Australian Seismological Report - 1999

Compiled by

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Earthquake-buckled railway near Meckering WA, 1968 (photo by Alice Snooke)

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INTRODUCTION

This report follows the style of the annual seismological reports published by BMR/AGSO since 1980. Its purposes are to contribute to the reduction in earthquake risk faced by the Australian community, and to provide information on Australian and world earthquakes for scientists, engineers and the general public.

Based on the history of Australian earthquakes of the last 100 years, we expect two earthquakes of at least magnitude 5.0 in Australia each year, large enough to cause minor structural damage. We expect a large earthquake of magnitude 6 or more to occur somewhere in Australia every 5 years or so on average, the last one in 1997 was in northwest Western Australia. Large and even moderate-sized intraplate earthquakes may pose a serious threat to life and property as was so tragically demonstrated by the moderate sized earthquake magnitude 5.6 near Newcastle in 1989. Analysis of the small earthquakes will yield clues to the cause, location and style of future large ones.

The report has six main sections: the **Australian region earthquakes** section contains a summary of the 1999 seismicity with a State by State breakdown and a brief description of the more important earthquakes; **Isoseismal maps** describing those that were widely felt; **Accelerograph data** which tabulates recordings from the strong motion network; **Network operations** which gives details of the seismographs that operated in Australia during the year; and **Principal world earthquakes** which lists the largest and most damaging earthquakes that took place world-wide during 1999.

In this report we refer to the *magnitude* of an earthquake and *intensity* caused by an earthquake. These terms and others used in the report are defined in an appendix.

AUSTRALIAN REGION EARTHQUAKES, 1999

The 76 earthquakes of magnitude ML 3 or more recorded in 1999 on AGSO's National Seismographic Network and State and regional networks are listed in Table 1 and plotted in Figure 1. Twelve of these earthquakes had a magnitude of at least ML 4. Some of the 1999 earthquakes near the major urban areas triggered the Urban Monitoring network of accelerographs.

There were no deaths or injuries and only minor non-structural damage attributable to earthquakes in Australia during the year. The largest earthquake in Australia in 1999, a magnitude 5.1 aftershock of the 1988 sequence near Tennant Creek in the Northern Territory was below the average annual maximum magnitude of 5.3 to 5.5.

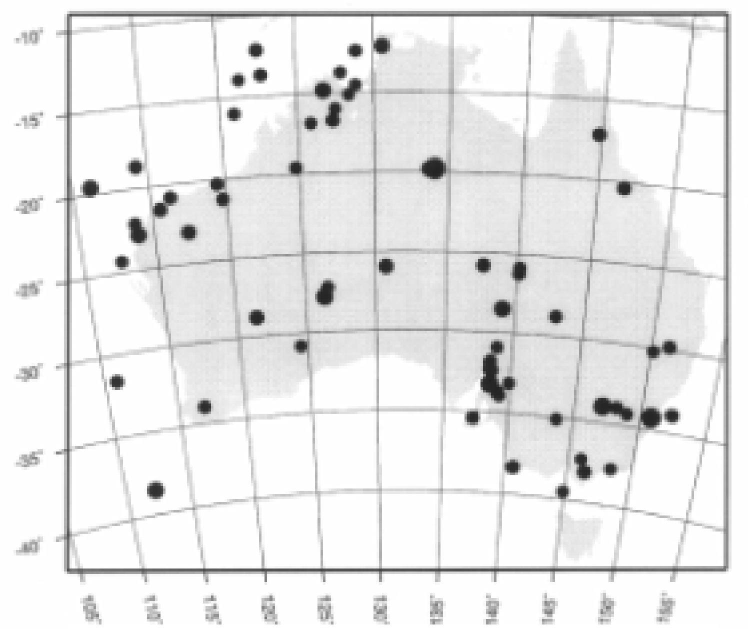


Figure 1 Australian epicentres 1999, M≥3

In Figure 2 below we have plotted the cumulative number of earthquakes in 1999 versus magnitude as points (crosses) on the best fit bi-linear recurrence relation to the mean annual cumulative number of past events. In deriving the long-term average rate of earthquake occurrence different time periods were used for selected magnitude ranges depending on the capacity of the monitoring networks at the time to record complete datasets (M≥4 since 1980, M≥5 since 1965 and M≥6.0 since 1900). The recording time period is too short and the paleoseismological record too scant to give any indication of a maximum magnitude should there be such a limit on earthquake size.

The largest recorded Australian earthquake was the magnitude Ms 7.2 event in 1906 off the WA coast. None of the known Recent fault scarps is indicative of a larger event though there are many known apparently older faults capable of generating a larger earthquake.

The year's seismicity was below average throughout the observed magnitude range as it was the previous year. The slope or ‘b’ value at low magnitudes parallels the average long-term trend but at a lower frequency of occurrence.

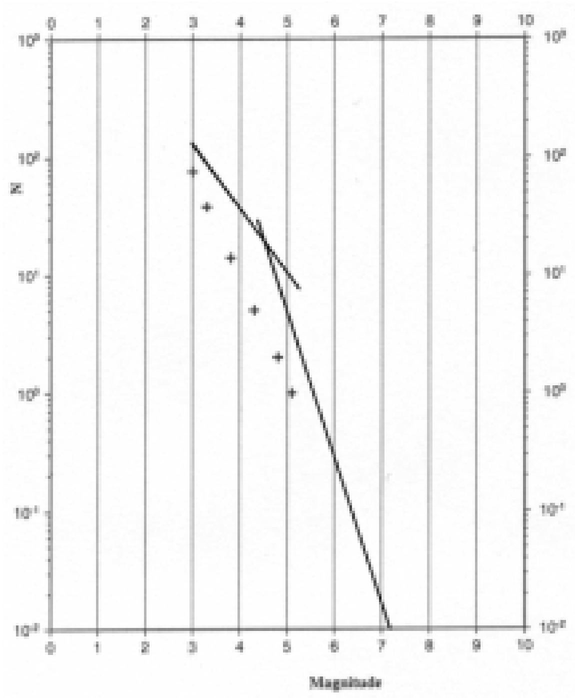


Figure 2 The cumulative number of earthquakes in 1999 plotted against magnitude ML (the crosses) superimposed on the best fit annual cumulative plot for the 20th century. The N(0) and b values for each segment are (3.77, -0.55) and (6.96, -1.25).

Kevin McCue and Cvetan Sinadinovski

Western Australia

One hundred and sixty earthquakes were located in the region of Western Australia in 1999, 30% fewer than the previous year. The largest with a magnitude of ML 4.2 occurred on 18 January 185 km S of Warburton in Zone 5 of Gaull, Michael-Leiba and Rynn's (1990) zoning scheme.

There were five earthquakes of magnitude ML 4.0 or greater located 105 km S of Exmouth (ML 4.0), 400 km NW of Exmouth (ML 4.0), 690 km S of Albany (ML 4.0) and 60 km S of Kalumburu (ML 4.0). There were a further 34 earthquakes of magnitude ML 3 or greater. Fifteen of these were offshore and the rest were scattered throughout Western Australia.

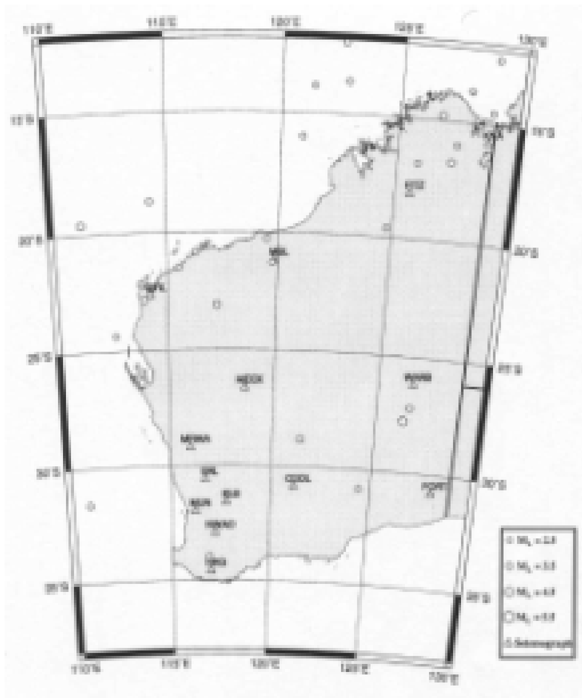


Figure 3 WA epicentres 1999, ML≥2.5

Eighty two earthquakes were located in the Southwest Seismic Zone, about half the number located in 1998. The largest, magnitude at magnitude ML 3.2, was located 25 km SW of Kojonup. Yorkrakine, 18 km N of Kellerberrin continued to be the most active area with 16 earthquakes, although the largest was a minor magnitude ML 2.6. Nine earthquakes were located near Meckering. The remainder were scattered throughout the zone - Kalannie (6), Miling (1), Cadoux/Manmanning (7), Burakin (2), Moora (1), Wongan Hills (2), Wyalkatchem (8), Mukinbudin (2), Bonnie Rock (1), Bencubbin (4), Quairading (2), Northam (1), Wooroloo (3), Corrigin (1), Beverley (1), Boddington (1), Darkan (3), Tambellup (2), Kojonup (5), Cranbrook (2) and Walpole (3).

Off-shore (Zones 3 and 4) Twelve earthquakes were located in Zone 3, located offshore between Geraldton and north of Dampier. The largest, magnitude ML 4.0 occurred on 25 June and was located 105 km S of Exmouth. It was felt at Bullara and Ningaloo Stations and Coral Bay.

Four earthquakes, magnitudes ML 2.0, 2.6, 3.3 and 3.0 were located 115 km, 465 km, 475 km and 995 km W of Perth. There were two other earthquakes in Zone 4, one with magnitude

ML 4.0 located 400 km NW Exmouth. Two earthquakes were located near Ashmore Reef on the northern extension of Zone 4.

South-east (Zone 5) Eight earthquakes were located in this zone with another one just to the north-west of the zone about9 km NE Leonora (ML 3.0). The largest event was a magnitude ML 4.2 located 105 km S of Warburton on 21 January. Two events were located near the Bounty Gold Mine.

Carnarvon Basin (Zone 8) Seven earthquakes were located in this zone. The largest had a magnitude ML 3.6 and was located 45 km WNW of Paraburdoo.

Canning Basin (Zone 9) The largest of three earthquakes, magnitude ML 3.0 was located 70 km E of Marble Bar.

Tobin Lake (Zone 10A) There were no earthquakes in the Tobin Lake Region.

Offshore north west (Zone 11) Four earthquakes were located in this zone.

Halls Creek Mobile Belt (Zone 14) Nine earthquakes were located in this zone, the largest with magnitude ML 4.0 occurred on 2 December and was located 60 km south of Kalumburu. Several small earthquakes were located about 100 km offshore north of Wyndham.

Earthquake Swarm

Kellerberrin (Yorkrakine) This swarm which commenced in 1997 continued through the year though there were only 16 earthquakes in the area, the largest of them magnitude ML 2.6.

Peter Gregson and Kevin McCue

Northern Territory

The largest Australian earthquake in 1999 was that near Tennant Ck NT on 15 April, its magnitude ML5.1. The shaking was felt strongly in the town about 40 km east of the epicentre and at a similar distance to the west, despite the time of day, near midday when the noise level is high. The epicentre was on the Eastern Lake Surprise Fault which consists of a series of en-echelon fault segments formed in 1988. Opposite is a focal mechanism with particularly tight control on azimuth and dip of both nodal planes. The east-west plane bisects the northern (blue) arm of the nearby Warramunga seismic array. Nodal plane and stress axes descriptors are summarised in Table 4. The east-west nodal plane dips to the north and parallels the trend of the en-echelon fault segments but dips in the opposite direction.

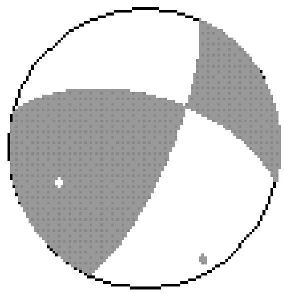


Figure 4 Mechanism of the Tennant Ck NT earthquake, ML 5.1, 15 April 1999

Table 4 Focal mechanism solution - Tennant Ck earthquake

	strike	*dip*	*Slip dirn*
Nodal plane #1	024	61	196
Nodal plane #2	105	76	294
P- axis	337	10	-

This earthquake was the second of nine aftershocks near Tennant Ck in the year, all of which had magnitudes of 3 or more and this one was the largest for several years.

The other two notable NT earthquakes were those near Uluru on 14 August, magnitude 3.6, and north-east of Darwin between Melville Island and the mainland on 12 November, magnitude 3.9. This small local earthquake was felt throughout Darwin and was enthusiastically reported so an isoseismal map was drawn up. A number of such earthquakes have been recorded in the Darwin area in recent years which seems to be something new, a change in the seismicity pattern over the last 25 years since a local seismograph was installed.

Kevin McCue

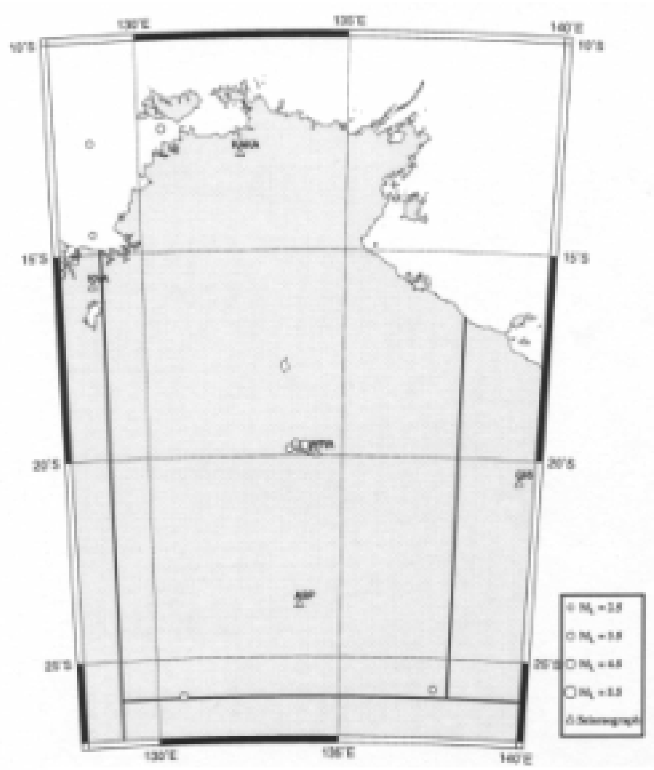
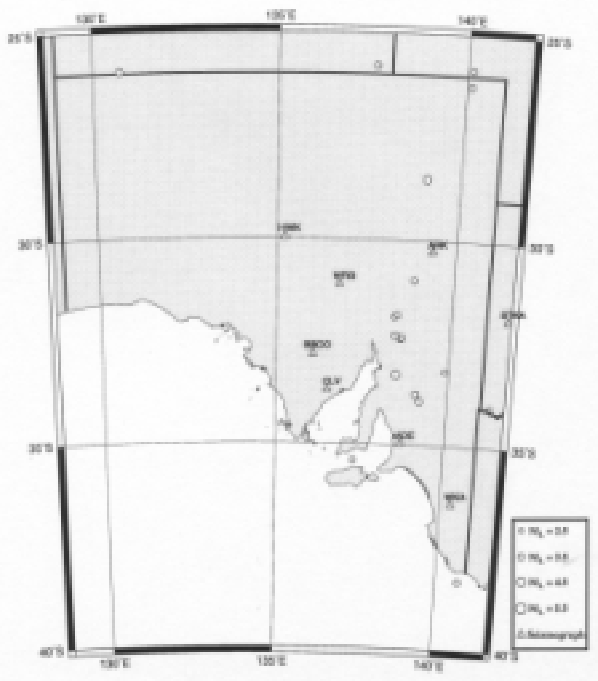


Figure 5 Epicentres in the Northern Territory 1999 ML ≥2.5

South Australia

This was a year of relatively low seismicity (Love, 1999). Only 154 events were located in the state, well down on the number before 1996. There were however 14 events over magnitude 3 which is about normal. Twenty eight of the events were reported felt, a number of these near Carrieton.

Activity occurred in the usual areas: Adelaide Fold Belt, Eyre Peninsula and the South East. There was one unusual event in the north-east of the state, a magnitude 4.0 event near Mulka Homestead. In the South East, there was a magnitude 3.3 event south of Port McDonnell on 6 February that appears to be unusually deep at around 35 to 40 km near the crust/mantle boundary. Any association with the Recent volcanoes of Mt Gambier and Mt Schank is conjectural at this stage. After a break of over a year, some activity occurred near the epicentral region of the1997 Burra event. Two portable instruments were established in the area and recorded a few more events, but nothing large. Following the largest event of the year, a magnitude 4.1 earthquake near Gladstone, portable recorders were again placed in the epicentral area, but little follow-up activity occurred.



David Love

Figure 6 Epicentres in South Australia 1999 ML 2.5

Victorian and Tasmanian Earthquakes

On 13 January at 0840 PM EDST an earthquake of magnitude ML 3.7 occurred about 11 km northeast of Moe, and 123 km east of Melbourne. The earthquake was felt throughout the Latrobe Valley and the outer eastern suburbs of Melbourne. No damage reports were received. The depth of this event was about 12 kilometres. This earthquake almost certainly occurred on the Yallourn fault, the same fault that was responsible for the magnitude ML 5.0 Thomson reservoir earthquake of September 1996. The Yallourn fault defines the northern boundary of the Latrobe Valley and may be capable of generating earthquakes up to magnitude M 7.5.

On Saturday 27 March at 08:20 am EDST an earthquake of magnitude ML 2.1 occurred under Maldon, 16 km NW of Castlemaine in central Victoria, about 120 km NW of Melbourne. The earthquake was felt in Maldon and was preceded by a foreshock of magnitude ML 1.6 at 08:07 am which was also felt in Maldon. The series of events continued on Monday, March 29 at 03:48 am with an event of magnitude ML 1.5, also felt in Maldon.

An earthquake of magnitude ML 1.8 near Yarra Junction on July 8 at 0944 UTC was felt at Mt Evelyn and Lilydale. On Friday 20 August at 03:10 am AEST a magnitude ML 2.2 earthquake occurred about 1 km north of Epping in the outer northern suburbs of Melbourne. It occurred at a very shallow depth of about 2 kilometres. Although the magnitude was small, it was strongly felt in the epicentral area. Many residents of the suburbs of Mill Park and South Morang were woken by the earthquake.

On 9 October at 0817 UTC an earthquake of magnitude ML3.0 near Orbost in north-eastern Victoria was felt in the Orbost region. On Sunday 31 October at 16:40 AEDT a small earthquake of magnitude ML 2.0 occurred at a depth of about 10 km under Belgrave in the Dandenong Ranges, about 35 km east of Melbourne. It was felt and heard in the epicentral area, and was reported by many as being similar to a loud nearby explosion. Reports were received from Selby, Ferntree Gully and Rowville. It is likely that this was another event on the Selwyn Fault.

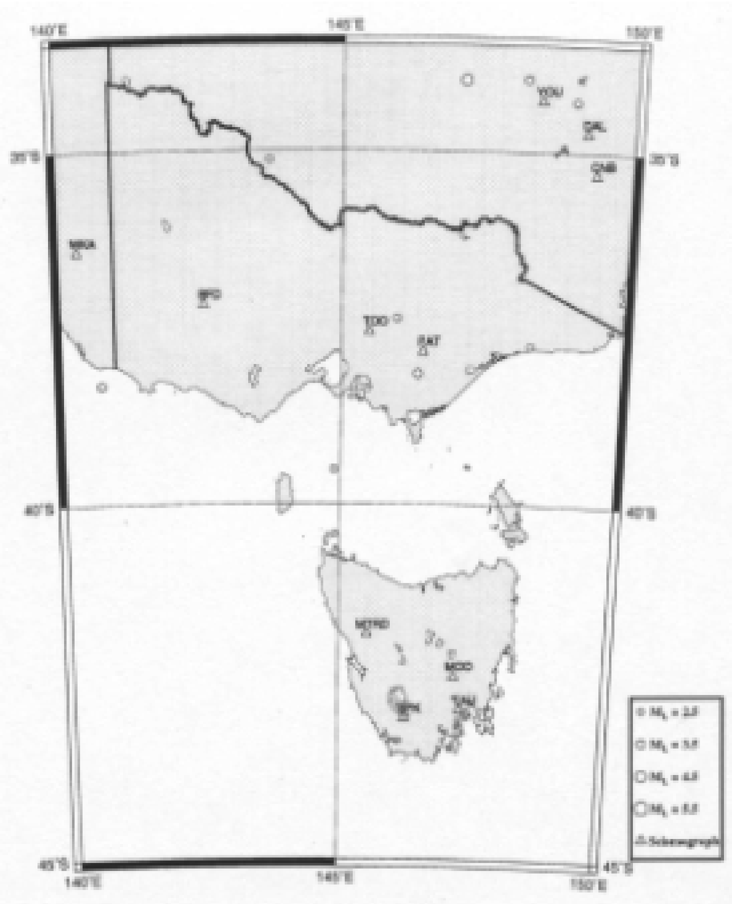


Figure 7 Epicentres in Victoria and Tasmania in 1999, ML≥2.5

The township of Moe in eastern Victoria was hit by a magnitude 3.5 earthquake on 13 January and while there was no damage the town was strongly shaken. Reports were also received from as far as the eastern suburbs of Melbourne that the earthquake was felt there. This was the largest earthquake of the year in Victoria.

Tasmania was even quieter with no earthquakes of magnitude 3 or more.

Wayne Peck, Vaughan Wesson and Gary Gibson

New South Wales and ACT

A magnitude ML 4.8 earthquake about 7 kilometres southwest of Appin (between Sydney and Woollongong) at lunchtime on 17 March, shook a large area of south-eastern NSW and was felt throughout the metropolitan area of Sydney. The earthquake tripped electrical circuit breakers causing loss of power supply to over 1000 homes. Reports were received of minor damage within the epicentral region so an intensity survey was undertaken. Additional reports were received via the SRC web page. No foreshocks or aftershocks were recorded.

This earthquake generated the biggest set of accelerograms ever recorded in Australia and in the Sydney Basin, an important region with a high population density and extensive infrastructure network including dams, LNG storage facility and a nuclear research reactor. Four of the instruments were installed under the Joint Urban Monitoring Program, the remaining accelerographs installed on or near large dams by the water authorities and on the research reactor facility.

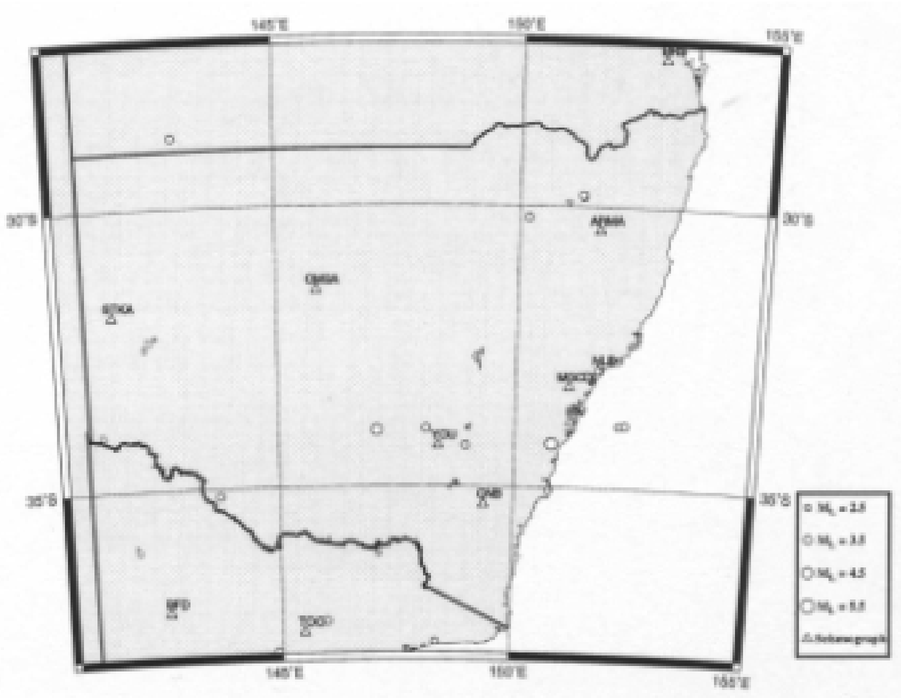


Figure 8 NSW epicentres 1999, ML ≥ 2.5

Because of the dense seismograph and accelerograph network in the southern Sydney Basin the focal depth of this earthquake was well constrained at 8 ± 2 km, near but probably below the base of the Sydney Basin sediments. AGSO and SRC seismologists each separately compiled a focal mechanism from first motions but they are so different that the solutions are not published here.

Other small earthquakes near Grenfell on 5 March with magnitude 2.8 and near West Wyalong on 14 March with magnitude 4.4 were also widely enough felt that isoseismal maps could be prepared. An earthquake of magnitude ML 3.0 occurred on Tuesday 27 April at 07:14 am EST. This earthquake was located between Glen Innes and Inverell, about 150 km north of Tamworth in northern New South Wales. It was felt most strongly in Gilgai and Tingha, and was also reported felt in Inverell. It was followed by an event of magnitude ML 2.8 twelve minutes later, as well as another aftershock of magnitude ML 1.3 at 11:41 am EST.

An earthquake of magnitude ML 1.9 at Eugowra east of Forbes on 6 June at 08:08 pm AEST was widely felt within the town. In August 1994 this small town experienced an earthquake swarm with several hundred events being felt.

On 30 July an earthquake of magnitude ML 2.0 occurred in Kanimbla Valley in the Blue Mountains region of New South Wales, about 110 km west of Sydney. The earthquake woke many people in Lithgow and was also reported felt in Oberon.

Earthquakes in urban areas generate a lot of local interest and one example was the north Canberra earthquake of 21 June, too small to cause damage but apparently an unwelcome surprise to the local population.

An earthquake of magnitude ML 2.5 that occurred near Bowral, south of Sydney was felt on 29 September.

Two earthquakes in the Tasman Sea east of the Sydney/Newcastle region were recorded on 18 August . These events were near the eastern edge of the Sydney Basin, too far offshore to be felt.

Kevin McCue and Wayne Peck

Queensland

The three earthquakes tabulated below were widely felt but following the funding review and eventual cessation of monitoring at the University of Queensland in 1999 no further investigation was made of these earthquakes.

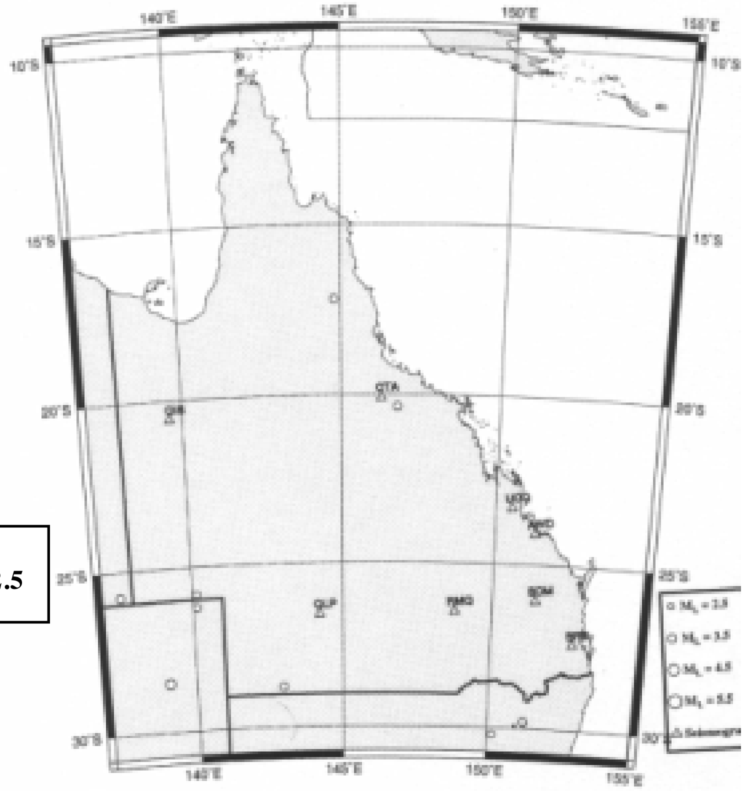


Figure 9 Queensland epicentres, 1999, ML ≥ 2.5

Date	*Time*	*Long E*	*Lat S*	*ML*	*Place*	*Comment*
1999-02-11	1245	144.797	17.181	3.4	Chillagoe	Limited reports
1999-03-25	1226	146.797	20.247	3.4	Mt Glenroy	Felt Ravenswood, Mingela and St Pauls
1999-04-24	??	146.966	20.159	2.7	Ravenswood	Felt Ravenswood

Russell Cuthbertson

NETWORK OPERATIONS 1999

Western Australia The Narrogin station (NWAO) is an IRIS (Incorporated Research Institutions for Seismology) station. A Guralp 3 component broad-band borehole seismometer was installed down the borehole 2 metres from the top on 08 March 1999.

Ballidu (BAL/BLDU) The station was destroyed in a house fire on 14 September. A new upgraded station transmitting digital data to Canberra via Telstra circuits was opened on 11 October at a new location nearby.

Kalgoorlie (KLG) With the demise of Woolibar the old KLG site was re-occupied on 23 January using the Woolibar seismometer.

Kellerberrin (KLB/KLBR) A new digital station was established on 1 November 1999 close by the old location with data being transmitted to Canberra via Telstra circuits. The old analogue station was closed on 10 February 2000.

Morawa (MRWA/MORW) The station was upgraded and digital data transmitted to Canberra via Telstra circuits from 7 October 1999. The seismometer was moved about 5 km to a quieter site.

Rocky Gully (RKG/RKGY) A new digital station was established on 25 November 1999 close by with data being transmitted to Canberra via Telstra circuits. The old analogue station was closed on 24 January 2000.

South Australia No changes occurred in the South Australian network, although the important station at Partacoona (PNA) was closed for about three months.

Eastern Australia No significant changes occurred in the Eastern Australian network.

Russell Cuthbertson, Peter Gregson, David Love, Kevin McCue and Wayne Peck

ACCELEROGRAPH DATA

In Western Australia and the Northern Territory

As part of an Australia-wide urban monitoring program two accelerographs were operated in Perth at the East Perth Power Station (EPS) and Kings Park (KPK). The sites were chosen to monitor the response of differing soil foundations, as part of an Australia wide urban monitoring program.

Two plate boundary earthquakes triggered the accelerographs in Darwin but the interesting event was the small local magnitude ML 3.9 on 12 November for which an isoseismal map was constructed and which triggered the rock store accelerograph DRS.

In Eastern Australia

Several interesting accelerograms were recorded in south-eastern Australia during the year as listed in Table 3. Some of these were free field recordings, mostly on JUMP recorders others in structures such as the Black Mountain Tower ACT, at the Inlet Tower at Googong Dam and Lucas Heights research reactor in NSW. There were more strong motion records collected during the March Appin NSW earthquake than in any other single event in Australia. A sample recording at Avon is shown below with strong body and surface waves.

A preliminary analysis of pga recorded in SE Australia by Brown and others (2001) includes their plot for magnitude 5.1 earthquakes shown above with the Sadigh (1997) predicted pga (lower solid line) for the western USA on rock. The agreement is surprisingly good given the difference in tectonic setting, at least over the distance range of recordings. The wide scatter is typical of all tectonic settings where there are many more data

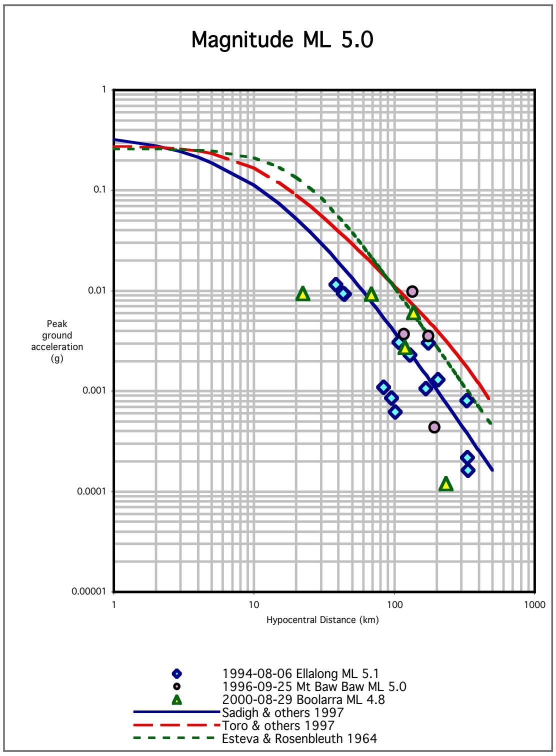


Figure 10 Attenaution in Eastern Australia

P Gregson, K McCue, G Gibson and W Peck

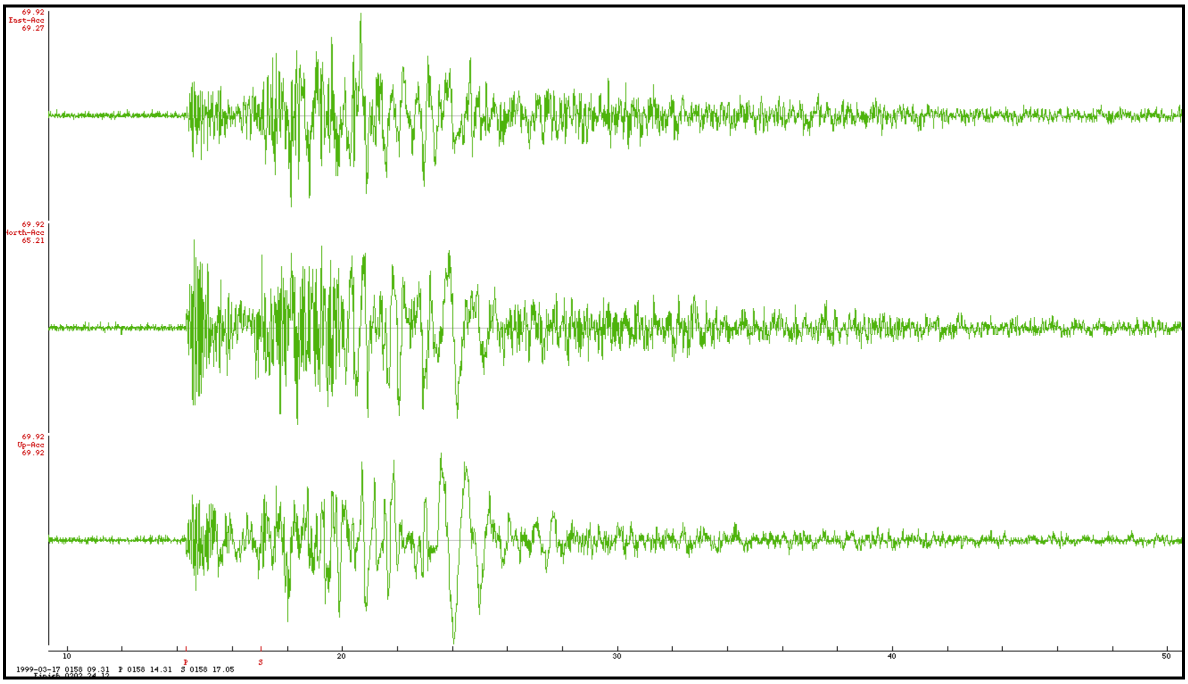
In South Australia

JUMP instruments recorded a number of accelerograms including several from the following earthquakes:

- 6 August at Melrose, magnitude 3.0, recorded at NAP and PTP.
- 18 August at Gladstone magnitude 4.1, recorded at NAP, PTP, WHY and TUK.
- 15 November in Investigator Strait, magnitude 3.3, recorded at GHS and TUK.

David Love

Figure 11 Accelerogram of the Appin NSW earthquake in March. The lower trace is the vertical axis. pga ~ 2.1mm/s^2



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: Brisbane 12:07 pm, Melbourne 11:45 am, Hobart 11:45 am, Adelaide 11:10 am, Perth 9:39 am, 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; Luck, 1991).

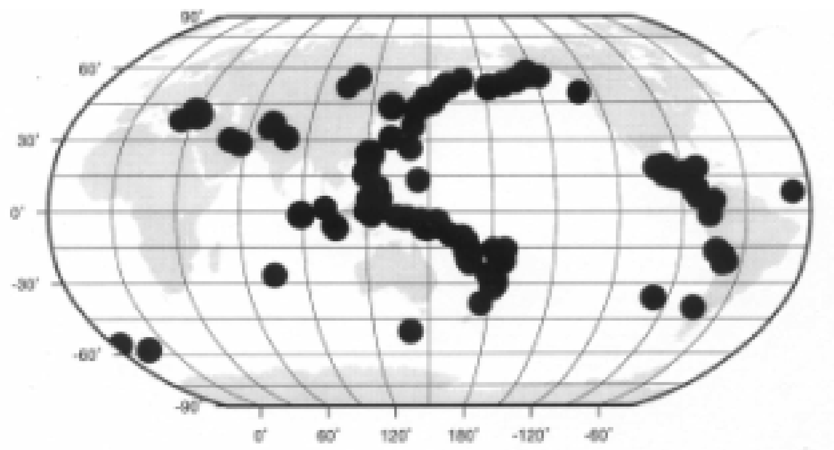
AGSO converted from Omega to GPS recording of time signals to correct the station clocks following the announcement of the closure in 1997 of the Omega station near Sale in Victoria.

PRINCIPAL WORLD EARTHQUAKES and TSUNAMIS, 1999

Table 5 lists earthquakes that occurred throughout the world in 1999 of magnitude 7.0 or greater, or that caused fatalities or substantial damage. The data were extracted from the AGSO database compiled from the USGS list of world earthquakes (NEIC, 1999) and are plotted in the Figure below. The death toll was very high, almost double the average of 10,000 earthquake casualties per year in the 20th century.

Paradoxically there were fewer earthquakes than in an average year, no great earthquake of magnitude 8 or greater and only 10 shallow major earthquakes of magnitude 7 or more. The year started badly when a large shallow earthquake struck the populated western Colombia region of Armenia and Pereira on 25 January. Un-reinforced masonry buildings and buildings on unstable slopes bore the brunt of the damage and their collapse caused the death-toll of more than 880 residents.

The New Zealand Society for Earhquake Engineering (NZSEE) sent two earthquake engineers to inspect and report back on the earthquake, the ground motion and the causes of damage, and any lessons applicable for New Zealand. Lessons learned will eventually be incorporated into the joint Australian-New Zealand Loading Code.



A major magnitude 7.7 earthquake on the western end of the North Anatolian fault in western Turkey near Izmit resulted in 15 000 deaths and 33 000 injuries. Non-compliance with building codes and town-planning regulations was blamed for the collapse of so many buildings. A new motorway linking Istanbul and Ankara suffered serious damage as did port facilities and an important oil storage farm, the strong shaking greatly exceeded the design earthquake. A second major earthquake in November on the Anatolian Fault east of the August surface rupture caused further misery and despair with another 600 fatalities and more than 3000 further injuries.

On 20 September, Taiwan was shattered by the year's second equal largest earthquake, magnitude 7.7. A major surface fault caused dramatic damage to a concrete gravity dam and bridge whilst several otherwise well built buildings tilted or even fell right over when the foundations failed during strong shaking. More than 2400 people died in this earthquake which is one measure of the effectiveness of applying building codes compared with the loss of life in Turkey.

In Vanuatu a similar-sized earthquake on 26 November did not cause a national disaster because of the comparative lack of population and infrastructure but a 6m+ tsunami was generated which caused additional damage and loss of life. A sea frame tide gauge operated by the National Tidal Facility at Flinders University recorded several waves with an amplitude approaching 1m in the first half hour of the wave train. The tsunami had almost dispersed by the time it hit the Australian coast where tide gauges showed the only evidence of its passing.

Information including annual reports on tsunamis can be obtained from the ITIC homepage at: http://www.shoa.cl/oceano/itic/frontpage.html.

Kevin McCue

REFERENCES

Ambraseys, N.N., and Free, M. W., 1997 — Surface-wave magnitude calibration for European region earthquakes. Journal of Earthquake Engineering, **1** (1), 1 - 22.

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.

Brown, A., Gibson., G., Sinadinovski C. & McCue, K. 2001 — Measurements of PGA and attenuation in south-eastern Australia. *NZSEE*, 2001 Conference, Wairakei NZ.

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., 1977 — Preliminary catalogue of tsunamis for the New Guinea/Solomon Islands region, 1768-1972. BMR Report 180.

Everingham, I.B., McEwin, A.J., & Denham, D., 1982 — Atlas of isoseismal maps of Australian earthquakes. *Bureau of Mineral Resources, Australia*, *Bulletin* **214**.

Fredrich, J., McCaffrey, R., and Denham, D., 1988 – Source parameters of seven large earthquakes determined by body wave inversion. *Geophysical Journal*, **95**, 1 – 13.

Gaull, B, Michael-Leiba, M.O., and Rynn, J.A.W. 1990 — Probabilistic Earthquake Risk Maps of Australia. Aust. J Earth Sciences, 37, 169 - 187.

Geist, E.L., 2000 — Origin of the 17 July 1998 Papua New Guinea Tsunami: Earthquake or Landslide. Seismological Research Letters, 71, 3, 344 – 350.

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.

Gutenberg, B., 1945 — Amplitudes of P, PP and SS, and magnitudes of shallow earthquakes. *Bulletin of the Seismological Society of America*, **35**, 57-69.

Kanamori, H., 1978 — Quantification of earthquakes. *Nature*, **271**, 411-414.

Love, D 1999. — Recent earthquakes in South Australia, MESA Journal v13.

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., 1995 — (Compiler) Atlas of isoseismal maps of Australian earthquakes, part 3. *Australian Geological Survey Organisation,* Record 1995/44.

McCue, K.F., Boreham, B., Van Dissen, R., Gibson, G., Jensen, V., and McKavanagh, B., 1996 — A Paleoseismology Case Study: the Lake Edgar Fault Scarp in Tasmania, in Proceedings of the 13th AGC, Canberra, 19-23 February 1996, GSA Abstracts 41, Geoscience for the Community.

McCue K.F., & Gregson, P.J., 1997 — Australian Seismological Report, 1995. AGSO Record 1997/62.

McCue K.F., Gregson, P.J., & Sinadinovski, C., 1999 — Australian Seismological Report, 1996. AGSO Record 1999/08.

McGregor, P.M., & Ripper, I.D., 1976 — Notes on earthquake magnitude scales. *Bureau of Mineral Resources, Australia*, *Record* 1976/76.

Mountford, H., Love, D., and Sinadinovski, C., 1997 — The Burra ML 5.1 earthquake. **in** Earthquakes in Australian Cities - Can we ignore the risks? Proceedings of the Australian Earthquake Engineering Society Seminar, Brisbane, 2-3 October 1997.

NBS 1972 — NBS frequency and time broadcast services. Ed P. P. Viezbicke, Special publication 236, US Department of Commerce, Boulder, Colorado.

NEIC 1997 — Quick Epicentre Determinations and Preliminary Determination of Epicentres.

Richter, C.F., 1958 — Elementary Seismology. *Freeman & Company, San Francisco*.

Ripper and Letz, 1999 — The Sissano lagoon (Aitape) tsunami: which earthquake was responsible? PNGGS Report 99/7.

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 1997 — *Scientific Event Network Bulletin*, *Smithsonian Institution, Washington, USA*.

Tsunami Newsletter 1997 — International Tsunami Information Centre, Vol XXX, 1997.

Van Dissen, R., McCue, K.F., Gibson, G., Jensen, V., Somerville, M., Boreham, B., McKavanagh, B., and Goede, A., 1997 — The Lake Edgar Fault: Evidence for Repeated Quaternary Dispalcement on an Active Fault in Southwest Tasmania. in Proceedings of the Seminar 'Earthquakes in Australian Cities - can we ignore the risks?' Australian Earthquake Engineering Society, Brisbane 2-3 Oct 1997.

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**.

Table 1 Australian earthquakes 1999, magnitude ML ≥ 3.0

Source	Date	UTC	Lat	Long	Depth	ML	Location
MUN	19990112	30822.5	-27.749	126.316	5	3.7	Warburton WA, 181 km S
SRC	19990113	94000.2	-38.161	146.374	0	3.5	Moe Vic. Felt. This earth-quake was felt at Moe and other towns near the epicentre where shaking lasted 3 or 4 seconds and houses shook strongly though there was no serious damage. It was felt as far as the eastern suburbs of Melbourne.
MUN	19990118	145042.3	-27.779	126.339	5	4.2	Warburton, 184 km S
MUN	19990122	723.1	-33.97	116.936	1	3.2	Kojonup, 25 km SW
ADE	19990122	151543.8	-33.761	139.084	10	3.5	Burra SA. Felt
MUN	19990123	44110.3	-19.595	111.212	5	4.0	Exmouth, 398 km NW
MUN	19990123	225614.3	-21.464	115.553	5	3.4	Onslow, 48 km ENE
AUST	19990126	53655.3	-33.924	139.201	8	3.2	Eudunda area, SA. Felt
AUST	19990202	235913.5	-26.241	140.122	0	3.2	Haddon Corner, SA
ADE	19990206	50729.1	-38.319	140.703	46	3.4	Near Mt. Gambier, SA
AUST	19990211	124524.3	-17.181	144.797	0	3.4	Chillagoe, Qld. Felt
AUST	19990221	65136.5	-28.767	142.962	0	3.3	Near Bulloo Downs Homestead, Qld
AUST	19990301	12852.7	-25.8	137.594	0	3.5	Pangunna Lake NT
MUN	19990305	34626.9	-18.689	114.281	5	3.5	Dampier, 335 km NW
MUN	19990306	153028.1	-23.069	117.269	5	3.6	Paraburdoo, 44 km WNW
AUST	19990306	235440.9	-28.506	139.072	5	4.1	Near Mungeranie Homestead, SA
AUST	19990310	637.6	-33.975	148.124	3	3.2	Grenfell NSW. Felt
AUST	19990314	1331.8	-34.001	147.077	2	4.4	West Wyalong, NSW. Felt
SRC	19990317	15810.6	-34.234	150.77	8	4.8	Appin NSW. Minor damage and felt widely throughout the Sydney area. Isoseismal map and several accelero-grams recorded.
AUST	19990317	72120.2	-30.979	138.871	0	3.1	Blinman SA
MUN	19990322	12222.5	-16.692	127.312	5	3.5	Warmun, 104 km WNW
AUST	19990325	122608.8	-20.359	146.755	0	3.4	Ravenswood, Qld. Felt
MUN	19990327	220927.4	-30.832	124.441	5	3.0	Zanthus, 86 km ENE
MUN	19990329	151249.3	-15.126	128.375	5	3.0	Kununurra, 80 km NW
MUN	19990401	223942.9	-15.984	120.917	5	3.1	Broome, 260 km NNW
AUST	19990402	63649.6	-19.832	133.944	0	3.1	Tennant Creek NT
MUN	19990404	94824.6	-12.367	128.867	5	3.2	Darwin, 215 km W
MUN	19990410	222754.6	-19.621	124.752	5	3.2	Fitzroy Cr, 183 km SSW
AUST	19990411	204111.6	-19.893	134.123	6	3.0	Tennant Creek NT
AUST	19990415	45552.6	-19.791	134.044	6	**5.1**	Tennant Creek NT. Felt in Tennant Creek and White Devil Mine (50 km W of Tennant Creek)
SRC	19990416	105121.1	-37.379	145.983	0	3.1	Lake Mountain, Vic
MUN	19990418	214314.9	-13.679	122.766	5	3.2	Scott Reef, 107 km ENE
AUST	19990426	211436.7	-29.823	151.266	0	3.3	Tingha NSW. Felt
AUST	19990426	212656.5	-29.803	151.256	0	3.2	Tingha NSW
AUST	19990501	181155.1	-19.826	134.046	0	4.0	Tennant Creek NT. Felt
MUN	19990502	155915.5	-20.82	116.3	5	3.2	Near Dampier WA
AUST	19990510	100225.7	-19.754	134.017	14	4.6	Tennant Creek NT
MUN	19990519	233121.5	-13.73	127.88	5	3.0	200 km North of Wyndham WA
AUST	19990525	4421.4	-30.21	150.175	0	3.1	Boggabri NSW
AUST	19990529	193943.6	-19.808	133.857	0	3.8	Tennant Creek NT
AUST	19990531	191538.3	-25.853	140.135	10	3.1	Near Haddon Corner Qld
AUST	19990618	100411.7	-19.789	133.803	0	3.5	Tennant Creek NT

AUST	19990623	55011.3	-35.133	143.72	8	3.1	Moulamein NSW
MUN	19990625	3611.3	-22.85	113.91	5	4.0	100 km south of Exmouth, WA. Felt at Bullara and Ningaloo Stations, and at Coral Bay.
AUST	19990713	14248.2	-34.28	148.962	8	3.1	Frogmore NSW. Felt
AUST	19990722	192129.3	-19.711	133.798	3	3.5	Tennant Creek NT
MUN	19990727	54828	-13.71	127.86	5	3.0	Joseph Bonaparte Gulf, WA
AUST	19990806	3334.1	-31.872	138.367	17	3.0	Hawker, SA. Felt
MUN	19990811	44317.8	-14.519	128.837	5	3.0	Joseph Bonaparte Gulf, WA
AUST	19990814	124550.9	-25.955	130.72	0	3.6	Uluru area NT
AUST	19990818	1451.1	-33.888	152.302	2	3.3	Tasman Sea
AUST	19990818	1915.9	-33.901	152.175	0	3.0	Tasman Sea
ADE	19990818	110155	-33.28	138.478	6	4.3	Jamestown SA. Felt
MUN	19990825	122308.1	-24.34	112.57	5	3.0	Indian Ocean, near Cape Cuvier, WA
AUST	19990902	1627.4	-32.332	138.403	1	3.5	Near Carrieton SA. Felt
ADE	19990906	83705.7	-31.835	138.447	10	3.2	Hawker SA. Felt
AUST	19990911	194711.6	-39.518	144.889	0	3.0	Bass Strait
MUN	19990925	112421.4	-12.11	122.56	5	3.5	Ashmore Reef WA
SRC	19991009	81711.7	-37.759	148.353	0	3.0	Orbost Vic. Felt.
MUN	19991010	40002.2	-31.59	110.86	5	3.3	Indian Ocean
MUN	19991014	194252.6	-38.54	112.25	5	4.0	Southern Ocean
MUN	19991017	132814.8	-13.9	121.35	5	3.0	Near Scott Reef WA
MUN	19991029	61557	-22.17	113.78	18	3.2	Near Learmonth WA
ADE	19991031	123639.5	-32.407	138.572	5	3.5	Carrieton SA. Felt
MUN	19991104	183647.5	-15.97	127.48	5	3.0	Wyndham area, WA.
ADE	19991106	145523.5	-32.389	138.595	3	3.1	Carrieton, SA. Felt.
MUN	19991109	50522.2	-28.82	121.39	5	3.6	Leonora WA. Felt.
MUN	19991112	075753	-12.079	130.561	5	3.9	Near Darwin NT. Felt.
ADE	19991115	31627.9	-35.405	137.326	5	3.3	Investigator Strait, SA. Felt.
AUST	19991121	214005.5	-19.839	133.635	0	3.6	Tennant Creek, NT
MUN	19991130	151255.4	-21.24	119.77	5	3.2	Marble Bar, WA
MUN	19991201	152554.8	-27.18	126.59	5	3.2	Great Victoria Desert, WA
MUN	19991202	195009.5	-14.82	126.74	5	4.0	Kalumburu area, WA
MUN	19991209	192902.7	-20.27	119.48	5	3.2	Port Hedland area, WA
MUN	19991216	123636.1	-16.84	125.88	5	3.0	Wyndham Range, WA
ADE	19991231	84838.5	-33.18	139.904	0	3.0	Near Peterborough SA

Table 2. Large or Damaging Australian Earthquakes, 1788 - 1999

Date UTC	*Time*	*Lat °S*	*Long °E*	*ML*	*Ms*	*$AUS loss (1994$)*	*Location*
1873 12 15	0400	26.25	127.5		6.0		SE WA
1884 07 13	0355	40.5	148.5		6.2		NE Tasmania
1885 01 05	1220	29.0	114.0		6.5		Geraldton WA
1885 05 12	2337	39.8	148.8		6.5		NE Tasmania
1892 01 26	1648	40.3	149.5		6.6		NE Tasmania
1897 05 10	0526	37.33	139.75		6.5		Kingston SA
1902 09 19	1035	35.0	137.4		6.0		Warooka SA
1903 04 06	2352	38.43	142.53	4.6			Warrnambool Vic
1903 07 14	1029	38.43	142.53	5.3			Warrnambool Vic
1906 11 19	0718	21.5	104.5		7.2		Offshore WA
1918 06 06	1814 24	23.5	152.5	6.0	5.7		Gladstone Qld
1920 02 08	0524 30	35.0	111.0		6.0		Offshore WA
1929 08 16	2128 23	16.99	120.66		6.6		Broome WA
1935 04 12	0132 24	26.0	151.1	5.2	5.4		Gayndah Qld
1941 04 29	0135 39	26.92	115.80		6.9		Meeberrie WA
1941 06 27	0755 49	25.95	137.34		6.5		Simpson Desert
1946 09 14	1948 49	40.07	149.30	6.0	5.4		West Tasman Sea
1954 02 28	1809 52	34.93	138.69	5.4	4.9	107M	Adelaide SA
1961 05 21	2140 03	34.55	150.50	5.6		3M	Bowral NSW
1968 10 14	0258 50	31.62	116.98		6.8	31M	Meckering WA
1970 03 10	1715 11	31.11	116.47	5.1	5.1		Calingiri WA
1970 03 24	1035 17	22.05	126.61	6.7	5.9		L Mckay WA
1972 08 28	0218 56	24.95	136.26		6.2		Simpson Desert
1973 03 09	1909 15	34.17	150.32	5.6	5.3	2M	Picton NSW
1975 10 03	1151 01	22.21	126.58		6.2		L Mckay WA
1978 05 06	1952 19	19.55	126.56		6.2		L Mckay WA
1979 04 23	0545 10	16.66	120.27	6.6	5.7		Broome WA
1979 04 25	2213 57	16.94	120.48		6.1		Broome WA
1979 06 02	0947 59	30.83	117.17	6.2	6.1	10M	Cadoux WA
1983 11 25	1956 07	40.45	155.51	6.0	5.8		Tasman Sea
1985 02 13	0801 23	33.49	150.18	4.3		.09M	Lithgow NSW
1986 03 30	0853 48	26.33	132.52		5.8		Marryat Ck SA
1988 01 22	0035 57	19.79	133.93		6.3	1.3M	Tennant Ck NT
1988 01 22	0357 24	19.88	133.84		6.4		Tennant Ck NT
1988 01 22	1204 55	19.94	133.74		6.7		Tennant Ck NT
1989 12 27	2326 58	32.95	151.61	5.6	4.6	1 270M	Newcastle NSW
1994 08 06	1103 52	32.92	151.29	5.3		34M	Ellalong NSW
1997 08 10	092035.2	16.10	124.38		6.3		Collier Bay WA

Published on www.aees.org.au, last updated 17 July 2006, Kevin McCue, Australian Seismological Centre

Table 3 Australian accelerograph data, 1999

Date UTC	*Time*	*Lat°S*	*Long°E*	*ML /mb*	*Recording Site * Epicentre*	*H/E ~ km s-p sec*	*Comp*	*T sec*	*Acc mms^{-2}*
01 09	12 09				DPH	600? km	SZ	.14	.3
							SN	.12	.2
							SE	.12	.4
03 14	00 13	34.0	147.08	4.4	COTA	220 km	SZ	.2	.2
							SN	.25	.2
							SE	.3	.1
03 17	01 58	34.23	150.77	4.8	LBX	1.74s	SZ	.3	2.8
							SN	.25	1.5
							SE	.2	15
					AVO	2.74s	SZ	.8	2.1
							SN	.5	2.0
							SE	.75	2.1
					WUR	2.9s	SZ	.2	1.4
							SN	.2	2.8
							SE	.2	3.4
					LHB	4.0s	SZ	.2	3.5
							SN	.1	4.5
							SE	.5	2.9
					BJE	25.95s	SZ	.05	.3
							SN	.16	.4
							SE	.16	.4
					COTA	215 km	SZ	.5	.1
							SN	.3	.2
							SE	.1	.1
06 21	13 59	35.19	149.16	2.5	RNDA	1.8s	SZ	.08	2.3
							SN	.07	4.0
							SE	.08	3.9
					PHB	1.5s	SZ	.02	.3
							SN	.07	.3
							SE	.02	.3
08 06	08 21				NAP	5.3s	SZ	.06	.3
							SN	.1	.4
							SE	.2	.3
					PTP (soil site)	5.4s	SZ	.05	.85

							SN	.11	.55
							SE	.06	.50
08 18	11 01	33.28	138.48	4.3	PTP	6.07s	SZ	.05	2.9
							SN	.12	3.6
							SE	.17	3.5
					WHY	10.54	SZ	.06	.7
							SN	.06	.7
							SE	.05	.4
					TUK	19.5s	SZ	.12	.07
							SN	.11	.06
							SE	.1	.06
10 20	08 29				DPH	61 s	SZ	1.1	1.0
							SN	.3	1.0
							SE	.25	2.3
11 12	07 57	12.10	130.55	3.9	DRS	6.46s	SZ	.03	2.9
							SN	.03	4.0
							SE	.06	3.3

~ H/E is hypocetral/epicentral distance in km or seconds S-P or distance over focal depth in km

* Site details are listed in McCue and others (1999)

Table 5 Large or destructive World earthquakes, 1999 (from NEIC)

Date	*Time UTC*	*Lat*	*Long*	*Depth*	*mb*	*Ms*	*Mw*	*Location*
19990119	33533.8	-4.567	153.182	116	5.7		7.0	New Ireland Region
19990125	181916.	4.427	-75.749	17	6.0	5.7	6.2	Colombia, 883 deaths, 3626 injuries and 250 000 homeless
								in the Armenia-Calarca-Pereira area. Many landslides.
19990206	214759	-12.80	166.649	90	6.3	7.3	7.4	Santa Cruz Islands
19990211	140853	34.75	69.641	33	5.3	5.9	6.0	Afghanistan, 60 deaths and 500 injuries. 7000 homes
								destroyed in the Maidan-Shahr region. Felt Pakistan.
19990304	85201.4	5.359	121.787	33	6.4	6.5	7.1	Celebes Sea. Minor damage at Zamboanga. Felt.
19990308	122546	52.065	159.574	33	5.8	6.8	6.9	Off East Coast of Kamchatka. Felt (VI) at Petropavlovsk
19990320	104747	51.573	-177.63	50	6.3	6.8	6.8	Andreanof Islands, Aleutian Islands. Felt strongly on Adak
								and Amchitka
1990328	190510	30.55	79.42	10	6.4	6.6	6.6	Xizang-India border. 96 killed, 300 injured. Landslides
19990403	61719.8	-16.68	-72.68	102	6.1		6.8	Near Coast of Peru
19990405	110804	-5.62	149.579	150	6.2	7	7.4	New Britain Region
19990408	131033	43.604	130.382	563	6.5		7.1	E. Russia - N.E. China Border Region
19990413	103848	-21.39	-176.50	165	6.5	6.8		Fiji Is Region
19990506	230053	29.48	51.83	33	5.8	6.3	6.2	Southern Iran, Fars Province 26 killed, 100 injured
19990510	203302	-5.173	150.915	137	6.5		7.1	New Britain Region
19990615	204206	18.4	-97.45	70	6.5	6.5	7.0	Central Mexico, 19 killed and landslides
19990516	5115.4	-4.794	152.489	33	6	7	7.1	New Britain Region
19990517	100756	-5.17	152.826	33	5.5	6.9	6.7	New Britain Region
19990615	204206	18.403	-97.446	71	6.5	6.5	7.0	Central Mexico
19990817	139.8	40.702	29.987	17	6.3	7.8	7.7	Turkey. Some 15 000 people killed, 33,000 injured and
								extensive damage in the
								provinces of Istanbul, Kocaeli and Sakarya. Felt as far east
								as Ankara. Surface rupture approx. 40 km long with 2.7 m
								of strike-slip offset observed in the region between
								Sapanca Lake and the Izmit Gulf.
19990820	100221	9.239	-84.125	33	6	6.8	7.0	Costa Rica. Some damage in western Panama. Felt in
								Costa Rica and in southern
								Nicaragua and much of western Panama.

19990920	174718	23.728	121.058	33	6.6	7.7	7.7	Taiwan. 2400 people killed, 8700 injured, damage to roads and utilities disrupted on Taiwan. Most of the casualties and damage occurred in Nantou and Tai-ching Counties. Land-slides blocked a river in Yunlin County. Felt as far as Hong Kong and Quanzhou, China.
19990930	163116	16.197	-96.872	63	6.6	7.5		Oaxaca, Mexico. At least 33 people killed, 161 injured, 20,000 buildings damaged, utilities disrupted and roads blocked by landslides in the state of Oaxaca.
19991112	165719	40.73	31.122	10	6.3	7.5	7.2	Turkey. At least 619 people killed, 3300 injured landslides and extensive damage in the Duzce-Bolu Kaynasli area.
19991115	54243.1	-1.377	88.99	10	6.3	6.9	7.0	S Indian Ocean. Felt in the Colombo area, Sri Lanka
19991117	32740.3	-5.969	148.841	33	5.9	7.0	7.0	New Britain region. Felt
19991119	135646	-6.375	148.808	33	6.0	7.0	7.0	New Britain region
19991126	132115	-16.43	168.227	33	6.5	7.3	7.5	Vanuatu Islands. At least 5 people killed and 100 injured on Pentecost Island. At least 3 people killed and 2 others missing off the south coast of Pentecost Island by a local tsunami which was also recorded at Suva, Fiji. The tsunami caused damage throughout central Vanuatu. Runup measured (Caminade et al, 2001) 6 to 6.6 m on the south coast of Pentecost Is. at the village of Baie Martelli which was badly destroyed
19991206	231230	57.455	-154.566	33	6.5	6.7	7.0	Kodiak Island region. Felt on Kodiak Island and in Alaska
19991211	180336	15.776	119.767	33	6.5	7.1	7.3	Luzon, Philippine Is. 5 people died and 40 injured on Luzon
19991221	141457	-6.82	105.65	56	6.1		6.6	Sunda Strait, 5 killed qnd 220 injured on West Java
19991229	132919	-10.91	165.394	33	5.7	6.8	6.8	Santa Cruz Islands

Table 6a The 10 largest 20th century earthquakes in the World

http://neic.usgs.gov/neis/eqlists/10maps_world.html

Place	*Date*	*magnitude*	*Latitude*	*Longitude*
1. Chile	1960 05 22	9.5 Mw	38.2 S	72.6 W
2. Alaska	1964 03 28	9.2 Mw	61.1 N	147.5 W
3. Russia	1952 11 04	9.0 Mw	52.75N	159.5 E
4. Ecuador	1906 01 31	8.8 Mw	1.0 N	81.5 W
5. Alaska	1957 03 09	8.8 Mw	51.3 N	175.8 W
6. Kuril Is	1958 11 06	8.7 Mw	44.4 N	148.6 E
7. Alaska	1965 02 04	8.7 Mw	51.3 N	178.6 E
8. India	1950 08 15	8.6 Mw	28.5 N	96.5 E
9. Chile	1922 11 11	8.5 Mw	28.5 S	71.0 W
10. Indonesia	1938 02 01	8.5 Mw	5.25 S	130.5 E

Table 6b Most Destructive Known Earthquakes to 1999

(50,000 deaths or more, listed in order of greatest number of deaths)
(From http://neic.usgs.gov/neis/eqlists/eqsmosde.lis)

Date	Region	Place	Deaths	Magnitude
1556 January 23	China	Shansi	830 000	
1976 July 27	China	Tangshan	255 000	8.0
1138 August 9	Syria	Aleppo	230 000	
1927 May 22	China	Xining	200 000	8.3
856+ December 22	Iran	Damghan	200 000	
1920 December 16	China	Gansu	200 000	8.6
893+ March 23	Iran	Ardabil	150 000	
1923 September 1	Japan	Kwanto	143 000	8.3
1908 December 28	Italy	Messina	70 – 100 000	7.5
1290 September	China	Chihli	100000	
1667 November	Caucasia	Shemakha	80 000	
1727 November 18	Iran	Tabriz	77 000	
1755 November 1	Portugal	Lisbon	70 000	8.7
1932 December 25	China	Gansu	70000	7.6
1970 May 31	Peru		66 000	7.8
1268	Asia Minor	Silicia	60 000	
1693 January 11	Sicily		60 000	
1935 May 30	Pakistan	Quetta	30-60 000	7.5
1783 February 4	Italy	Calabria	50 000	
1990 June 20	Iran		50 000	7.7

+ Note that these dates are prior to 1000 AD. No digit is missing.

APPENDIX 1

ISOSEISMAL MAPS

Five of the 1999 earthquakes were sufficiently widely felt that questionnaires were distributed and the returned forms collated for GA to draw up isoseismal maps, at; Grenfell, West Wyalong, Appin NSW, Canberra ACT, and Darwin NT.

The format of these maps is the same as those printed in the three volumes of the AGSO (BMR) Isoseismal Atlas (Everingham and others, 1982; Rynn and others, 1987; McCue, 1995).

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.

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.

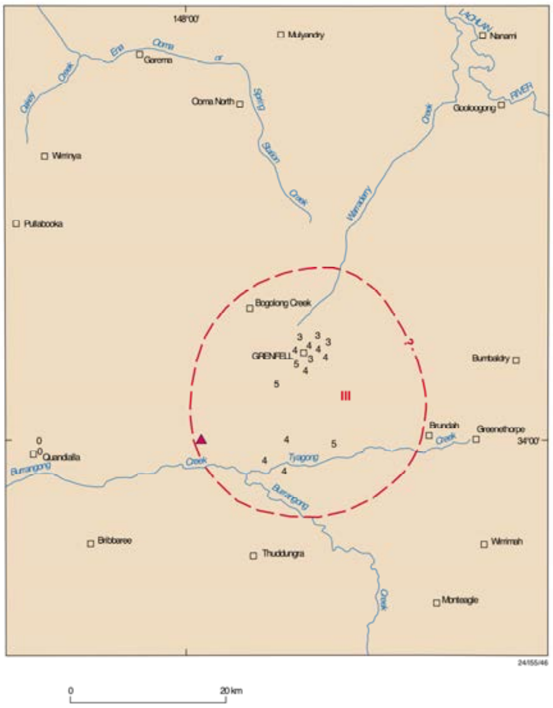
MMXI Wooden frame structures destroyed. Great damage to railway lines. Great damage to underground pipes.

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.

Isoseismal map of the Grenfell NSW earthquake 5 March 1999, ML 2.8

This earthquake at 1 am local time was the second and largest of three micro-earthquakes near Grenfell. There are too few reports to be confident of the isoseismal shown on the accompanying map, which is why the line is dashed. The bang and shaking did wake several but not all sleepers. Given the low magnitude, the epicentre must have been close to Grenfell.

One of the residents contacted by phone said that the event *sounded like blasting a stump*, a very country-Australia description. One window was reported cracked and a tree is reported to have been uprooted.



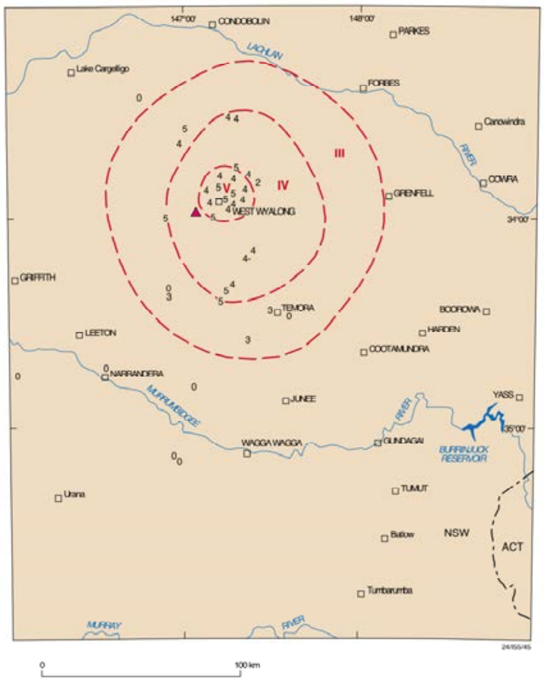
Contributors: This map was compiled by A McEwin and Y Li

Isoseismal map of the West Wyalong NSW earthquake 14 March 1999, ML 4.4

This magnitude ML 4.4 earthquake occurred at 10 am EST on Sunday 14 March. The shaking interrupted the service at the Uniting Church in West Wyalong where members of the congregation described it as a large truck going past. One person sitting down and enjoying morning tea in West Wyalong heard the roof rattling and thought the air conditioner had collapsed. She said it took some time to realise that an earthquake had occurred. Another email correspondent 9 km south of West Wyalong said the shaking rattled the windows and crockery and knocked a frying pan off the kitchen counter. No damage was reported to AGSO.

Many of the felt reports came from West Wyalong but the earthquake was felt out to a distance of about 75 km from the epicentre.

One correspondent from Ariah Park wrote that it *generally sounded like a loud rumbling sound, quiet at first, then got louder and louder. Shook for approximately 5 to 10 seconds.*

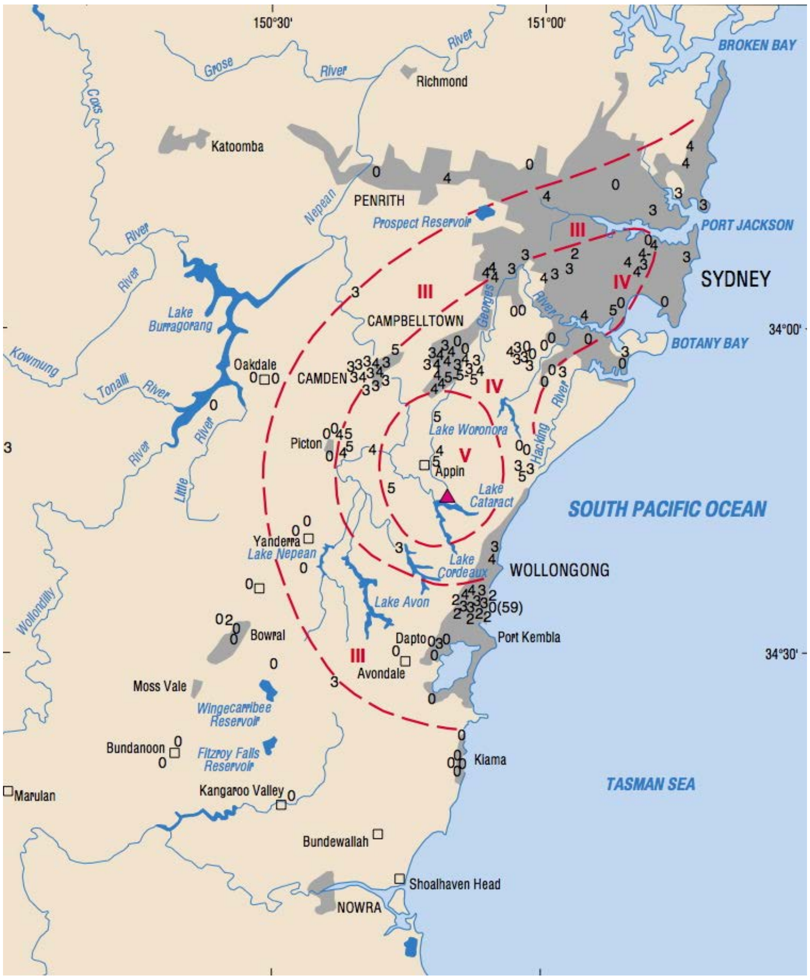


Contributors: This map was compiled by A McEwin and Y Li and modified by K McCue

Isoseismal map of the Appin NSW earthquake
17 March 1999, ML 4.8

Appin is at the centre of a coal mining area in the Sydney Basin south of Sydney. Most of the mines are underground and the residents are quite used to bangs and shakes. This one at lunchtime lasted longer than the usual mine event and reportedly caused some minor isolated cases of damage.

The epicentre was between the major urban areas of Sydney and Wollongong so many felt reports were received by phone, mail and email, especially as a result of a questionnaire distributed at Wollongong University by Leonie Jones.



The resultant isoseismal map is unusually asymmetric, elongated along the coastal belt north of Sydney. This could be due to the earthquake mechanism or to the local foundation conditions at the reporting sites, people are more likely to reply to the earthquake questionnaire or by email if they felt it rather than if they didn't. One respondent at Stanwell Park said he nearly fell off the bench he was sitting on and that the 10 year old brickwork was cracked. Police at Camden and Liverpool said that electrical failures had been reported to them and at San Souci a fan apparently fell off a table. People at Campbelltown and Sylvania reported that the shaking was *really scary*. A resident of Ambervale heard an explosion and thought it was a car accident. She reported that cracks formed at the wall/ceiling joint in parts of the house. Many people within 100 km of the epicentre reported that it felt like something, a truck, a skydiver etc., hitting the house.

The area is particularly well instrumented with accelerographs and seismographs because of the high investment in regional infrastructure including large dams and a nuclear research reactor. Consequently there were more strong motion records collected following this earthquake than in any other single event in Australia. This will enable a correlation between MM intensity and a recorded ground motion parameter such as pga, pgv or spectral amplitude, or a correlation of local attenuation with 'standard relationships' derived overseas.

A similar sized earthquake occurred near Appin early in the morning of 16 November 1981.

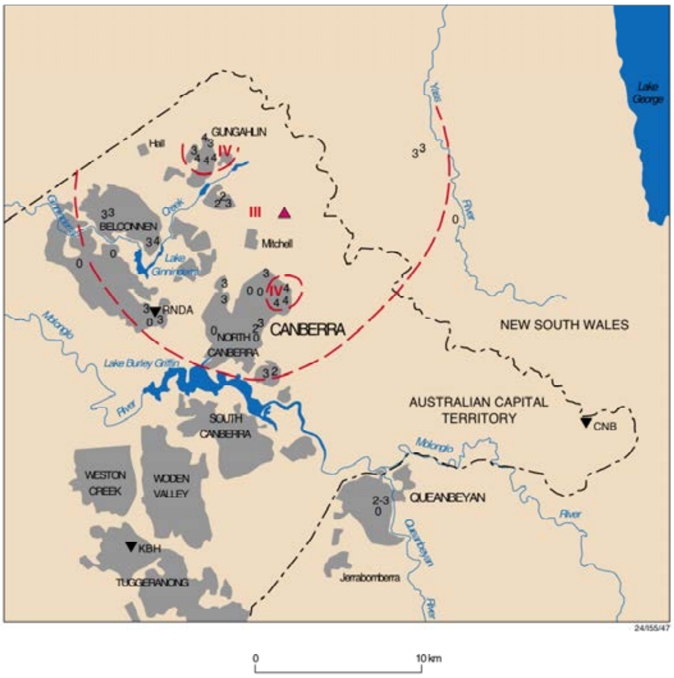
Contributors: This map was compiled by Kevin McCue, Andrew McEwin, Y Li, Wayne Peck and Adam Pascale. Lesley Hodgson and Leonie Jones distributed questionnaires.

Isoseismal map of the Canberra ACT earthquake
21 June 1999, ML 2.5

This microearthquake occurred just before midnight on Sunday 21 June and aroused a lot of interest amongst local residents of the Canberra suburbs of Hackett and Ngunnawal, and emergency services personnel who were trying to determine what had happened. Most described the sound, like an explosion, rather than the shaking which was very short.

The following colourful email report gives a flavour of the experience of one Gunghalin resident which was probably a fairly common experience judging by conversations with police at the time who were investigating a possible explosion:

I was in bed in that state of relaxed bliss that precedes the onset of sleep, when a loud, somewhat muffled noise caused me to sit bolt upright. The house shook momentarily and the glass in the windows of my bedroom rattled in its frame. My first thought was that my house was a road-rage target or that a ham-fisted burglar was breaking into my house. The possibility of an earthquake also passed through my mind. I looked at my watch: spot on the witching hour; 'It must be a paranormal phenomenon', I thought. I got up and checked the front door of the house and the door to the garage. Nothing amiss was apparent. 'Bloody earthquake', I thought and returned to bed.

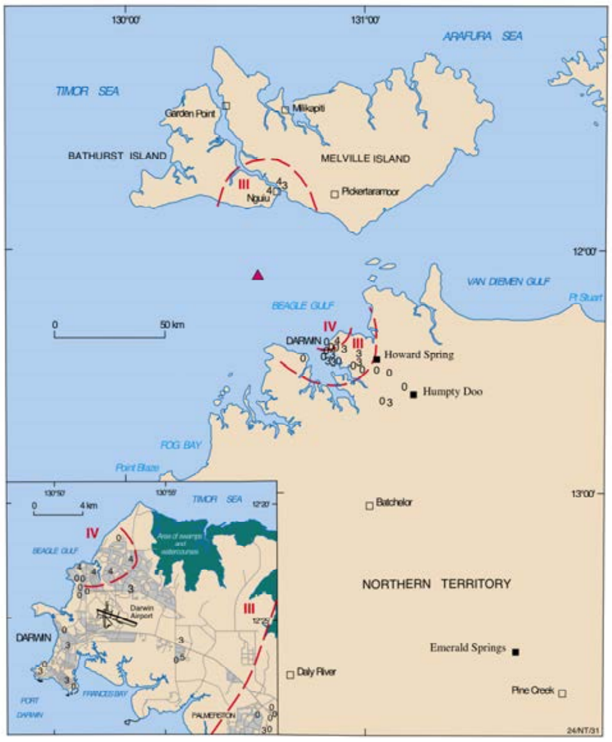


In Aranda, one person lying in bed reading thought that a large possum was jumping on the deck but resolved that it must have been an earthquake because possums aren't that big. A neighbouring sleeping seismologist was not awakened.

Several people reporting this earthquake mentioned feeling a similar event on Friday afternoon and indeed a slightly smaller earthquake ML 2.3 was recorded on local seismographs. The computed epicentres of the two earthquakes are identical within the accuracy of the locations.

Contributors: This map was compiled by A McEwin, Y Li and K McCue

Isoseismal map of the Darwin NT earthquake
12 November 1999



This earthquake was reported felt throughout Darwin. An ABC Darwin reporter said the shaking on the second floor of their two storey building was strong and lasted about 30 seconds. At the Bureau of Meteorology it was reported as a high frequency vibration (Ed. As opposed to the low frequency shaking associated with large earthquakes in the Banda Sea typically 600 km away north of Darwin). There was no damage which can probably be attributed to the 40 km distance from Darwin and requirements of the wind loading code; Darwin is in the cyclone belt which imposes requirements for appropriate connections between roof and walls, walls and floor and floor and foundations.

The earthquake was reported felt as far south as Noonamah though not in Palmerston which is closer to the epicentre. A number of people at Nguiu on Melville Island reported quite strong shaking though others said they hadn't felt it.

This is the largest known local earthquake within 100 km of Darwin. Measures of its magnitude ranged from 3.7 to 4.1. On 30 September 1992 a magnitude 5.1 earthquake offshore Maningrida in Arnhem Land was felt throughout Darwin.

Contributors: This map was compiled by Liz Saikal and Kevin McCue.

APPENDIX 3

GLOSSARY

In this report we refer to the *magnitude* of an earthquake and *intensity* caused by an earthquake, the terms are very different. 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

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

Shocks as small as magnitude 1.0 are reported felt, whereas earthquakes of magnitude 5 or more may 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 terms used for magnitudes below 5 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

$$ML = \log A - \log A_o$$

where A *is* the maximum trace amplitude (zero-to-peak) in millimetres on a standard Wood-Anderson seismogram, and A_o 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 using other instruments by correcting for the difference in magnification (Willmore, 1979) 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.

Surface-wave magnitude (Ms) The surface-wave magnitude was originally defined for shallow earthquakes in the distance range $\Delta = 20\text{–}160°$, and in the period range

$T = 17\text{–}23$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

$$MD = a\ logt\ + b\ \Delta + c$$

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. This is a most convenient way to measure magnitude and many other forms of this equation have been used. It is usually calibrated against Richter magnitude.

Seismic moment magnitude (Mw) Kanamori (1978) defined a world magnitude scale Mw from the seismic moment M_o

$$M_o\ = \mu\ A\ d$$

and

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

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 (M (Rp)) 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. They derived the expression:

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

Additional information on magnitudes is available in McGregor & Ripper (1976), Båth (1981), Denham (1982), Everingham & others (1987), and Ambraseys and Free (1997).

Intensity

The intensity of an earthquake is a subjective estimate of its effects on people and buildings and should not be confused with magnitude which is a measure of the amplitude of seismic waves recorded on a seismogram. In this report we use the modified Mercalli (MM) scale (Eiby, 1966) 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.