°E
DEPTH: 2 km (G)

▲	*Epicentre*
IV	*Zone intensity designation*
4	*Earthquake felt (MM)*
0	*Earthquake not felt*



ISOSEISMAL MAP OF THE BORUMBA RESERVOIR EARTHQUAKE, QUEENSLAND I DECEMBER 1991



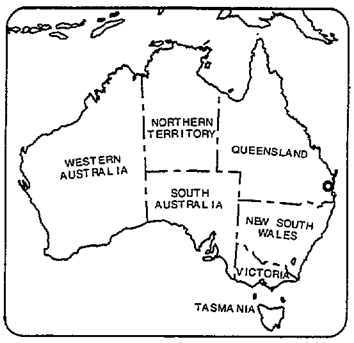


Figure 22

DATE: 1 DECEMBER 1991
TIME: 18:13:47
MAGNITUDE: 3.6 ML (GSQ)
EPICENTRE: 26.53°S, 152.50°E
DEPTH: 2 km (G)

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*

1:05 am AEST, due to the smaller magnitude and its occurrence when most people were asleep.

Proston Qld, 22 November

A microearthquake magnitude ML 2.7 was felt at 4:39 am on 23 November (AEST) in an area 15 km northeast of Proston (Figure 21). The epicentre was located using phase arrival times from the Wivenhoe Dam network to the south and Bundooma Dam seismograph to the west.

Borumba Reservoir Qld, 1 December

Modified Mercalli intensities of IV were assocoated with a magnitude 3.6 earthquake at 5:13 am on 2 December (AEST), located near Borumba Reservoir south of Gympie (Figure 22). Isolated reports of damage were received. An aftershock at 9:45 am on 4 December was felt by several people at Borumba Reservoir.

Cranbrook WA, 13 December

The earthquake occurred at 1.48 p.m. WSST. The maximum MM intensity reported was V at a location 20 km northwest of Cranbrook (Figure 23) where a skid mounted bed unit moved off its foundation.

The radius of the MMIV isoseismal was 45 km and the earthquake was felt to distances of 90 km. Only one other earthquake has been reported within 20 km of this location.

D Love, S Greenhalgh, K Malpas, R Cuthbertson, P Gregson, K McCue

NETWORK OPERATIONS 1991

The Armidale NSW seismograph in the Cooney Tunnel was moved to the University of New England's Newholme Farm about 10 km north of Armidale because of mining activity under the tunnel.

In Newcastle, changes to the network involved removing the analogue seismograph from the University of Newcastle and installing a triaxial digital Kelungi seismograph at Quorrobolong (QFS) near Cessnock. The network includes KIM at Merewether a Kelungi, NLD at North Lambton which comprises a Kelungi recorder on site and analogue recorder at the Newcastle Regional Museum, and a Kelungi accelerograph at the Newcastle Police station.

In Queensland, the Department of Resource Industries closed the Mt Hope seismograph but installed new recorders on Peter Faust Dam and Glenlyon Dam. The University of Central Queensland installed a seismograph at Byfield northeast of Rockhampton and moved the campus recorder.

There were no significant changes to the SA or WA networks.

Graeme Small, Peter Gregson, Kevin McCue Russel Cuthbertson & David Love

THE NEWCASTLE MICROZONATION STUDY

(Abstract from Somerville, Kagami & McCue, 1991) In the magnitude 5.6 Newcastle, NSW earthquake of 28 December 1989, the area with highest seismic intensity (MM VIII) was some 10 km from the epicentre (McCue & others, 1990). In the absence of local instrumental data for the event, various explanations of the intensity distribution have been advanced.

A causative relationship has been suggested, with support from wave propagation calculations, in the close spatial correlation between the area with highest

ISOSEISMAL MAP OF THE CRANBROOK EARTHQUAKE, WESTERN AUSTRALIA
13 DECEMBER 1991

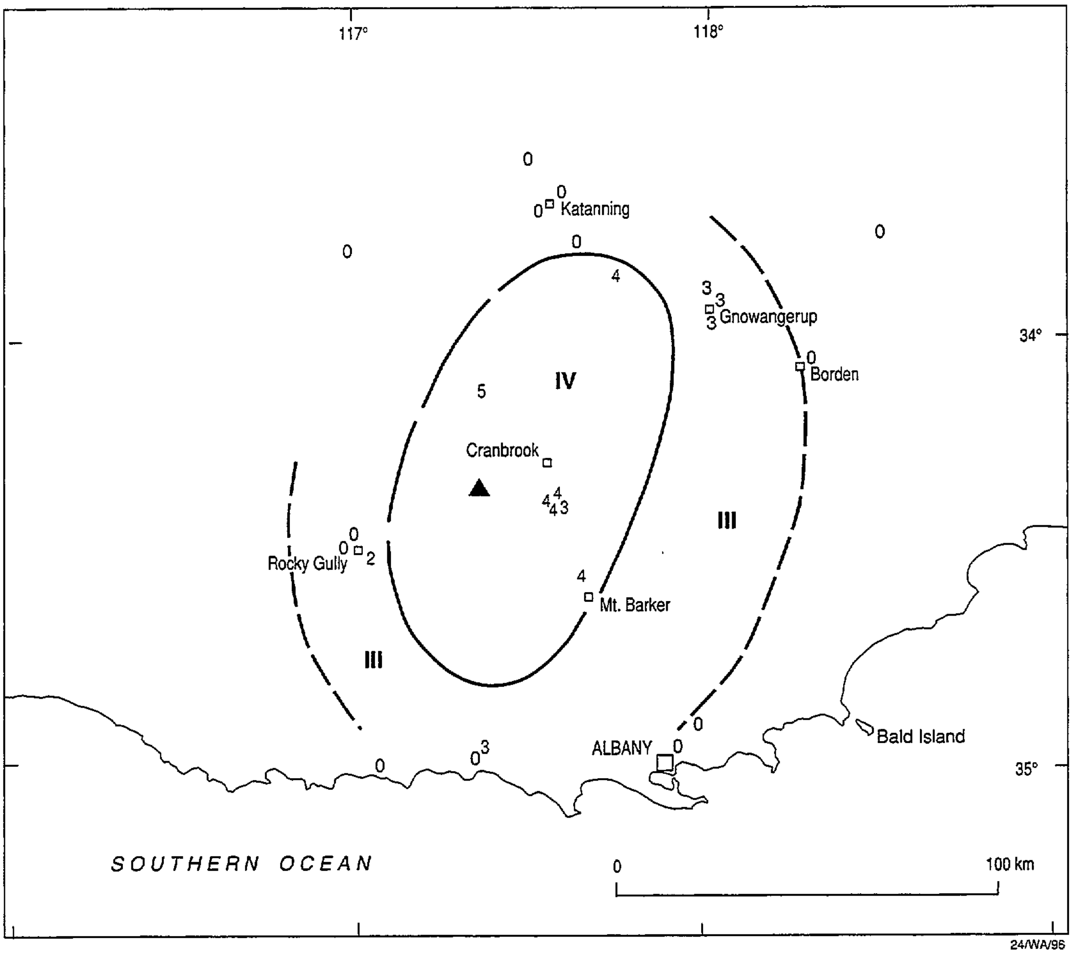
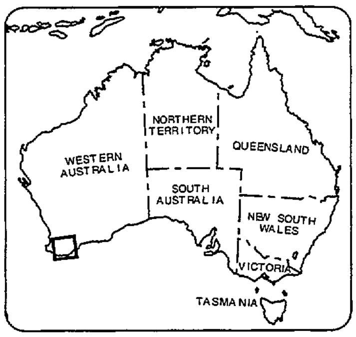


Figure 23

DATE: 13 DECEMBER 1991
TIME: 04:48:17.6 UTC
MAGNITUDE: 4.3 ML (MUN)
EPICENTRE: 34.39°S, 117.36°E

▲ *Epicentre*
IV *Zone intensity designation*
4 *Earthquake felt (MM)*
0 *Earthquake not felt*



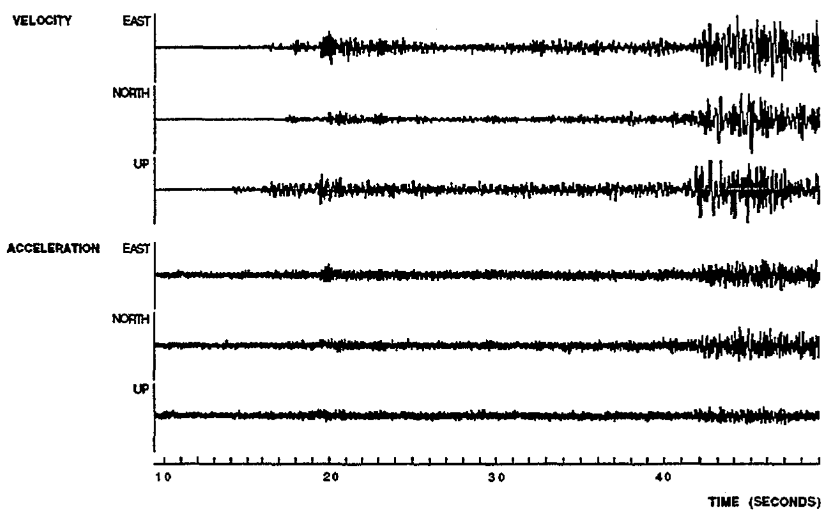
seismic intensity and the area with alluvial and/or fill cover. An alternative interpretation correlates damage with structural vulnerability rather than site geology.

New evidence for amplified response of alluvial sites has been obtained from a microtremor monitoring experiment using 1-Hz seismometers. Amplified response was observed at frequencies ranging from 1.5 Hz to 10 Hz, at sites with alluvial depth ranging from 40m to 5m. Most of these observations can be interpreted straightforwardly in terms of fundamental-mode (quarter-wavelength) resonance of the alluvium overlying a substratum of much greater rigidity. At some sites there is amplification but the quarter-wavelength resonance is not identifiable, due to a steep interface between the alluvium and the substratum, or perhaps the lack of a sharp rigidity contrast. The microtremor results, while useful for determining site resonance frequencies, are not expected to replicate the degree of amplification under earthquake excitation. The microtremor amplification factors are generally higher than the factor 3±1 inferred from the MM intensity distribution of the 28 December, 1989 earthquake.

M.R. Somerville, H. Kagami and K.F. McCue

ACCELEROGRAPH DATA

There were no accelerographs at Tennant Creek to record either of the two magnitude 5^+ earthquakes there in 1991.



In Western Australia There were 16 accelerograms recorded from 13 earthquakes in the South-West Seismic Zone in 1991. Of these 8 were from the Cadoux area, the largest on 8 January had a magnitude of ML 3.3. The maximum acceleration from this event was 29 mm^{-2}, recorded at a hypocentral distance of 14 km. An ML 3.2 earthquake near Cadoux on 25 November was recorded on 2 Cadoux accelerographs and at Goomalling at a distance of 75 km where the ground motion had a peak acceleration of 6 mms^{-2}.

Of the 5 Meckering events, the largest was ML 2.2, which had a peak ground acceleration of 225 mms^{-2} at a distance of 5 km.

In Eastern Australia The combined accelerogram and seismogram above was obtained from one of the digital recorders in a network of six instruments near Cairns. This recorder is equipped with both a three-component, velocity transducer (top three traces) and a three-component accelerometer (bottom three traces). The acceleration traces show a much lower signal to noise ratio than the velocity traces but usable accelerations can be obtained for the latter part of the record.

The peak acceleration was 0.0005g, at a distance of 206km from this magnitude 4.4 earthquake near Georgetown on 6 August. Although this ground motion is exceedingly small it is hoped that the collection of more of this sort of data will eventually yield attenuation relations based on local data. Seismic risk determinations in

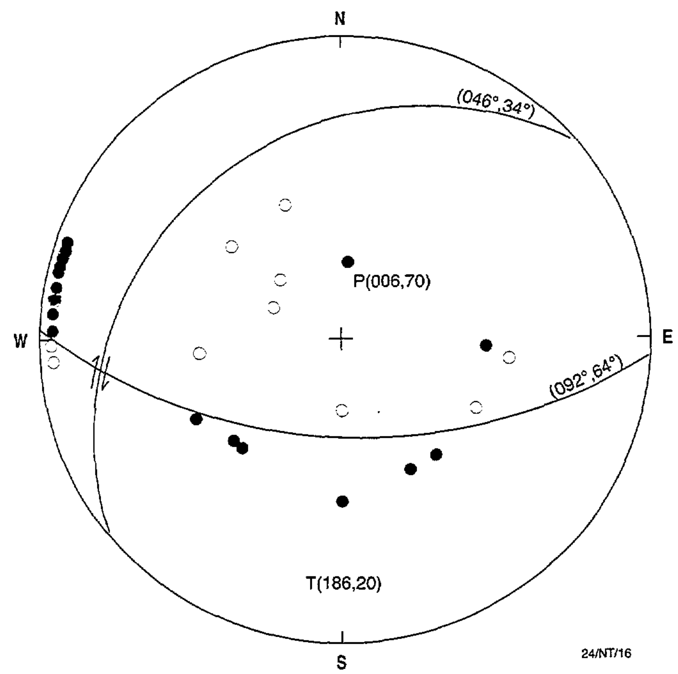
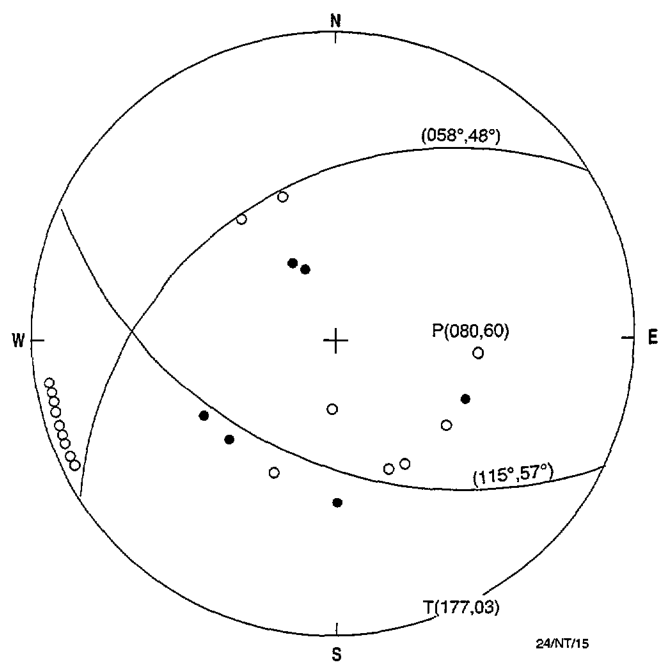


Figure 25 Focal mechanism of the Tennant Creek aftershocks on 19 June (top) and 8 July. A Lambert equal area projection was used. Solid circles are compressions, open circles dilatations. The nodal planes and poles are plotted with strike and dip as marked.



Queensland are currently based on attenuation relationships obtained using interstate or overseas data.

The seismograph network near Cairns monitors seismicity in the area of the proposed Tully-Millstream Hydroelectric Scheme. The network is operated by the Queensland Electricity Commission with data analysed by the Department of Resource Industries to June 1993 and thereafter by the Department of Earth Sciences, University of Queensland.

No other significant accelerograms were recorded in Eastern Australia

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TIME ZONES IN AUSTRALIA

The Standard Time Act of 1895 introduced Greenwich Mean Time (GMT) to Australia and standardised time zones within the States; Eastern, Central and Western Standard Time, 10, 9:30 and 8 hours ahead of GMT. According to Paul Payne of the Sydney Observatory; prior to 1895 the times of the capital cities for noon in Sydney were: Melbourne 11:45 am, Adelaide 11:10 am, Perth 9:39 am, Hobart 11:45 am, Brisbane 12:07 pm, which times correspond closely to the difference in longitude from Sydney. Towns near the capital cities probably adopted the same time but what standard was adopted in isolated towns is not known.

GMT is a measure of Earth rotation relative to the Sun at the longitude of Greenwich UK. The Coordinated Universal Time (UTC) scale, synonymous with GMT since 1970, is derived from the US National Bureau of Standards atomic frequency standard which emulates the Caesium resonance frequency to within a few parts in 10^{13}. Integral second corrections are applied to UTC as required so that it never differs from UT (the Earth rotation time with respect to the sun and corrected for polar motion) by more than 0.7s (NBS, 1972; J. McK. Luck, 1991).

AUSTRALIAN EARTHQUAKE FOCAL MECHANISMS

The Tennant Creek aftershocks of June and July were large enough to warrant investigation of their mechanisms. NEIC reported both as magnitude Mb 5.1 and they were recorded worldwide. Cursory examination of the first arrivals at stations of the nearby Warramunga array suggested that either their mechanisms or their locations were different.

The June event was relocated, the epicentre west of Lake Surprise and at a focal depth of 3 km (constrained by a pP of 0.9 s at Wattenberg). The errors in location are ±10 km. The mechanism is a surprising but well constrained normal fault (Figure 25). The east-west nodal plane dipping at 64° to the south is tightly constrained between the array elements, the two northern-most 'red' elements showing dilatations, the rest recording clear compressions. The other nodal plane strikes at 045° (±15°) and dips at 32° (±12°); it is not so well constrained but parallels and is down-dip from the Western Lake Surprise scarp.

The July event was also relocated. The focal depth is again constrained by a 0.6 s time difference of the pP-P at Wattenberg and again the epicentre is west of Lake Surprise with similar location errors. In contrast with the compressions from the June event at most WRA array stations, every array element showed a clear dilatation but the mechanism is another normal solution, reasonably similar to the first. Both mechanisms are the reverse of the mechanisms of the 1988 mainshocks in the sense that the P and T axes are interchanged which may be simply explained as follows.

A horst block was thrown up during the mainshocks in 1988, bound by the Western Lake Surprise Fault in the south and the Kunayungku Fault in the north. A re-

Earthquakes M > 6.0, 1991

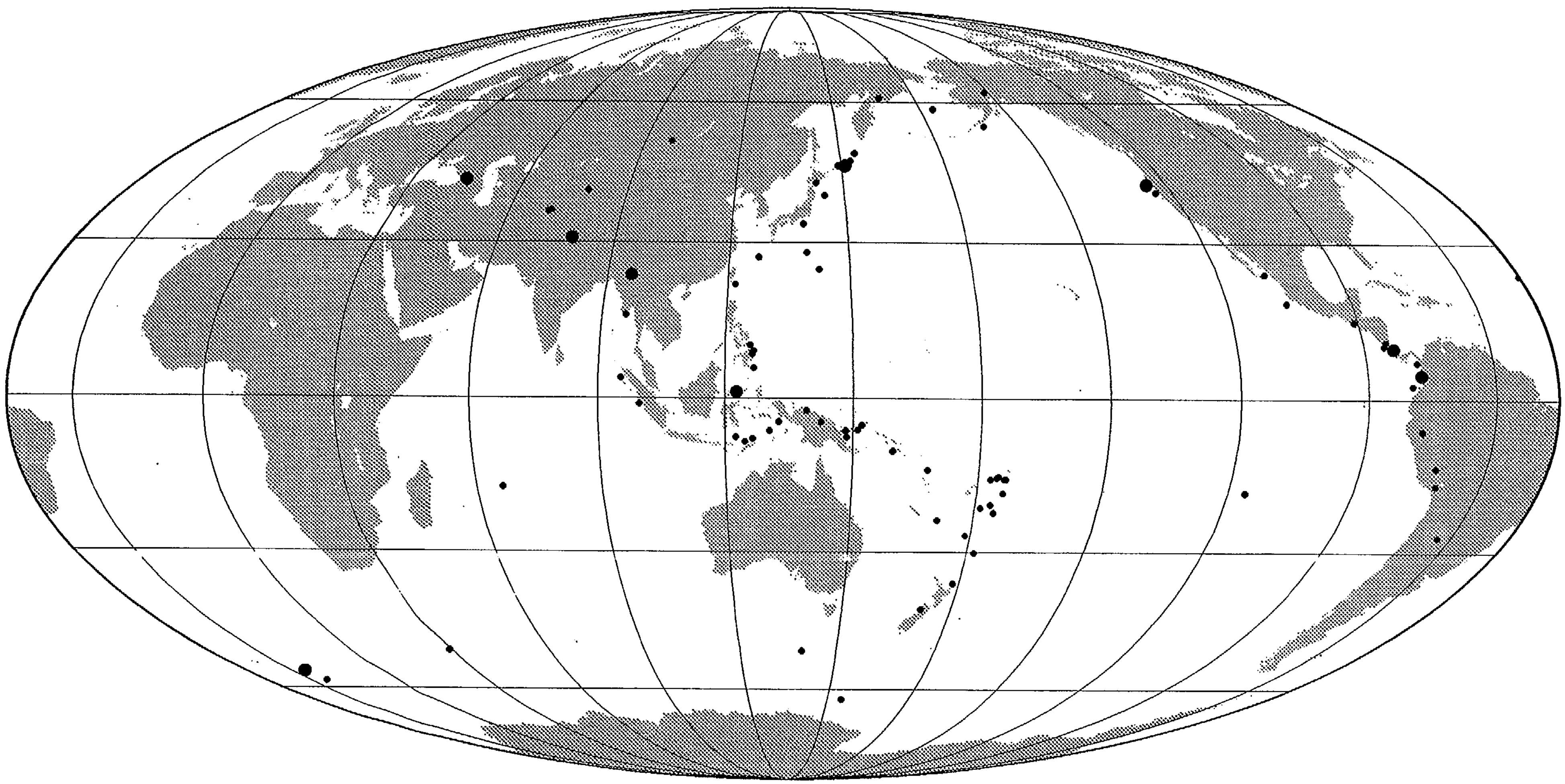

Figure 26 Principal world earthquakes, $M \geq 6$ (large dots $M \geq 7$). Data extracted from the AGSO World Earthquake Database.

orientation of the regional stress has occurred in the intervening 3 years as indicated by the long aftershock sequence. Redistribution of pore fluid pressures has resulted in a decrease in the effective vertical stress leading to settlement along the southern limb of this block.

PRINCIPAL WORLD EARTHQUAKES, 1991

Table 7 lists earthquakes that occurred throughout the world in 1991 of magnitude 7.0 or greater, or that caused fatalities or substantial damage. There were no great earthquakes, and 5 of the 8 earthquakes of magnitude Ms 7 or more occurred around the Pacific rim. The other 3 were in the Alpide belt, in Burma, Northern India and the Eastern Mediterranean. The largest at magnitude Ms 7.4 occurred on 22 April in Costa Rica. The most destructive earthquake of 1991 was in Northern India on 19 October. At least 2000 people were killed, more than 1800 injured and 18 000 buildings were destroyed. Landslides occurred in the epicentral region and a 30 m deep crack was noted in the Yttarkashi area. Figure nn shows the location of these earthquakes.

World-wide, more than 2800 people died in earthquakes in 1991, compared with 52 000 and 530 in 1990 and 1989 respectively, and the average for the century of 10 000 per year.

This information is from the monthly 'Earthquake Data Reports' published by the United States Geological Survey and the SEAN Bulletin of the Smithsonian Institution (SEAN, 1991).

Peter Gregson and Kevin McCue

MONITORING OF NUCLEAR EXPLOSIONS

Underground nuclear explosions presumed to have occurred during 1991 are listed in Table 8. Except for one small Mururoa test, believed to be less than 0.5 kt (Department of Scientific and Industrial Research, New Zealand), all of the other listed events were recorded by Australian seismic stations. Only 2 nuclear weapon states conducted tests this year, the U.S. and France. The largest French nuclear test was held at Fangataufa, and the remaining 5 were at Mururoa. At the US test site in Nevada eight tests were conducted.

The approximate yield (in kilotons) of an underground nuclear explosion can be determined empirically from its average body-wave magnitude mb (Table 9).

During the year, the Soviet Republic of Kazakhstan closed the main Soviet test site at Semipalantinsk following its declaration of independence, and as a response to President Bush's unilateral nuclear cuts of 27 September, President Gorbachev announced a 1 year moratorium on Soviet tests. However the US continued to assert the need to have a testing program, on the grounds that it is more secure and stable to periodically test the reliability of their nuclear weapons, than just maintaining a stockpile and not testing it (Pacific Research, Vol. 4, 1991).

D Jepsen

REFERENCES

Anderson, J.A. & Wood, H.O., 1925 — Description and theory of the torsion seismometer. *Bulletin of the Seismological Society of America*, **15**, 1-72.

Båth, M., 1981 — Earthquake magnitude - recent research and current trends. *Earth Science Reviews*, **17**, 315 - 398.

Bisztricsany, E., 1958 — A new method for the determination of the magnitude of earthquakes. *Geofizikai Kozlemenyek*, **7**, 69-96.

Denham, D., 1982 — Proceedings of the workshop on Australian earthquake magnitude scales. BMR, Canberra, 21 May 1982. *Bureau of Mineral Resources, Australia, Record* 1982/29.

Eiby, G., 1966 — The Modified Mercalli Scale of earthquake intensity and its use in New Zealand. *New Zealand Journal of Geology and Geophysics*, **9**, 122-129.
Everingham, I.B., Denham, D., & Greenhalgh, S. A., 1987 — Surface-wave magnitudes of some early Australian earthquakes. *BMR Journal of Australian Geology & Geophysics*, **10**, 253-259.
Everingham, I.B., McEwin, A.J., & Denham, D., 1982 — Atlas of isoseismal maps of Australian earthquakes. *Bureau of Mineral Resources, Australia, Bulletin* **214**.
Gregson, P.J., 1992 - Mundaring Geophysical Observatory Annual Report 1990. *Bureau of Mineral Resources, Geology and Geophysics, Record* 1992/18.
Greenhalgh, S., Denham, D., McDougall, R., & Rynn, J.M.W., 1989 — Magnitude-intensity relations for Australian earthquakes. *Bulletin of the Seismological Society of America*, **78**, (1), 374-379.
Gregson, P.J., (1992) - Mundaring Geophysical Observatory Annual Report 1991. AGSO Record (in prep.)
Gutenberg, B., 1945 — Amplitudes of P, PP and SS, and magnitudes of shallow earthquakes. *Bulletin of the Seismological Society of America*, **35**, 57-69.
Jones, T. D., Gibson G., McCue, K. F., Denham, D., Gregson, P. J., and Bowman, J. R., 1991. Three large intraplate earthquakes near Tennant Creek, Northern Territory, Australia, on 22 January 1988, *BMR J. Australian Geology & Geophysics*, **12**(4), 339-343.
Kanamori, H., 1978 — Quantification of earthquakes. *Nature*, **271**, 411-414.
Luck, J. McK., 1991 — Report to National Time Committee of National Standards Commission, Australia on 21st General Assembly of the International Astronomical Union. Buenos Aires, 21 July - 2 August 1991.
Marshall, P.D., & Basham, P.W., 1973 — Rayleigh wave magnitude scale Ms. *Pure and Applied Geophysics*, **103**, 406-414.
McCue, K.F., 1980 — Magnitude of some early earthquakes in Southeastern Australia. *Search*, **11**(3), 78-80.
McCue, K.F., Kennett, B., Gaull, B., Michael-Leiba, M. ,Weekes, J. & Krayshek C., 1989 — A century of earthquakes in the Dalton-Gunning region of New South Wales. BMR Journal of Australian Geology & Geophysics, 11, 1, pp 1-9.
McCue, K.F., Wesson, V, & Gibson, G., 1990 — The Newcastle New South Wales earthquake of 28 December 1989. *BMR Journal of Australian Geology & Geophysics*, **11**, 559-567.
McGregor, P.M., & Ripper, I.D., 1976 — Notes on earthquake magnitude scales. *Bureau of Mineral Resources, Australia, Record* 1976/76.
McKavanagh, B., Boreham, B., Cuthbertson, R., McCue, K., & Gibson, G., 1993— The Bajool earthquake sequence of 1991, and implications for the seismicity of Central Queensland. Aust Journal of Earth Sciences, 40, 455-460..
NBS 1972 — NBS frequency and time broadcast services. Ed P. P. Viezbicke, Special publication 236, US Department of Commerce, Boulder, Colorado.
Richter, C.F., 1958 — Elementary Seismology. *Freeman & Company, San Francisco*.
Rynn, J.M.W., Denham, D., Greenhalgh, G., Jones, T., Gregson, P., McCue, K.F., & Smith, R.S., 1987 — Atlas of isoseismal maps of Australian earthquakes, part 2. *Bureau of Mineral Resources, Australia, Bulletin* **222**.
SEAN 1991 — *Scientific Event Network Bulletin, Smithsonian Institution, Washington, USA*.
Somerville, M.R., Kagami, H., & McCue, K., 1993 — Seismic amplification determined from mocrotremor monitoring at alluvial sites in Newcastle. Bulletin of the New Zealand National Society for Earthquake Engineering, June 1993.
Willmore, P., 1979 — Manual of seismological observatory practice. *World Data Centre for Solid Earth Geophysics, US Department of Commerce, Boulder, Co, USA*, Report **SE-20**.

APPENDIX Modified Mercalli (MM) Scale of Earthquake Intensity (after Eiby, 1966)

MMI 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 ten 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.

MMII 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 I may be more noticeable.

MMIII Felt indoors, but not identified as an earthquake by everyone. Vibrations 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.

MMIV Generally noticed indoors, but not outside. Very light sleepers may be awakened. 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 building are heard to creak. Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock, and the shock can be felt by their occupants.

MMV 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. Glassware and crockery may be broken. Some windows crack. A few earthenware toilet fixtures crack. Hanging pictures move. Doors and shutters swing. Pendulum clocks stop, start, or change rate.

MMVI Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily. Slight damage to masonry D. Some plaster cracks or falls. Isolated cases of chimney damage. Windows and crockery broken. Objects fall from shelves, and pictures from walls. Heavy furniture moves. Unstable furniture overturns. Small school bells ring. Trees and bushes shake, or are heard to rustle. Material may be dislodged from existing slips, talus slopes, or slides.

MMVII 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 crack. Weak chimneys break, 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.

MMVIII Alarm may approach panic. Steering of motor cars 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. Decayed wooden piles break. 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.

MMIX 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 shift 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.

MMX 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.

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

MMXII 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 By-law, 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 workmanship are good. Few buildings erected prior to 1935 can be regarded as Masonry 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 Buildings with low standards of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally.

Notes

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

The `weak chimneys' listed under MM VII are unreinforced domestic chimneys of brick, concrete block, or poured concrete.

The `domestic water tanks' listed under MM VII are of the 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. Hot-water cylinders constrained only by supply and delivery pipes may move sufficiently to break pipes at about the same intensity.

Table 1 Australian earthquakes, 1991, ML ≥ 3.0

Date	*Time UTC*	*Latitude °S*	*Longitude °E*	*Depth km*	*Magnitude ML*	*Place*
1- 1	0303 15.0	-20.000	134.000	0	3.9	Tennant Ck NT
1- 3	0940 56.6	-19.932	133.861	2	4.4	"
1- 3	1404 53.9	-19.906	133.831	2	4.7	"
1- 4	0247 41.5	-28.962	146.578	5	3.6	Qld/NSW border
1- 7	1246 14.0	-19.900	133.800	0	3.0	Tennant Ck NT
1- 8	0527 8.1	-30.620	117.070	3	3.3	Cadoux WA
1- 9	1022 38.4	-17.340	123.880	5	3.7	Derby WA
1-10	0407 14.6	-32.335	138.185	26	3.1	Quorn SA
1-10	1107 28.0	-37.778	139.462	5	3.2	Beachport SA
1-11	2330 58.8	-38.280	111.270	5	3.1	Offshore SW WA
1-13	1252 35.0	-19.900	133.800	0	3.4	Tennant Ck NT
1-14	1443 51.5	-30.629	151.551	0	3.1	Tamworth NSW
1-22	0044 12.0	-19.900	133.800	0	4.0	Tennant Ck NT
1-24	1456 7.0	-19.900	133.800	0	3.6	"
1-24	1458 37.0	-19.900	133.800	0	3.7	"
2- 4	0827 34.3	-18.720	115.710	5	3.7	Dampier WA
2- 9	0124 7.4	-15.467	139.761	5	3.3	G Carpentaria Qld
2-11	1532 32.0	-19.900	133.800	2	3.2	Tennant Ck NT
3- 4	0014 39.7	-33.542	136.336	3	3.0	Whyalla SA
3- 7	0128 8.9	-20.021	133.809	2	4.8	Tennant Ck NT
3- 7	0622 52.0	-19.900	133.800	2	3.2	"
3- 9*	0136 31.2	-30.760	121.420	11	4.2	Kalgoorlie WA
3-15	0429 39.3	-29.360	124.650	1	3.0	SE Laverton WA
3-17	0938 26.5	-28.090	114.010	5	3.3	Kalbarri WA
3-21	0537 37.0	-19.900	133.800	2	3.1	Tennant Ck NT
3-23	1513 2.0	-19.900	133.800	2	3.2	"
3-24	0311 37.1	-21.910	115.960	5	3.0	Karratha WA
3-25	0146 47.5	-42.300	147.379	3	3.0	Oatlands Tas
3-25	1842 31.1	-34.122	136.948	1	3.1	Tumby Bay SA
3-28	2126 2.2	-38.572	146.266	21	3.6	Morwell Vic
4- 9	1400 8.0	-20.650	116.990	5	3.4	Karratha WA
4-10	0606 34.2	-30.720	121.420	5	3.1	Kalgoorlie WA
4-14	0746 22.2	-26.790	111.530	5	3.7	Carnarvon WA
4-18	0451 5.2	-25.960	135.200	5	3.1	NT/SA border
4-20	1508 58.9	-27.380	112.510	5	3.1	Carnarvon WA
4-22	1635 59.6	-20.240	134.280	5	3.3	Tennant Ck NT
5- 1	2239 58.2	-36.950	144.096	9	3.2	Maldon Vic
5- 3	1728 7.2	-37.158	143.663	4	3.5	"
5- 5	1426 47.4	-31.028	139.203	3	3.1	Flinders R SA
5- 6	0709 1.4	-13.910	130.990	5	3.0	Darwin NT
5- 7	0528 39.7	-18.800	118.410	5	3.0	Pt Hedland WA
5- 7	1656 31.2	-19.900	133.800	2	3.9	Tennant Ck NT
5- 7	1702 27.6	-19.900	133.800	2	3.0	"
5- 9	0750 27.6	-36.900	144.108	1	3.3	Bradford Hills Vic
5-10	0412 1.2	-19.900	133.800	2	3.0	Tennant Ck NT
5-10	0605 12.1	-19.900	133.800	2	3.1	"
5-11	0051 13.0	-19.900	133.800	2	3.3	"
5-11	0904 10.6	-36.427	140.053	10	3.0	Willalooka SA
5-15	0906 43.6	-22.320	113.040	10	3.0	Learmonth WA
5-20	1336 54.0	-34.076	148.827	3	3.5	Cowra NSW
5-21	0212 54.7	-15.450	125.490	5	3.0	Kununurra WA
5-26	1004 24.2	-19.900	133.800	2	3.7	Tennant Ck NT

Table 1 (cont.)

6-14	1222	52.4	-32.600	122.320	5	3.6	Norseman WA
6-17	0452	45.3	-19.970	121.680	5	3.1	Broome WA
6-19	1138	24.7	-19.790	133.950	3	**5.1**	Tennant Ck NT
6-23	1326	17.3	-22.850	130.660	5	3.0	NT/WA border
7- 2	0648	0.0	-29.940	111.280	5	3.4	Carnarvon WA
7- 8	1045	34.2	-19.861	133.866	5	**5.0**	Tennant Ck NT
7- 8	1059	45.0	-19.900	133.900	5	3.3	"
7-17	0234	11.1	-32.540	150.910	3	3.2	Singleton NSW
7-17	1315	41.5	-34.020	136.320	5	3.2	Eyre Peninsula SA
7-25	0922	28.0	-19.830	133.970	5	3.8	Tennant Ck NT
7-25	1652	52.0	-19.800	134.000	5	3.2	"
8- 1	0132	15.8	-19.900	133.800	2	3.0	"
8- 4	2328	6.1	-19.880	134.223	12	4.3	"
8- 5	0357	59.6	-19.900	133.800	2	3.2	"
8- 5	1800	52.3	-22.210	109.140	5	3.5	Exmouth WA
8- 6	1411	40.8	-17.858	143.363	5	4.4	Georgetown Qld
8-17	0628	55.2	-34.344	139.154	10	3.7	Truro SA
8-18	1156	57.4	-16.610	128.610	5	3.9	Kununurra WA
8-18	1205	26.9	-16.560	128.590	5	3.0	"
8-30	1404	23.8	-20.530	119.670	5	3.3	Marble Bar WA
8-31	0406	52.8	-20.640	119.570	5	3.0	"
9- 2	2213	59.5	-32.720	139.000	3	3.7	Peterborough SA
9- 2	2219	15.4	-32.720	139.000	2	3.2	"
9- 5	0611	45.4	-25.090	112.680	5	3.0	Carnarvon WA
9-21	1339	43.6	-16.890	121.580	23	3.1	Broome WA
9-23	2119	58.1	-20.720	120.710	5	4.0	Shay Gap WA
9-24	0436	50.5	-27.520	149.140	10	4.3	St George Qld
9-28	1505	25.9	-27.720	148.980	5	3.6	"
10- 6	2259	8.3	-16.859	129.089	5	3.2	Kununurra WA
10- 6	2259	37.4	-16.877	129.087	5	3.6	"
10- 9	1646	15.6	-16.551	128.565	5	3.7	WA/NT border
10-14	1257	3.8	-19.700	133.900	5	3.8	Tennant Ck NT
10-18	0907	27.7	-20.500	114.126	5	4.3	Exmouth WA
10-25	0505	56.1	-20.460	119.907	5	3.0	Offshore WA
11- 5	0926	49.8	-32.840	122.100	5	3.8	Salmon Gums WA
11-18	0449	29.2	-20.400	119.420	5	3.4	Port Hedland WA
11-20	2203	10.0	-19.900	133.800	2	3.4	Tennant Ck NT
11-22	0711	6.2	-36.512	146.075	0	3.0	Benalla Vic
11-22	1739	14.6	-26.127	151.698	3	3.0	Proston Qld
11-24	0801	21.6	-34.724	149.186	12	3.1	Dalton NSW
11-24	1438	46.7	-19.370	117.000	5	3.1	Dampier WA
11-25	0142	54.3	-30.770	117.140	2	3.2	Cadoux WA
11-28	0418	59.8	-23.109	132.107	5	3.1	Papunya NT
11-28	1050	51.0	-19.900	133.800	2	3.0	Tennant Ck NT
11-29	0812	23.4	-31.519	138.353	9	3.3	Moralana SA
11-29	0945	46.6	-31.527	138.359	9	3.5	"
12- 1	1813	48.0	-26.486	152.620	10	3.6	Jimna Qld
12- 9	1910	26.0	-19.900	133.800	5	3.3	Tennant Ck NT
12- 6	1458	41.9	-26.763	112.167	5	3.3	Carnarvon WA
12-11	1759	55.6	-30.394	117.745	2	3.2	Beacon WA
12-13	0448	17.6	-34.389	117.360	1	4.3	Cranbrook WA

* Rockburst

Table 2. Large or damaging Australian earthquakes, 1788 - 1991

Source #	Date UTC	Time	Lat °S	Long °E	Depth km *	ML	Ms	Location
ET	1873 12 15	0400	26.25	127.5	0 G		6.0	SE WA
MML	1884 07 13	0355	40.5	148.5	0 G	6.4		West Tasman Sea
MML	1884 09 19	1027	40.8	149.5	0	6.4		"
ET	1885 01 05	1220	29.0	114.0	0 G		6.5	Geraldton WA
MML(b)	1885 05 12	2337	39.8	148.8	0 G	6.5		West Tasman Sea
MML	1892 01 26	1648	40.4	149.5	0 G	6.6		"
MML	1892 01 26	16 56	40.4	149.5	0	6.0		"
ADE	1897 05 10	0526	37.33	139.75	0 G	6.5		Kingston SA
ADE	1902 09 19	1035	35.0	137.4	14	6.0		Warooka SA
KMc	1903 04 06	2352	38.43	142.53		4.6		Warrnambool Vic
KMc	1903 07 14	1029	38.43	142.53		5.3		Warrnambool Vic
G&E	1906 11 19	0718	21.5	104.5	5		7.3	Offshore WA
UQ	1918 06 06	1814 24	23.5	152.5	15	6.2	5.7	Gladstone Qld
EDG	1920 02 08	0524 30	35.0	111.0	0 G		6.0	Offshore WA
BMR	1929 08 16	2128 23	16.99	120.66	3N		6.6	Broome WA
EDG	1935 04 12	0132 24	26.0	151.1	0 G	5.2	5.4	Gayndah Qld
BMR	1941 04 29	0135 39	26.92	115.80	0 G	7.0	6.8	Meeberrie WA
BMR	1941 06 27	0755 49	25.95	137.34	0 G		6.5	Simpson Desert
MML	1946 09 14	1948 49	40.07	149.30	0 G	6.0		West Tasman Sea
ADE	1954 02 28	1809 52	34.93	138.69	4 G	5.4	4.9	Adelaide SA
	1961 05 21	2140 03	34.55	150.50		5.6		Bowral NSW
BMR(f)	1968 10 14	0258 50	31.62	116.98	5	6.9	6.8	Meckering WA
BMR	1970 03 10	1715 11	31.11	116.47	1	5.1	5.1	Calingiri WA
BMR	1970 03 24	1035 17	22.05	126.61	0 G	6.7	5.9	L Mckay WA
BMR	1972 08 28	0218 56	24.95	136.26	10		6.2	Simpson Desert
	1973 03 09	1909 15	34.17	150.32		5.6	5.3	Picton NSW
MUN(f)	1975 10 03	1151 01	22.21	126.58	0		6.2	L Mckay WA
BMR	1978 05 06	1952 19	19.55	126.56	17		6.2	L Mckay WA
BMR	1979 04 23	0545 10	16.66	120.27	34	6.3	5.7	Broome WA
BMR(f)	1979 06 02	0947 59	30.83	117.17	5	6.2	6.1	Cadoux WA
CGS	1983 11 25	1956 07	40.45	155.51	19	6.0	5.8	Tasman Sea
BMR	1985 02 13	0801 23	33.49	150.18		4.3		Lithgow NSW
BMR(f)	1986 03 30	0853 48	26.33	132.52	5		5.8	Marryat Ck SA
BMR(f)	1988 01 22	0035 57	19.79	133.93	5		6.3	Tennant Ck NT
BMR(b)	1988 01 22	0357 24	19.88	133.84	5		6.4	Tennant Ck NT
BMR(b)	1988 01 22	1204 55	19.94	133.74	5		6.7	Tennant Ck NT
BMR	1989 12 27	2326 58	32.95	151.61	13	5.6	4.6	Newcastle NSW

* G,N indicate depth restrained, or set at normal depth, by the geophysicist
\# ET - Everingham & Tilbury (1972), G&E - Gregson & Everingham (1991)
EDG - Everingham & others (1987), MML - Michael-Leiba (1989)
a,b,f - aftershock, related event, surface faulting observed

Table 3. Australian Seismographic Stations, 1991

Code#	Name	Lat° S	Long°E	Elev.m	Operator	Type*
Queensland						
AWD	Awoonga Dam	24.078	151.316	110	GSQ	1
BDM	Boondooma Dam	26.112	151.444	320	GSQ	1
BGR	Glenroy	20.549	147.105	160	GSQ	1
BLP	Blunder Park	17.76	145.42	650	GSQ	
BRS	Mt Nebo Brisbane	27.392	152.775	525	QLD	5
BSL-	Bruslee	20.275	147.299	185	GSQ	1
BYFQ+	Byfield	22.820	150.626	80	UCQ	8
CCQ	Carron Creek	17.85	145.57	740	GSQ	
CVL	Colinsville	20.590	147.105	160	GSQ	1
CRC	Cracow	25.253	150.279	290	GSQ	1
CTAO	Charters Towers	20.088	146.255	357	QLD	2
DLB	Dalbeg	20.151	147.264	70	GSQ	1
DNG	Doongara	20.555	146.475	280	GSQ	1
FGT	Fig Tree	20.970	147.776	220	GSQ	1
GLD+	Glenlyon Dam	28.9694	151.4797	48	GSQ	
GVA	Glen Eva	21.489	147.483	200	GSQ	1
HRD	H Road	17.76	145.65	260	GSQ	
MCP	Mt Cooper	20.552	146.806	300	GSQ	1
MHP-	Mt Hope	21.396	146.802	200	GSQ	1
MNH	Munroe Hill	17.97	145.80	40	GSQ	
MTMQ	Mt Morgan	23.763	150.390	170	UCQ	8
PFD+	Peter Faust Dam	20.3858	148.3746	12	GSQ	
QIS	Mount Isa	20.556	139.605	330	BMR	1
QLP	Quilpie	26.584	144.235	210	BMR	1
RMQ	Roma	26.489	148.755	360	BMR	1
RVH	Ravenshoe	17.63	145.48	880	GSQ	
SCY	Sunday Creek	17.88	145.34	690	GSQ	
UCQ2+	UCQ Campus	23.3287	150.5244	27	UCQ	1
UKA	Ukalunda	20.899	147.127	200	GSQ	1
WBA	Buaraba	27.353	152.308	100	GSQ	1
WMB	Mt Brisbane	27.115	152.550	160	GSQ	1
WPM	Pine Mountain	27.536	152.735	35	GSQ	1
WRC	Reedy Creek	27.187	152.663	190	GSQ	1
WTG	Toogoolawah	27.146	152.333	130	GSQ	1
WTR	Thallon Road	27.528	152.465	100	GSQ	1
WWH	Wivenhoe Hill	27.370	152.587	190	GSQ	1
Northern Territory						
ASPA	Alice Springs	23.667	133.901	600	BMR	3
MTN	Manton Dam	12.847	131.130	80	BMR	1
WRA	Warramunga	19.944	134.353	366	CAN	3
Western Australia						
BAL	Ballidu	30.607	116.707	300	MUN	1
COOL	Coolgardie	30.884	121.145	500	MUN	1
FORR	Forrest	30.799	128.067	530	MUN	1
KLB	Kellerberrin	31.578	117.760	300	MUN	1
KNA	Kununurra	15.750	128.767	150	PWD/MUN	1
MBL	Marble Bar	21.160	119.833	200	MUN	1
MEKA-	Meekatharra	26.6150	118.5333	520	MUN	1
MRWA	Morawa	29.218	115.996	300	MUN	1
MUN	Mundaring	31.978	116.208	253	MUN	2
NANU	Nanutarra	22.562	115.529	800	MUN	1
NWAO	Narrogin	32.927	117.233	265	MUN	4
WARB	Warburton	26.184	126.643	460	MUN	1
RKG	Rocky Gully	34.570	117.010	300	MUN	1

Table 3 (cont.)

NSW & ACT						
ARMA+	Armidale	30.4198	151.628	1.13	BMR	1
BWA	Boorowa	34.425	148.751	656	CAN	1
CAH	Castle Hill	34.647	149.242	700	CAN	1
CAN	Canberra (ANU)	35.321	148.999	650	CAN	1
CBR	Cabramurra	35.943	148.393	1537	CAN	1
CMS	Cobar	31.487	145.828	225	BMR	1
CNB	Canberra (BMR)	35.314	149.362	855	BMR	1
COO-	Cooney	30.578	151.892	650	BMR	1
DAL	Dalton	34.726	149.174	570	BMR	1
IVY	Inveralochy	34.972	149.718	770	CAN	1
JNL	Jenolan	33.826	150.017	829	CAN	1
KBH	Kambah	35.390	149.080	600	BMR	1
MEG	Meangora	35.101	150.037	712	CAN	1
NLD+	North Lambton	32.9003	151.7009	50	NCC	8
NPSD+	Newcastle Police	32.931	151.786	20	ASC	
QFS+	Quorrobolong	32.933	151.396	14	ASC	
RIV	Riverview	33.829	151.159	21	RIV	2
STK	Stephens Creek	31.882	141.592	213	BMR	7
WER	Werombi	33.950	150.580	226	CAN	1
YOU	Young	34.278	148.382	503	CAN	1
South Australia						
ADE/ADT	Adelaide	34.967	138.713	655	ADE	2
ARK	Arkaroola	30.276	139.339	520	ADE	1
CLV	Cleve	33.691	136.495	238	ADE	1
GEX	Naracoorte	37.0735	140.8251	80	ADE	1
HTT	Hallett	33.430	138.921	708	ADE	1
HWK	Hawksnest	29.958	135.203	180	ADE/BMR	1/8
KHC	Kelly Hill Caves	35.9825	136.9111	100	ADE	1
MGR2	Mt Gambier	37.8011	140.6865	60	ADE	1
NBK	Nectar Brook	32.701	137.983	180	ADE	1
PDA+	Parndana	35.8059	137.2389	140	ADE	8
PNA	Partacoona	32.006	138.165	180	ADE	1
RPA	Roopena	32.725	137.403	95	ADE	1
SDN	Sedan	34.5093	139.3374	125	ADE	8
THS	The Heights HS	34.7416	138.7733	340	ADE	1
WKA	Willalooka	36.417	140.321	40	ADE	1
WRG	Woomera	31.105	136.763	168	ADE	1
Victoria						
ABE	Aberfeldy	37.719	146.389	549	PIT	1
BEL	Bell's Track	37.761	146.389	545	PIT	1
BFD	Bellfield	37.177	142.545	235	BMR	1
BUC	Bucrabanyule	36.238	143.498	210	PIT	1
CRN	Cairn Curran	36.991	143.972	230	PIT	8
DRO	Dromana	38.360	144.997	170	PIT	1
DTM/DTT	Dartmouth	36.529	147.469	436	PIT	8
FRT	Forrest	38.534	144.997	210	PIT	1
GOG	North Grampians	36.888	142.400	265	PIT	8
GVL	Greenvale	37.619	144.901	188	PIT	1
HOP	Mount Hope	35.995	144.207	300	PIT	1
JEN	Jeeralang Junction	38.351	146.420	330	PIT	1
KOWA	Kowarra	35.791	144.521	85	PIT	1
MAL	Marshall Spur	37.749	146.292	1076	PIT	1
MEM	Merrimu	37.637	144.497	160	PIT	1
MCV	McVeigh	37.691	145.899	630	PIT	1
MIC	Mount Erica	37.944	146.359	805	PIT	1

Table 3 (cont)

Victoria (cont)						
TOT	Thompson Dam	37.8423	146.4057	680	PIT	8
MLW	Molesworth	37.137	145.510	280	PIT	1
PAT	Plane Track	37.857	146.456	771	PIT	1
PEG	Pegleg	36.985	144.091	340	PIT	1
POL	Poley Tower	37.626	145.801	1200	PIT	1
PNH	Panton Hill	37.635	145.271	180	PIT	1
RUS	Rushworth	36.662	144.947	145	PIT	1
SIN	Swingler Track	37.739	146.292	980	PIT	8
TMD	Thomson Dam	37.810	146.349	941	PIT	1
TOM	Thomson	37.810	146.348	941	PIT	1
TOO	Toolangi	37.572	145.490	604	BMR	5
TYR	Tyers	38.1083	146.4354	280	PIT	1
UYB	Upper Yarra	37.673	145.897	300	PIT	1
VPE	Vantage Point	37.642	145.937	650	PIT	1
WSK	Woodstock	36.814	144.055	210	PIT	1
Tasmania						
MOO	Moorlands	42.442	147.190	325	TAU	1
SAV	Savannah	41.721	147.189	180	TAU	1
SFF	Sheffield	41.337	146.307	213	TAU	1
SPK	Scotts Peak	43.038	146.275	425	TAU	1
STG	Strathgordon	42.751	146.053	350	TAU	1
SVR	Savage River	41.489	145.211	360	TAU	1
TAU	Tasmania Uni	42.910	147.321	132	TAU	2
TRR	Tarraleah	42.304	146.450	579	TAU	1
MCQ	Macquarie Is.	54.498	158.957	14	BMR	1/6
Antarctica						
CSY	Casey	66.2894	110.5289	56	BMR	1
MAW	Mawson	67.607	62.872	15	BMR	5/7
MCQ	(see Tasmania)					

Refers to contributors listed on page iii.

* Type of seismograph
1. Short period (vertical and/or horizontal); 2. World Wide Standardised Seismographic Station (WWSSN); 3. Seismic array; 4. Seismological research observatory (SRO); 5. Long and short period; 6. Broad-band vertical ; 7. Broad-band triaxial; 8 Kelunji digital triaxial triggered.

+/- Opened/closed this year

Table 4. Focal parameters 1991 earthquakes

Tennant Creek NT 19 June & 8 July		
	Azimuth (°)	dip (°)
P-axis	006, 080	70, 60
T-axis	186, 177,	20, 03
B-axis	260, 270	20, 34
Double couples		
A	046, 058	34, 48
B	092, 115	64, 57

Table 5. Australian accelerographs, 1991

Location	*Lat °S*	*Long °E*	*Elev (m)*	*Foundation*	*Type*	*Owner*
ACT						
ASC-AGSO	35.289	149.139	560	Soil	PIT	AGSO
Parliament House	35.310	149.123	600	Sandstone	PIT	AGSO
Corin Dam (2)	35.524	148.812	915	Granite	PIT	ACTE&W
Lower Cotter Dam	35.308	148.908	535	Basalt	PIT	ACTE&W
Telecom Tower (3)	35.275	149.096	810	Sandstone	PIT	TEL
New South Wales						
Oolong (OOL)	34.773	149.163	600	Weathered granite	SMA-1	AGSO
Ferndale (FND)	34.745	149.166	580	Granite	PIT	AGSO
Springfield (SPF)	34.765	149.151	580	Granite	PIT	AGSO
Wilton (WIL)	34.800	149.221	660	Granite	PIT	AGSO
Googong Dam (2)	35.425	149.264	620	Meta-sediments	PIT	ACTE&W
Hume Weir	36.110	147.043	600	Dam wall	SMA-1	DWR
Hume Weir	36.110	147.043	600	Dam wall	SMA-1	DWR
Hume Weir	36.110	147.043	600	Dam wall	SMA-1	DWR
Hume Weir	36.110	147.043	329	Downstream bank	SMA-1	DWR
Hume Weir	36.110	147.043	600	Left hand abutment	SMA-1	DWR
Lucas Heights LHB	34.052	150.979	80	Hawksbury sandstone	PIT	ANSTO
LHR	34.05	150.98	80	Reactor Building	PIT	ANSTO
Newcastle Police Stn NPSD+	32.931	151.786	20	Building basement	PIT	AGSO
South Australia						
Kangaroo Ck Dam	34.87	138.78	244	Slates/schists	MO2	EWSSA
Little Para Dam	34.75	138.72	102	Dolomite	MO2	EWSSA
Modbury Hospital	34.83	138.70	50	Marl & clay	MO2	PWDSA
Admin. Centre	34.925	138.608	50	Alluvium	MO2	PWDSA
Tasmania						
Gordon Dam	42.71	145.97	350	Quartzite	MO2	HEC
Victoria						
Jeeralang JNA	38.351	146.419	330	Mesozoic sediments	PIT	PIT
Plane Track PTA	37.357	146.357	771	Palaeozoic sediments	PIT	PIT
Phillip Institute PIT	37.683	145.061	116	Eocene sediments	PIT	PIT
Dartmouth Dam DDC	36.561	147.524	494	Dam crest	PIT	RWCV
	36.570	147.580	520	Hoist house	SMA-1	RWCV
Dartmouth Dam DDB	36.558	147.511	329	Ordivician meta-sediments	PIT	RWCV
	36.570	147.580	420	Downstream face	SMA-1	RWCV
	36.570	147.580	360	Access tunnel	SMA-1	RWCV
Animal Health Lab	38.15	144.39	10		SMA-1	CSIRO
	38.15	144.39	10		SMA-1	CSIRO
	38.15	144.39	10		SMA-1	CSIRO
Thomson Dam (TMT)	37.844	146.396	460	Outlet Tower	PIT	MMBW
Northern Territory						
Tennant Creek TCTY	19.642	134.183	370	Sediments	SSA-1	PIT

Table 5 (cont.)

Queensland						
Wivenhoe Dam	27.394	152.602	80	Crest	A700	BAWB
	27.395	152.603	28	Base	A700	BAWB
	27.347	152.631	78	Power Station	A700	QEC
	27.375	152.631	78	Power Station	A700	QEC
Splityard Ck. Dam	27.379	152.641	170	Dam Wall	A700	QEC
	27.375	152.641	65	Valve room	A700	QEC
Tully Millstream	17.76	145.42	65		PIT	QEC
	17.85	145.57	74		PIT	QEC
Western Australia						
Ballidu (BA-M)	30.607	116.707	300	Granite	MO2	AGSO
Cadoux						
Avery C. (CA-C)	30.851	117.160	300	Alluvium	MO2	AGSO
Emmott J. (CA-E)	30.895	117.123	320	Laterite	A700	AGSO
Kalajzic C. (CA-K)	30.718	117.141	380	LateriteGranite	MO2	AGSO
Kalajzic M. (CA-A)	30.746	117.151	320	Alluvium	A700	AGSO
Robb A. (CA-R)	30.781	117.138	360	Alluvium	MO2	AGSO
Shankland (CA-S)	30.810	117.132	400	W Granite	MO2	AGSO
Canning Dam						
Lower gallery (CD--L)	32.154	116.126	142	Granite	A700	AGSO
Upper gallery (CD-U)	32.154	116.126	202	Granite	A700	AGSO
Dowerin (DO-W)	31.010	116.982	300	Granite	PIT	AGSO
Goomalling (GO-O)	31.394	116.852	250	Granite	PIT	AGSO
Kununurra						
Dam abutment KNA	16.113	128.737		Phyllite	A700	WAWA
Dam wall KNW	16.113	128.738		Rock fill, 3m clay core	A700	WAWA
Meckering MEK	31.694	116.982	200	Alluvium		AGSO
Mundaring						
Weir MUW	31.958	116.164	140	Concrete wall 42m high	SMA1	WAWA
O'Connor museum MUC	31.957	116.162	106	Concrete floor	MO2	WAWA
North Dandalup NDD	32.52	116.01	205	Granite	A700	WAWA
Perth						
Telecom building PTB	31.953	115.850	10	Basement	SMA1	TEL
Telecom building PTM	31.953	115.850	40	Middle floor	SMA1	TEL
Telecom building PTT	31.953	115.850	70	Top floor	SMA1	TEL
Serpentine Dam						
Basement SEB	32.40	116.10		Granite	A700	WAWA
Wall SEW	32.40	116.10		Earthfill	A700	WAWA
Victoria Dam VID	32.04	116.06		Granite	A700	WAWA

ANSTO Australian Nuclear Science & Technology Organisation; BAWB Brisbane and Area Water Board; AGSO Australian Geological Survey Organisation, Canberra/Mundaring; EWSSA Engineering & Water Supply Department, South Australia; E&W ACT Electricity and Water Authority; HEC Hydroelectric Commission, Tasmania; MMBW Melbourne & Metropolitan Board of Works; PIT Seismology Research Centre, RMIT; PWDSA Public Works Department, South Australia; PWDWA Public Works Department, Western Australia; QEC Queensland Electricity Commission; TEL Telecom (ACT & Perth); RWCV Rural Water Commission, Victoria; DWR Department of Water Resources, NSW; WAWA Water Authority of Western Australia.

Table 6. Australian accelerograms, 1991

Month/ day	*Time*	*LatS*	*Long E*	*ML*	*Site*	*H/E km*	*Comp*	*T(S)*	*Acc mms^{-2}*
01 08	05 27	30.62	117.07	3.3	CA-K	14/13	SZ	0.030	26.0
							SN	0.037	27.0
							SE	0.037	29.0
08 06	14 11	17.86	143.36	4.4		206	S	0.2	5.0
11 25	01 42	30.77	117.14	3.2	CA-S	5/5	SZ	0.040	61.0
S-P 0.53s							SN	0.030	73.0
							SE	0.043	149.0
					CA-K	6/6	SZ	0.037	65.0
							SN	0.030	94.0
							SE	0.037	171.0
					GO-O	75/75	SZ	0.040	4.0
							SN	0.040	6.0
							SE	0.040	6.0
12 08	21 43	31.74	117.01	2.2	ME-3	5/5	SZ	0.025	225.0
							SN	0.036	225.0
							SE	0.030	225.0
					GO-O	42/42	SZ	0.035	3.0
							SN	0.035	6.0
							SE	0.035	6.0

Table 7. Principal world earthquakes, 1991

(Earthquakes of magnitude 7.0 or greater, or causing fatalities or substantial damage).
PAS Pasadena, BRK Berkeley, PMR Palmer, Alaska, PAL Palisades, New York, JMA Japan Meteorological Agency, TRI Trieste, NEIS US Geological Survey)*.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
05 Jan	14 57 11.5	Burma	23.613 N	95.501 E	6.2 mb, 7.1 Ms 7.3 Ms (BRK) 7.0 Ms (PAS)

Depth 20 km. Thirty two buildings and 380 hectares of farmland damaged in the Thabeikkyin area. Some landslides reported. Felt strongly at Mandalay. Felt in much of northwestern Burma from Hkamti to Sittwe. Also felt in the Silchar area, India and Thailand from Chiang Mai to Bangkok.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
31 Jan	23 03 33.6	Hundu Kush Region	35.993 N	70.423 E	6.4 mb 6.6 mb (BRK)

Depth 142 km. Estimated 200-400 people killed, many injured and many homes destroyed or damaged in Kanar, Nangarhar and Badakhshan Provinces, Afghanistan. At least 300 people killed, hundreds injured and several thousand houses damaged in the Malakand-Chitral-Penshawar area, Pakiston. Three people died of heart attacks, severe damage (VII) and landslides occurred in the Kharag area, URRS. Felt (VI) at Ishkashim, Parkhar, Dushanbe, Garm, Dzhirgatal, Lyangara and Gissar; (v) at Shaartuz, Sherkent, Gezan, Leninabad, Tashkent and Namangan; (IV) at Chimkent; (III) at Dzhambul and Frunze, USSR. Felt throughout northeastern Afghanistan, northern Pakistan and northern India as far away as Delhi. Also felt throughout Tajikistan and eastern Uzbekistan, USSR.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
13 Feb	15 49 38.9	France	44.885 N	6.760 E	3.8 ML (LDG) 3.7 ML (GEN) 3.6 MD (STR)

Depth 5 km. Nine people killed by an avalanche which was triggered by the earthquake.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
08 Mar	11 36 28.4	Eastern Siberia	60.904 N	167.023 E	6.4 mb, 6.6 Ms 6.6 Ms (BRK) 6.4 Ms (PAS)

Depth 13 km. Believed to be the largest earthquake ever located in this area.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
05 Apr	04 19 49.5	Northern Peru	5.982 S	77.094 W	6.5 mb, 6.8 Ms 6.7 Ms (BRK) 6.4 Ms (PAS)

Depth 20 km. Two events about 6 seconds apart. Depth based on second event. Fifty three people killed, 252 injured and extensive damage (VII) to 8.063 homes jin the Rioja-Moyabanba-Nueva Cajamarca area. Felt (VI) at Tarapato, (V) at Chiclayo, (IV) at Trujillo and (II) and Lima. Felt throughout northern Peru. Felt (IV) at Guayaquil and (III) at Quito, Ecuador. Felt strongly in much of southern Ecuador.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
18 Apr	09 18 30.4	Afghanistan-USSR Border Region	37.457 N	68.273 E	5.4 mb, 5.1 Ms

Depth 33 km. Several people killed and many injured in Badakhshan Province, Afghanistan. One person killed, 6 injured and about 1,000 buildings damaged (VII) in the Kabodiyen district, USSR. Landslides occurred in the Bagi-Dzhud area. Felt (VI) at Shaartuz, (IV) at Kalkhazabad and Leninskiy and (III) at Dushanbe, USSR.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
22 Apr	21 56 51.8	Costa Rica	9.685 N	83.073 W	7.4 Ms (BRK) 6.9 Ms (PAS)

Depth 10 km. Forty seven people killed, 109 injured, 7,439 homeless and severe damage (IX) in the Liman-Pandora area. Intensity X was observed in some zones of liquefaction within the epicentral area. Some damage (VI) also occurred in the San Jose-Alajuela area and landslides blocked roads between Liman

Table 7 (Cont.)

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude

and central Costa Rica. Twenty eight people killed, 454 injured, 2,400 homeless and 866 buildings destroyed (VII-VIII) in the Guabito-Almirante-Bocas del Toro area, Panama. Slight damage also occurred at David and Puerto Armelles, Panama. Felt (IV) at Colon and Panama City. Felt (III) in eastern El Salvador and (III) at San Salvador. Also felt in Nicaragua and Honduras and on San Andres Island, Colombia. Maximum uplift of 1.4 meters was observed near Limon and Sandblows and liquefaction caused subsidence of soils in the Bocas del Toro area. Ground cracks also occurred in the epicentral area. A 2 meter tsunami with maximim runup of 300 meters was observed in the Cahuita-Peurto Vieja area, Costa Rica. Tsunamis were also reported on Bastimentas, Carenero and Colon Islands and at Portobelo, Panama. The maximum amplitude of the tsunami in Panama was about 0.6 m. A 7 cm tsunami (peak to trough) was recorded on the tide gauge at Cristabal, Panama. Damage in Costa Rica estimated to be about 43 million U.S. dollars.

24 Apr	10 54 35.7	Turkey	39.597 N	41.118 E	4.5 mb

Depth 33 km. One person killed, 3 injured and some houses damaged in Erzurum Province.

29 Apr	09 12 48.1	Western Caucasus	42.453 N	43.673 E	6.2 mb 7.0 Ms 7.3 Ms (BRK) 6.9 Ms (PAS)

Depth 17 km. Two events about three seconds apart. Depth based on second event. At least 114 people killed, about 1,000 injured, 70 missing, 67,000 homeless and severe damage (VIII) and landslides in the Dzhava-Chiatura-Ambralauri area, USSR with 95 percent of buildings destroyed in the area. Felt (VI) in the Kutaisi area; (V) at Leninakan and Tbilisi; (IV) at Kiravakan and Spitak. Felt throughout the western Caucasus and Trans-Caucasus from Sukhumi to Graznyy and Yerevan, USSR. Landslides created a natural dam on the Patas River. This was breached several days later, causing additional damage in the Dzhava-Tskhinvali area. Also felt in Ardahan, Artvin, Kars and Rize Provinces, Turkey.

03 May	20 19 38.8	Western Caucasus	42.683 N	43.247 E	5.3 mb 5.2 Ms

Depth 10 km. At least 3 people killed by landslides in Georgia, USSR.

26 May	10 59 48.9	Kalimantan	5.865 N	116.746 E	5.1 mb 4.5 Ms

Depth 33 km. One person died from shock and there was slight damage at Ranau, Malaysia. Felt at Melapap Kota Kinabulu, Papar and along parts of the west coast of Sabah, Malaysia.

15 Jun	00 59 20.3	Western Caucasus	42.461 N	44.009 E	6.1 mb 6.1 Ms 6.5 Ms (BRK)

Depth 9 km. Two events about 2 seconds apart. Depth based on second event. At least 8 people killed, 200 injured and extensive damage (VIII) in the Dzhava-Tskhinvali area, USSR. Felt (VI) at Kutaisi, Subhumi and Tbilisi and (V) in northwestern Azerbaijan. Landslides occurred at Khieti.

15 Jun	11 15 28.0	Luzon, Philippine Islands	15.119 N	120.355 E	5.7 mb 5.5 Ms

Depth 10 km. Felt at Manila. This is the largest of a series of earthquakes associated with the eruption of Pinatubo Volcano. At least 137 people were killed and extensive damage was caused in Zambales Province by the eruptions.

20 Jun	05 18 52.5	Minahassa Peninsula	1.196 N	122.787 E	6.2 mb 7.0 Ms 7.2 Ms (BRK)

Depth 31 km. At least 1,500 houses were damaged (VI) in the Garantalo area. Felt (IV) in the Manado area and (II) at Paso.

21 Jun	06 27 39.9	El Salvador	13.399 N	89.618 W	5.3 mb

Depth 77 km. One person killed and three injured when a short circuit caused a fire in a home in the San Salvador area. Felt (IV) at San Salvador. Felt lightly in Guatemala City, Guatemala.

Table 7 (Cont.)

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
28 Jun	14 43 54.5	Southern California	34.262 N	118.002 W	5.8 mb 5.1 Ms 5.4 ML (PAS) 5.7 ML (BRK)

Depth 11 km. One person killed at Arcadia and one person died from a heart attack at Glendale. At least 100 people were injured although most involved only minor cuts and bruises. Damage in the Arcadia, Monrovia, Pasadena, San Marino and Sierra Madre areas estimated at 33.5 million dollars. Maximum intensity VII at Arcadia, Monrovia, Pasadena and Sierra Madre. Some rockslides occurred on mountain roads. Felt strongly throughout much of Southern California from Santa Barbara to San Diego and east as far as the Palm Springs-Indio area.

04 Jul	11 43 10.4	Timor	8.099 S	124.681 E	6.2 ms 6.5 Ms

Depth 29 km. Two events about 2.5 seconds apart. Twenty three people killed, 181 injured, at least 5,400 left homeless and about 1,150 buildings destroyed at Kalabahi, Alor. Estimated 7.7 million U.S. dollars damage occurred in the epicentral area. Felt at Dili.

12 Jul	10 42 21.2	Romania	45.364 N	21.057 E	5.3 mb 5.7 Ms 5.3 MD (TTG) 5.3 MD (TRI) 5.2 ML (BRA) 5.0 ML (KRA)

Depth 11 km. At least 2 people killed, 30 injured and some buildings damaged (VIII) in the Banloc-Deta-Timisoara area. Slight damage at Belgrade, Yugoslavia. Felt in Subotica-Nis area, Yugoslavia. Also felt at Sofia, Bulgaria and Szeged, Hungary.

23 Jul	19 44 50.2	Southern Peru	15.679 S	71.574 W	5.0 mb 4.7 Ms

Depth 5 km. At least 12 people killed, 30 injured and about 80 missing in the Maca-Chivay area. Felt (V) at Maca, Yanque, Lchupampa and Achoma. Felt (II) at Arequipa. Landslides occurred in the epicentral area.

24 Jul	09 45 41.8	Iran-Iraq Border Region	36.520 N	44.066E	5.4 mb 5.1 Ms

Depth 26 km. At least 20 people killed, many injured; at least 100 houses destroyed and many damaged in the Arbil-Dibs area, Iraq. felt at Mahabad and Piranshahr, Iran.

17 Aug	22 17 14.6	Off Coast of Northern California	41.821 N	125.397 W	6.2 mb 7.1 Ms 6.8 ML (BRK)

Depth 14 km. Felt (V) at Klamath, Phillipsville, Rio Dell and Trinidad; (IV) at Bridgeville, Fortuna, Myers Flat and Whitethorn. Also felt (V) at Lakeside, North Bend and Pistol River, Oregon; (IV) at Coos Bay, Coquille, Murphy, Reedsport, Rogue River, Roseburg, Sixes and Scottburg, Oregan. Felt as far as Sacramento, California and Eugene, Oregon.

18 Sep	09 48 13.1	Guatemala	14.646 N	90.986 W	5.7 mb 6.1 Ms

Depth 5 km. At least 25 people killed, and extensive damage in the Pachuta-Salala area. Landslides blocked many roads in the epicentral area. Felt (IV) at Guatemala City. Also felt (II) at San Salvador, El Salvador.

14 Oct	15 58 12.7	Solomon Islands	9.094 S	158.442 E	6.3 mb 7.1 Ms 7.0 Ms (BRK)

Depth 23 km. Two events about 10 seconds apart. Felt strongly throughout the Solomon Islands.

Table 7 (Cont'd)

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
19 Oct	21 23 14.3	Northern India	30.780 N	78.774 E	6.5 mb 7.0 Ms 7.0 Ms (BRK)

Depth 10 km. Two events about 1.6 seconds apart. At least 2,000 people killed, more than 1,800 injured and 18,000 buildings destroyed in the Chamoli-Uttarkashi area. Some damage occurred at Chandigarh and New Delhi. Felt in Northern India, Western Nepal and Northeastern Pakistan. Landslides occurred in the epicentral area. A 30 meter deep crack was noted in the Uttarkashi area.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
19 Nov	22 28 51.0	Near West Coast of Colombia	4.554 N	77.442 W	6.4 mb 7.0 Ms 6.8 MD (UVC) 6.4 Ms (BRK)

Depth 21 km. Two people killed and 28 houses damaged in Chaca Department. Minor damage (VI) to buildings in the Buenaventura and Cali areas. Felt strongly in many parts of Western Colombia. Felt (II) at Quito and Guayaauil, Ecuador.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
22 Nov	00 40 23.9	Western Arabian Peninsula	13.887 N	44.068 N	4.7 mb

Depth 10 km. Ten people killed, 39 injured, 17 houses destroyed and 87 damaged in western Yemen.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
28 Nov	17 19 55.5	Western Iran	36.924 N	49.603 E	5.6 mb 5.0 Ms

Depth 16 km. At least one person killed, 70 injured and damage in the Rudbar area. Landslides occurred on the road between Rudbar and Rasht. Felt in other parts of northern Iran and at Tehran.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
22 Dec	08 43 13.4	Kuril Islands	45.533 N	151.021 E	6.3 mb 7.4 Ms 7.3 Ms (BRK)

Depth 25 km. Complex event. Felt.

Date	Origin Time (UTC)	Region	Lat.	Long.	Magnitude
27 Dec	04 05 58.2	South Sandwich Islands	56.032 S	25.266 W	6.2 mb 7.2 Ms 7.1 Ms (BRK)

Depth 10 km. Complex event.

Table 8 Nuclear explosions detected, 1991

Date	*Time UTC*	*magnitude mb*	*Ms*	*Yield kt*	*Lat*	*Long*	*Site**	*Source*	*Comments*
03 08	210245.0	4.3			37.104N	116.074W	NTS	PDE	"coso"
04 04	190000.0	5.6	4.2		37.296N	116.313W	NTS	PDE	"bexar"
04 16	152959.3	5.4			37.245N	116.442W	NTS	PDE	"montello"
05 07	170000.0	4.1		0 - 10			Mur	ASAR	
05 18	171458.2	5.1			21.886S	139.013W	Mur	PDE	
05 29	185958.0	5.5			22.267S	138.766W	Mur	PDE	
06 14	175956.7	4.8		10 - 40			Mur	ASAR	
07 05	180000.0	3.8		0 -0.5			Mur	NZ	
07 15	180958.3	5.3			21.877S	138.963W	Mur	PDE	
08 15	155959.2	4.4		0 - 20	37.082N	116.015W	NTS	PDE	"floydata"
09 14	190000.0	5.5	4.2		37.226N	116.226W	NTS	PDE.	"hoya"
09 19	163000.6	4.0			37.236N	116.166W	NTS	PDE.	"distant zenith"
10 18	191200.0	5.2			37.063N	116.045W	NTS	PDE	"lubbock"
11 26	183500.0	4.6		0 - 20	37.096N	116.070W	NTS	PDE	"bristol"

Site:
* NTS Nevada Test Site, USA; Mur/Fan Mururoa/Fangataufa, French Polynesia; Ekaz East Kazakhstan, USSR; LopN Lop Nor China; NovZ Novaya Zemlya, Russia;

Source:
¤ PDE Preliminary Determination of epicentres, USA; USAEC United States Atomic Energy Commission; ASAR Alice Springs Array, Australia; WRA Warramunga Array, Australia.

§ not recorded in Australia.

Table 9. Yield versus magnitude for underground nuclear explosions

Magnitude mb Test site: Nevada	*Magnitude mb* Test site: Other	*Yield ktons*
0.0 - 4.5	0.0 - 4.8	< 10
4.6 - 4.8	4.9 - 5.1	5 - 20
4.9 - 5.0	5.2 - 5.4	10 - 40
5.1 - 5.3	5.5 - 5.7	20 - 80
5.4 - 5.6	5.8 - 6.0	40 - 150
> 5.6	> 6.0	>80