GEOSCIENCE AUSTRALIA

EARTHQUAKES

Australian Seismological Report, 1998

Kevin McCue & Cvetan Sinadinovski

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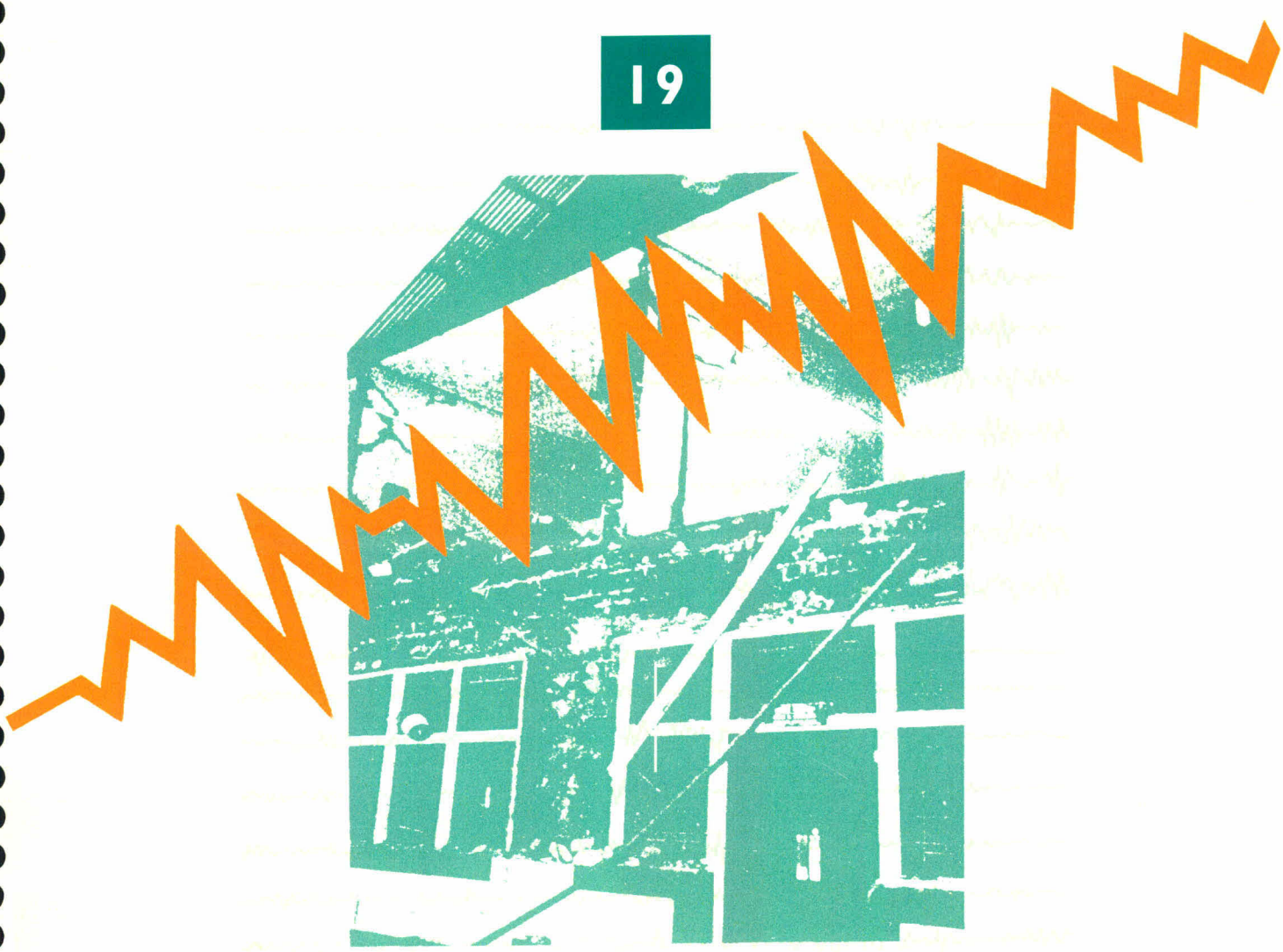

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GEOSCIENCE AUSTRALIA
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AGSO RECORD 2002/1

AUSTRALIAN SEISMOLOGICAL REPORT

1998

Compiled by
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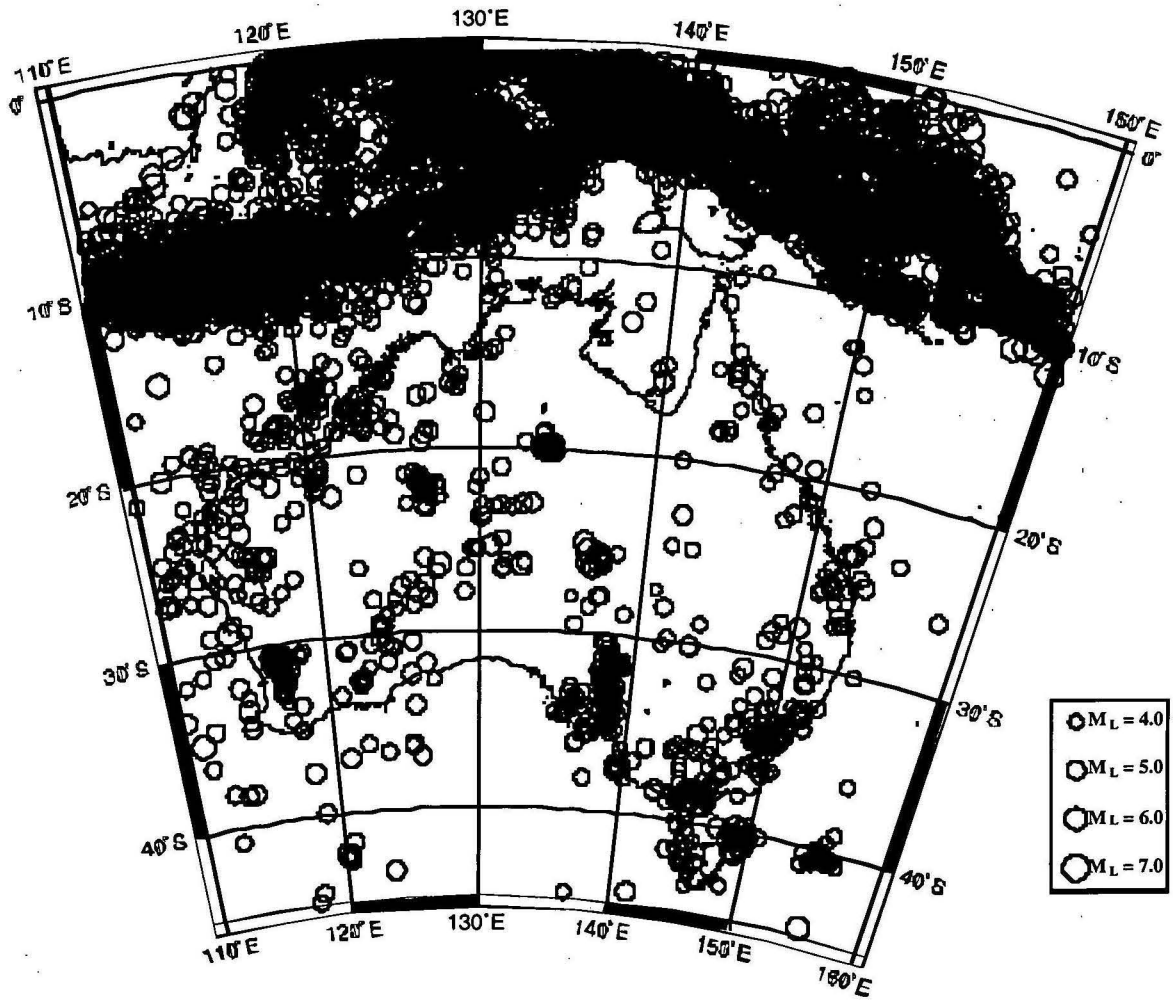

Australian region earthquakes, 1788 – 1998, M ≥ 4

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1998 Epicentres

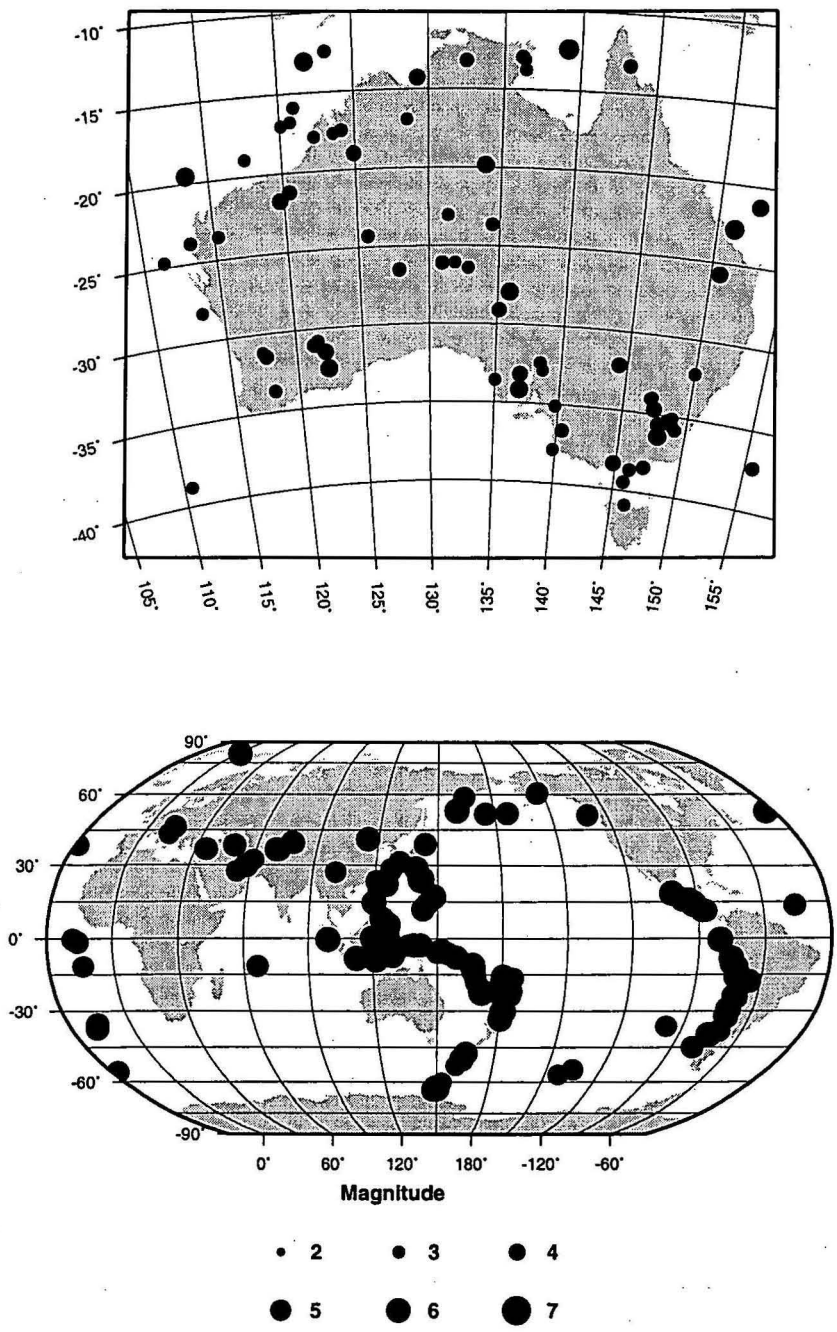


Figure 2 Australian earthquakes in 1998 with magnitude ML ≥3, and World earthquakes in 1998 with magnitude M ≥ 6

SUMMARY

The number of earthquakes in Australia in 1998 was below average across the whole magnitude range. There was no significant damage reported but eight of the earthquakes aroused sufficient public interest that isoseismal maps were compiled. The largest earthquake occurred in the Gulf of Carpentaria on 29 March with magnitude ML 4.9 but the most widely reported earthquake was that near Corryong Victoria on 17 July, its magnitude ML 4.3.

A significant number of accelerograms were recorded again despite the infrequent events. The Corryong Vic, Adelaide SA and ACT region earthquakes generated useful recordings where isoseismal maps were also compiled and the Darwin instruments again recorded several large Indonesian earthquakes felt in the Northern Territory.

Worldwide there were nearly 9000 deaths attributed to earthquakes. More than 2000 fatalities were caused by a 10m high tsunami that swept villages off the Sissano Lagoon sand spit on 17 July. Afghanistan bore the brunt of a magnitude Ms 6.9 earthquake on 30 May which killed an estimated 4700 people, injuring another 1500.

Most of the Nuclear weapons States abided by a self-imposed moratorium on testing in recognition of the changed international political climate but three underground nuclear explosions on the Indian subcontinent were detected by CTBT states worldwide and in Australia.

INTRODUCTION

Each year in Australia there are on average two earthquakes of at least magnitude 5.0, large enough to cause minor structural damage. Large earthquakes, of magnitude 6 or more, occur somewhere in Australia every 5 years or so on average, the last one in 1997 was in northwest Western Australia. The larger earthquakes are 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. This report contains information on the 1998 earthquakes and is the nineteenth compiled by the Australian Geological Survey Organisation (and its predecessor BMR) 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.

The report has six main sections: the **Australian region earthquakes** section contains a summary of the 1998 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; **Principal world earthquakes** which lists the largest and most damaging earthquakes that took place world-wide during 1998; and **Monitoring of nuclear explosions** which lists detected underground nuclear explosions in the year.

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, 1998

The 89 earthquakes of magnitude ML 3 or more recorded in 1998 on AGSO's National Seismographic Network and State and regional networks are listed in Table 1, and those known with magnitude ML ≥4 since 1788 are plotted in Figure 2 from the AGSO earthquake database. Some of the earthquakes triggered the Urban Monitoring network of accelerographs.

There were no deaths or injuries and no structural damage attributable to earthquakes in Australia during the year. The largest earthquake in Australia in 1998 occurred out under the Gulf of Carpentaria, its magnitude ML4.9, well below the average annual maximum magnitude of about 5.5.

In Figure 3 below we have plotted the cumulative number of earthquakes in 1998 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 since 1900). The recording time period is too short and the paleoseismological record too scanty to give any indication of a maximum magnitude. The largest recorded event was that in 1906 off the WA coast, Ms 7.2, and 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, in contrast with the seismicity for 1997 which was well above average.

The slope or 'b' value at low magnitudes parallels the average long term trend but at a lower frequency of occurrence.

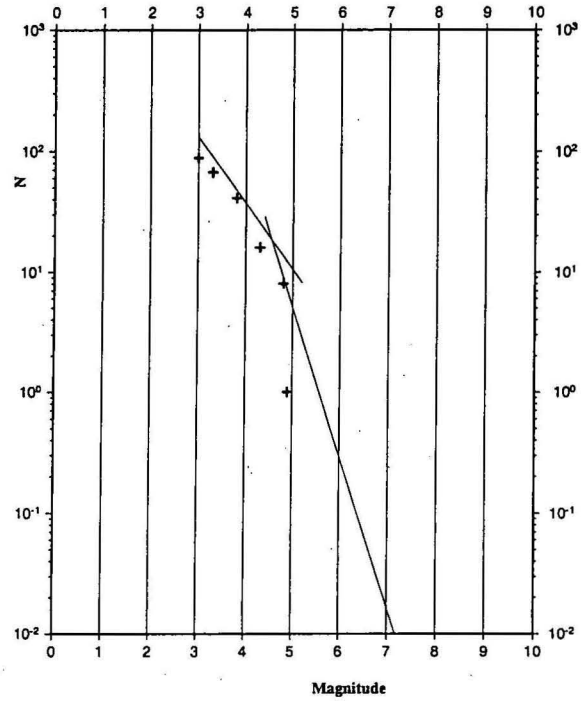


Figure 3 The cumulative number of earthquakes in 1998 plotted against magnitude ML (the crosses) superimposed on the best fit annual cumulative plot for the 20th century. The N(0) and b values for each segment are (3.77, -0.55) and (6.96, -1.25).

Kevin McCue and Cvetan Sinadinovski

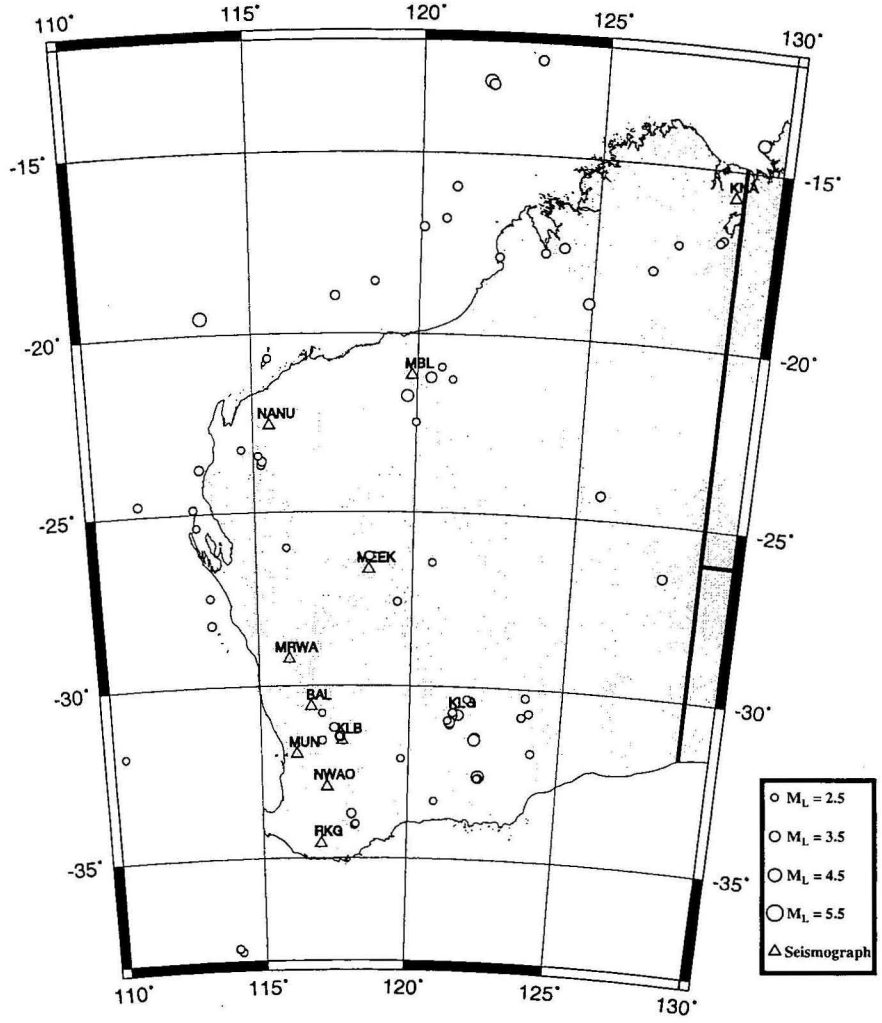
Western Australia

The seismograph network shown in Figure 4 is fairly sparse but low attenuation and low background noise ensure a detection threshold of 2.5 throughout the state with the aid of near-border seismographs in South Australia and the Northern Territory. The pattern of earthquakes in 1998 is not unusual though there was not the usual concentration of events in the SW Seismic Zone. Epicentres are scattered across the south of the State and east of the SW Seismic Zone and seem unrelated to the major boundary at the Fraser Fault between the Yilgarn Block and Albany Fraser Province (SE of the Kalgoorlie seismograph station KLG in Figure 4). In contrast the few events in the far north of WA do seem to highlight the boundary of the Kimberley Block, and others broadly delineate the continental/oceanic crust boundary. There were no earthquakes on the Darling Fault, one of the most striking geological boundaries in the State.

WA State Emergency Services advised AGSO that communities from Gosnells to Yanchep had reported earthquake activity on the night of Wednesday April 29 but Mundaring Observatory staff checked and nothing was recorded on WA seismographs. It was confirmed later that the cause of the noise and rattling were F111s on exercise.

None of the WA earthquakes of 1998 was large enough or felt widely enough to compile an isoseismal map though several were reported felt.

Where zone numbers are used in the text, they refer to source zones defined by Gaull and others (1990). More than 90% of the earthquakes were located within or just adjacent to these recognised zones.



Earthquake epicentres in Western Australia 1998, magnitude $M_L \geq 2.5$

Figure 4

Two hundred and forty earthquakes were located in the region of Western Australia during 1998, slightly fewer than in the previous year. The largest earthquake occurred on 2 November, had a Richter magnitude of 4.6 and was located off-shore, 280 km north of Exmouth. There were 34 earthquakes of magnitude ML 3.0 or greater during the year, six of which had a magnitude of ML 4.0 or more. Three of these were off-shore, 271 km N of Exmouth (ML 4.6), 112 km N of Scott reef (ML 4.5) and 172 km N of Kununurra (ML 4.2). Two (ML 4.3 and 4.0) were 68 km SE and 84 km NNE of Norseman respectively. The sixth (ML 4.0) was 63 km S of Marble Bar. Activity continued in the Kellerberrin area in the Southwest seismic zone.

Nine earthquakes were located in Zone 3 offshore from Carnarvon and Kalbarri. The largest being ML 3.2, 130 km NNW of Carnarvon. In addition there were 2 earthquakes (ML 4.6 & 2.1) 271 km N of Exmouth and 77 km S of Geraldton, respectively. Two earthquakes of magnitude ML 2.7 occurred in Zone 4, approximately 450 km SW of Albany. There was one earthquake 480 km S of Eucla and a magnitude 3.0 earthquake 776 km SW of Albany.

One hundred and fifty-eight earthquakes were located in the Southwest Seismic Zone compared to 220 in 1997. The largest (ML 3.6) occurred at Yorkrakine, 19 km N of Kellerberrin. This was the most active area were 93 earthquakes were located. Twelve earthquakes were located in the

Cadoux/Manmanning area, 11 near Meckering, 4 near Wyalkatchem and 3 each at Quairading, Williams and Katanning. Merredin, Beverley, Kulin, Narrogin and Gnowangerup each experienced two earthquakes. Single events were located near Buntine, Wubin, Burakin, Moora, Calingiri, Bolgart, Bencubbin, Talbot Brook, Hyden, Corrigin, Pingelly, Arthur River, Wagin, Kojonup, Nyabing , Tambellup and Boyup Brook.

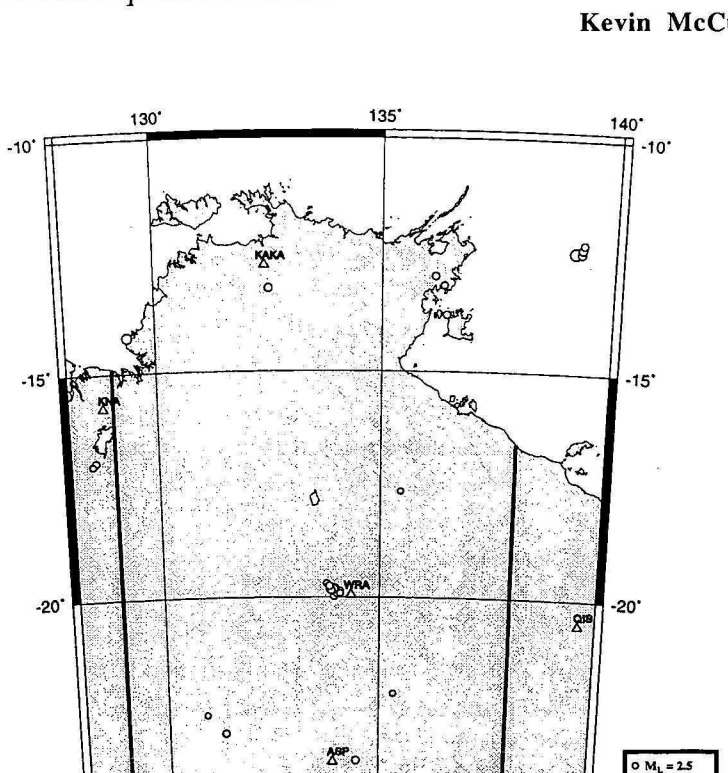
Of the eleven earthquakes in the South-east zone (zone 5), five were approximately 65 to 71 km SE of Norseman with the largest being a magnitude ML 4.3. Two events with magnitudes ML 4.0 and 3.7 occurred 85 km NNE and 90 km N of Norseman respectively. Only one of the seven earthquakes located in the Carnarvon Basin zone (5) had a magnitude of ML 3.0. This was located 117 km S of Nanutarra. Six earthquakes occurred in the Canning Basin zone (9), the largest ML 4.0 occurred 63 km S of Marble Bar. The Tobin Lake Region (Zone 10A) was devoid of earthquakes.

The four earthquakes located in the offshore north-west zone (11) were 205 to 290 km NW of Broome. All but one had magnitudes ML 3.0 or greater. One earthquake (ML 3.1) was north of the western end of the zone and another (ML 3.0) offshore, 16 km N of Broome. Seven earthquakes ranging from ML 2.8 to 3.8 were located in the Halls Creek Mobile Belt (Zone 14).

Earthquake Swarm

Kellerberrin (Yorkrakine) Swarm activity that started on 6 March 1996 (Gregson and others, 1998) continued into 1998. Ninety three earthquakes ranging from ML 1.5 to 3.6 occurred in the area 17-20 km north of Kellerberrin. More than half of them were in the six days following a magnitude ML 3.6 earthquake on 7 June.

Kevin McCue and Peter Gregson



Earthquake epicentres in Northern Territory 1998, magnitude $M_L \geq 2.5$

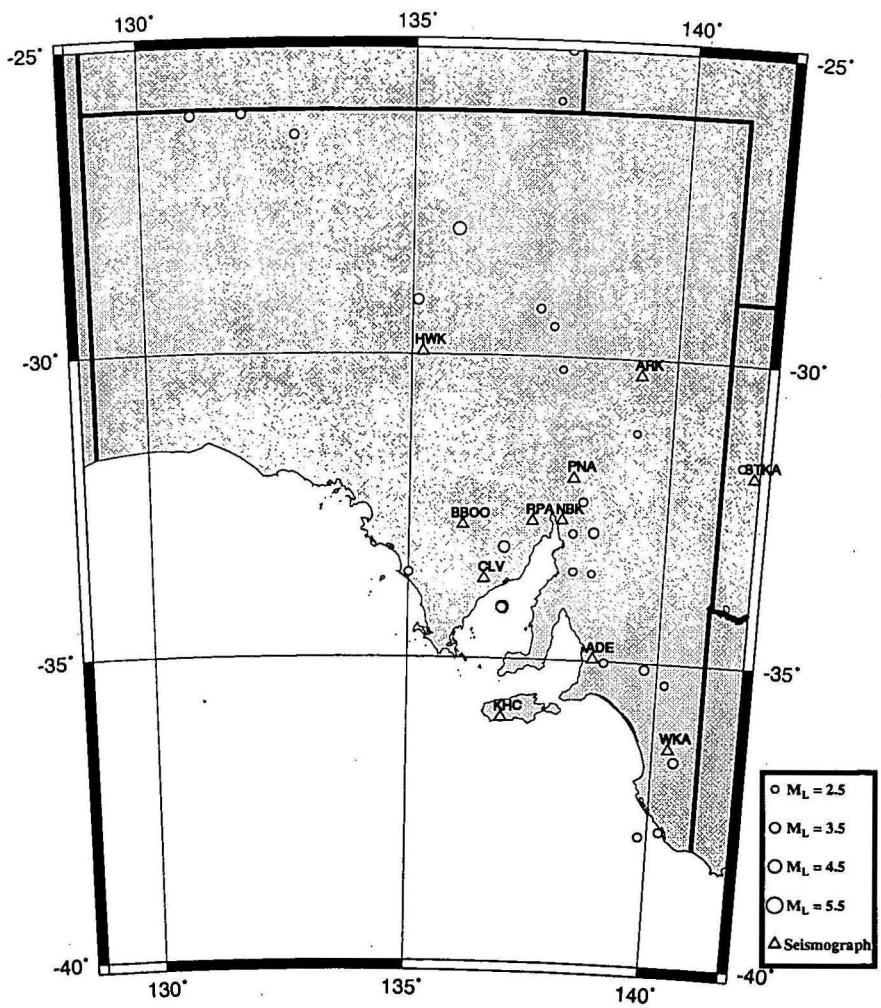
Figure 5

Northern Territory (Figure 5)

The largest earthquake in the Northern Territory was an aftershock on 25 June of the sequence that has continued spasmodically since January 1988 near Tennant Creek. It was at the western end of the Lake Surprise Fault and measured magnitude ML 4.1. Townsfolk 40 km away reported feeling the shaking. Numerous smaller aftershocks also occurred on the fault throughout the year.

Other small earthquakes occurred in the Simpson Desert and west of Alice Springs (ASP on the map) which is not unusual but there were others south of Darwin and along the west coast of the Gulf of Carpentaria near Groote Island which is unusual.

Kevin McCue



Earthquake epicentres in South Australia 1998, magnitude $M_L \geq 2.5$

Figure 6

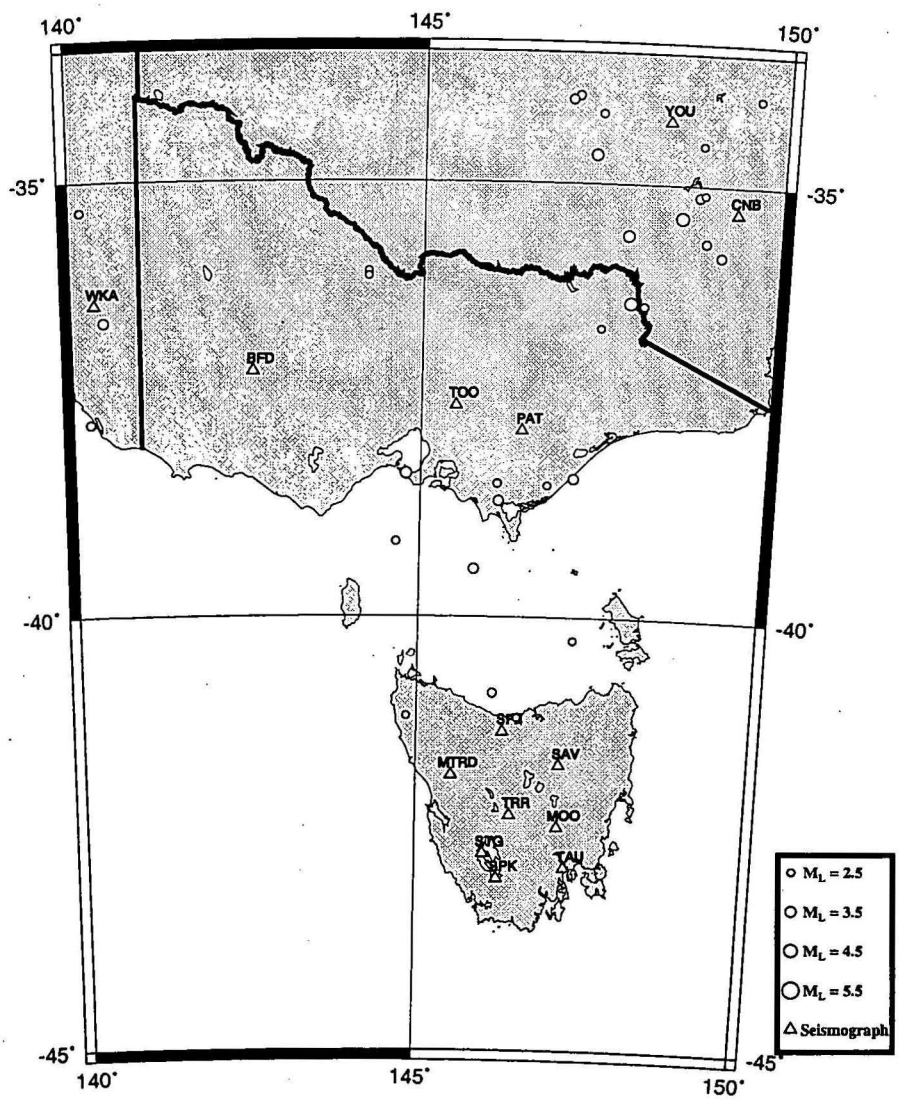
South Australia (Figure 6)

This was a year of relatively low seismicity. The number of events located was only 174, considerably down on earlier years of the decade. The deficit is in small events, with the number of events over magnitude 3 being about average on 12. There were 20 events reported felt.

Activity occurred in all the usual areas: Adelaide Fold Belt, Eyre Peninsula, and the South East. There was a surprising swarm in Spencer Gulf with 3 events having magnitudes from 3.0 to 3.6. Another earthquake of magnitude 3.5 occurred in what is normally a quiet area near Coober Pedy. Very little activity occurred near the epicentre of the large 1997 Burra event.

The 2 largest events in SA were at Cleve on the Eyre Peninsula on 26 February magnitude ML 4.5 and Oodnadatta in the mid-north on 9 June magnitude ML 4.2. Isoseismal maps were constructed for the earthquakes at Cleve and at Padthaway in the South-east on 11 March, magnitude ML3.7.

David Love



Earthquake epicentres in Victoria and Tasmania 1998, magnitude $M_L \geq 2.5$

Figure 7

Victorian and Tasmanian Earthquakes (Figure 7)

An earthquake of magnitude ML 2.6 near Port Sorell on the north coast of Tasmania was felt on 21 January.

On 5 May at 05:25 UTC an earthquake of magnitude ML 2.7 near Eskdale in north-eastern Victoria was felt in the Dartmouth township and in the Kiewa Valley.

An earthquake of magnitude ML 3.6 on 27 September was widely felt in Melbourne. The epicentre was near Mud Island in Port Phillip Bay, about 4 km north-east of Portsea. The earthquake was relatively deep by Victorian standards, occurring almost 20 km beneath the surface. It was felt throughout the Mornington Peninsula, in Geelong, and to Bundoora in the northern suburbs of Melbourne. This earthquake triggered the Melbourne Joint Urban Monitoring instruments. The maximum intensity reported was Modified Mercalli intensity IV.

Corryong earthquake Earthquake activity in the region for the last 12 months was dominated by the magnitude ML 4.5 earthquake that occurred south of Corryong on 17 July at 01:22 UTC. This event was felt over a wide area, as far north as Canberra and as far south as Orbost but no damage was reported. In Corryong a maximum intensity of MM IV was assigned from reports such as that the noise of the earthquake in Corryong was louder than a low flying jet. The isoseismal map is described in a later section.

The earthquake occurred at a depth of 19 kilometres. This is considered quite deep for an earthquake in southeastern Australia. It was followed by a magnitude ML 1.5 aftershock a few hours later. This was the largest earthquake to occur in Victoria since the Thomson Reservoir magnitude ML 5.0 earthquake of 25 September 1996.

The earthquake was felt at Dartmouth and Murray Darling Basin Commission (MDBC) staff at Dartmouth were informed of the magnitude and location of the earthquake by Seismology Research Centre staff within minutes of it occurring. Recordings of the event on the dam crest and downstream of the base of the dam were downloaded by SRC staff who happened to be on-site at the time of the earthquake and MDBC staff at Dartmouth were informed of the results within half an hour of the earthquake.

Note that this earthquake is northeast of a southwest-northeast trend of epicentres south of the reservoir . It is possible that all of these events are on a southwest-northeast trending fault that dips to the northwest under the reservoir.

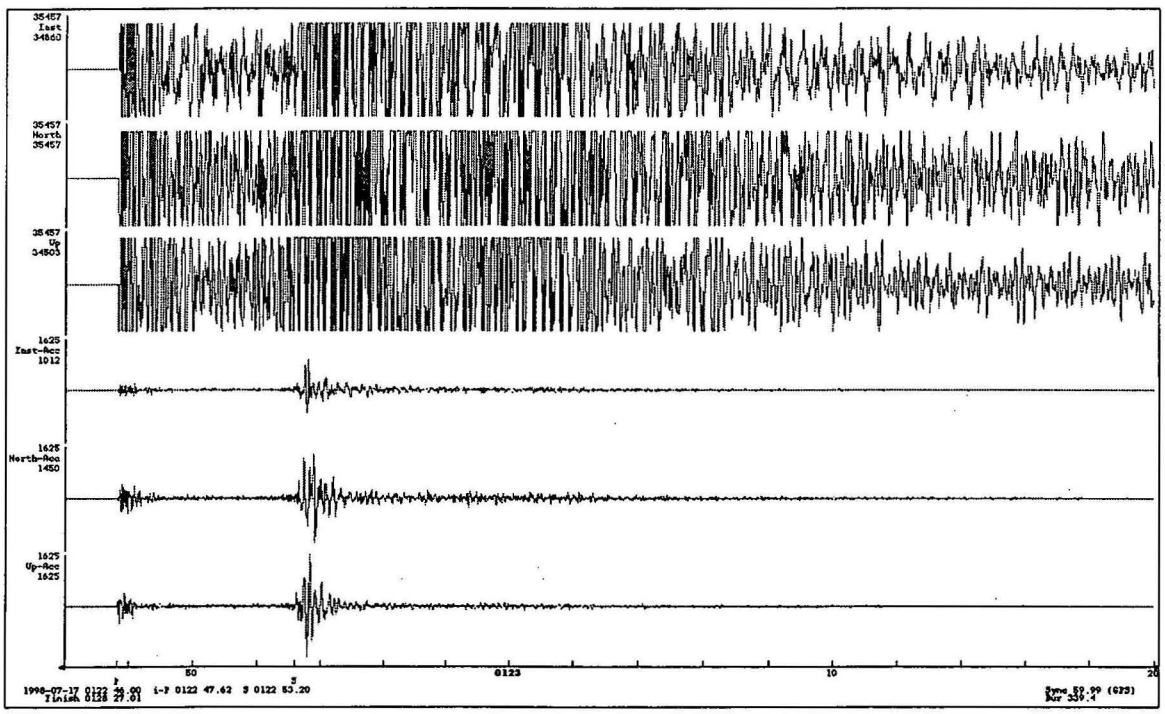


Figure 8: Combined seismogram/accelerogram recorded at Dartmouth Dam

Figure 8 is a combined six channel seismogram/accelerogram of the Corryong earthquake as recorded by the instrument installed on the crest of the embankment. The horizontal scale on this plot is Universal Coordinated Time with a mark every two seconds. The top three channels depict ground motion recorded by the sensitive three channel seismometer. The seismometer was driven to full scale, as would be expected from an earthquake of this magnitude at a distance of 45 kilometres. The bottom three channels depict acceleration as measured by the strong motion accelerograph. Peak ground acceleration recorded on the dam crest by this instrument was 0.049g (486 mm/s^2), on the vertical component.

Figure 9 below is a three channel accelerogram as recorded by the instrument located downstream of the toe of the dam. Peak ground acceleration recorded by this instrument was 0.039g (384 mm/s^2) on the north-south component.

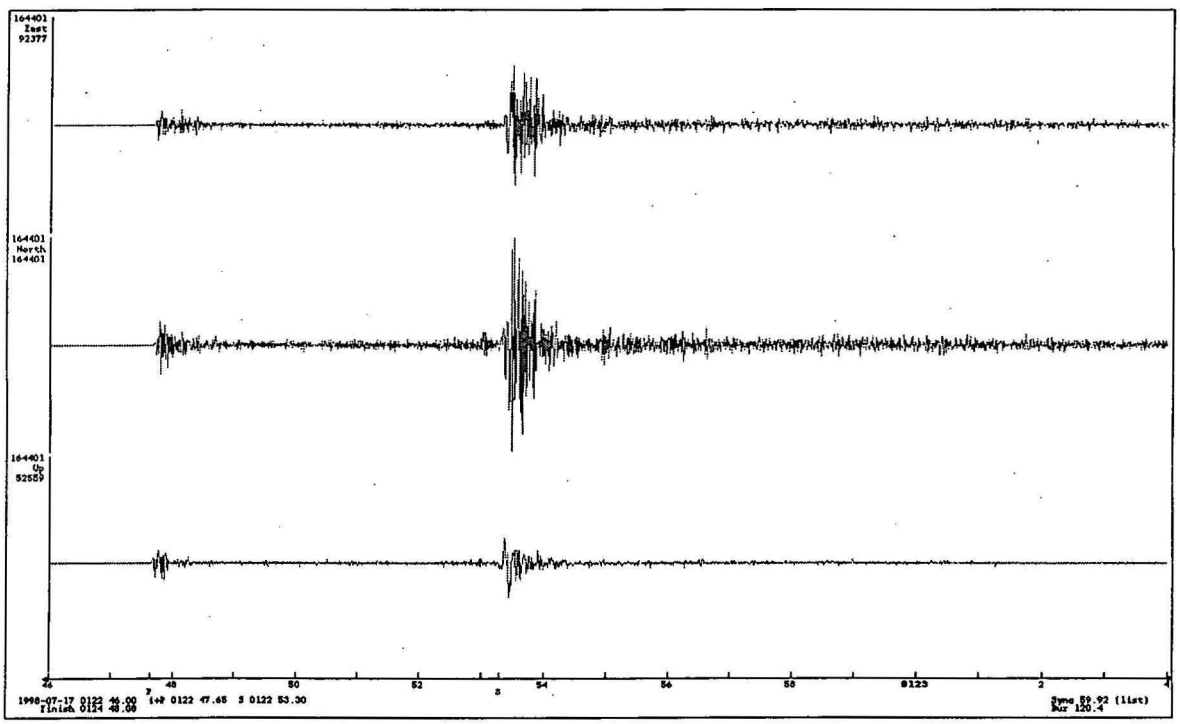


Figure 9: Accelerogram recorded at Dartmouth Dam base below the toe of the dam

These peak ground accelerations are well below the level at which one would expect damage to an engineered structure. Furthermore, the frequency of the seismic wave vibrations from this relatively small earthquake were too high, and the duration was too short (about 1 second) to cause significant resonance in the dam.

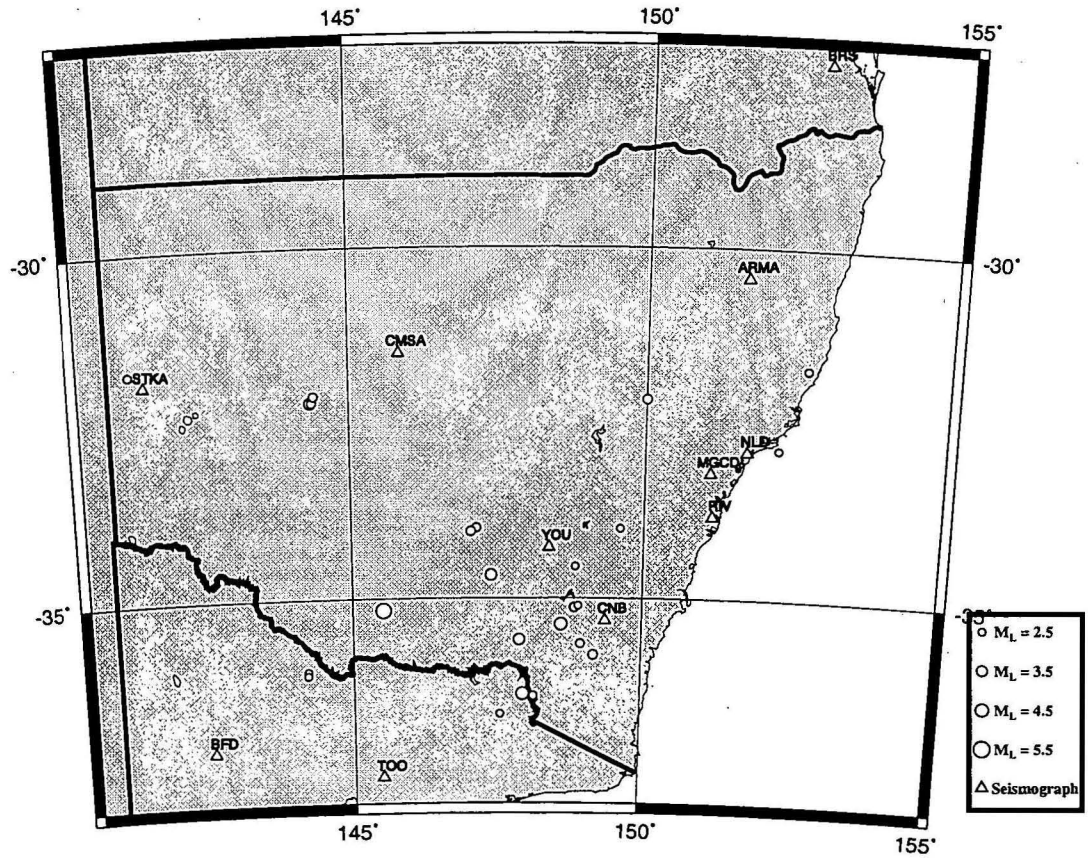
Several aftershocks occurred in July and August, the largest of which was a magnitude ML 2.0 event on August 26 at 0350 UT.

Wayne Peck, Vaughan Wesson and Gary Gibson

New South Wales and ACT

Most of the earthquakes in 1998 occurred in the southeast of the state although a small magnitude 2.6 event on 28 March offshore Newcastle was felt and reported by residents of Nelson Bay. The largest earthquake of the year, magnitude ML 4.2, had an epicentre just 60 km west of Canberra in the Brindabella Ranges where it was strongly felt. People in most Canberra suburbs reported their houses shaking and it was felt widely enough to draw up an isoseismal map. This earthquake triggered several accelerographs in the region.

On 22 May a magnitude ML 3.9 earthquake occurred near Cootamundra in New South Wales. It was felt in Cootamundra and Bethungra. An earthquake of magnitude ML 3.8 north of Ivanhoe in western NSW on 11 August at 18:25 UTC apparently caused no damage, nor was it widely reported.



Earthquake epicentres in NSW and ACT 1998, magnitude $M_L \geq 2.5$

Figure 10

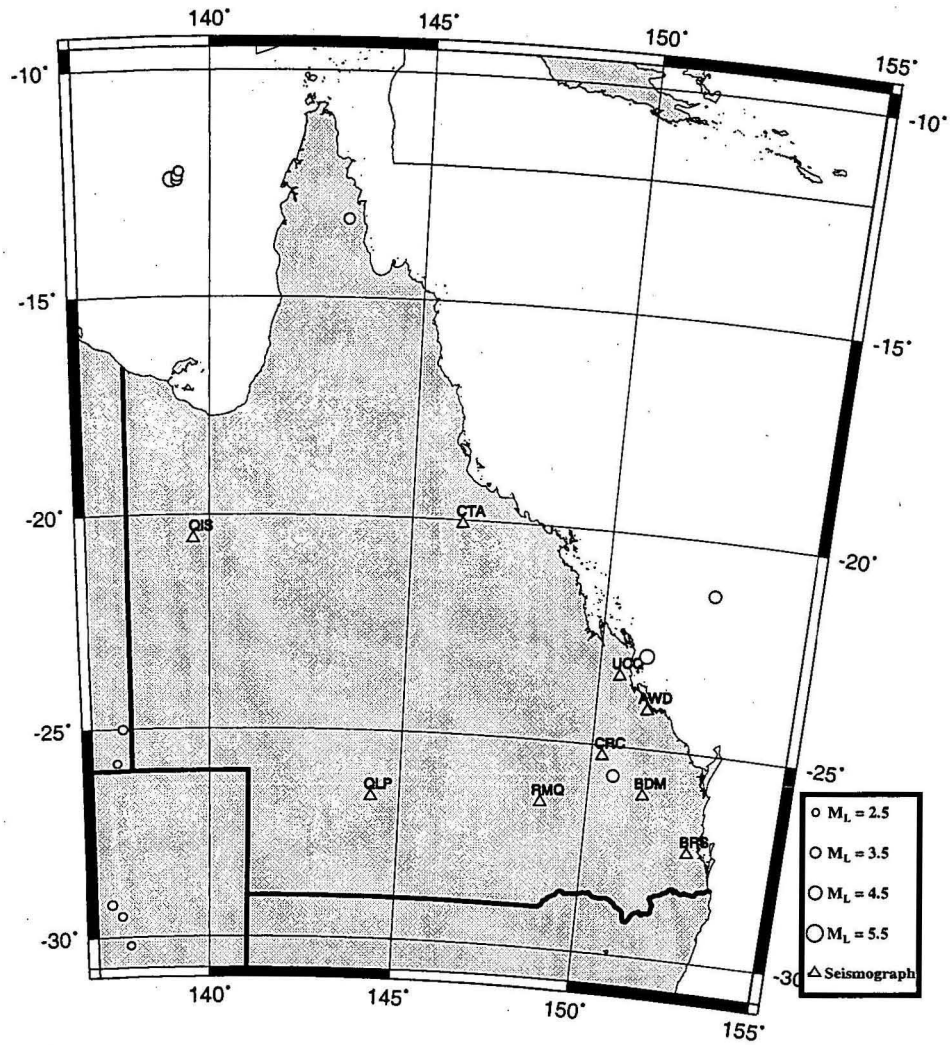
On 16 October at 13:46 UTC an earthquake of magnitude ML 3.9 occurred near Junee in southern New South Wales. This earthquake was reported felt in Junee, Temora, Wagga Wagga and Coolamon but no reports of damage were received. Three earthquakes above magnitude ML 2.5 occurred near West Wyalong during October.

On 7 November at 22:42 UTC an earthquake of magnitude ML 3.1 occurred near Wee Jasper in New South Wales, about 50km west of Canberra. This earthquake was reported felt. An earthquake of magnitude ML 2.5 occurred in the same area two days later. Earthquakes near Cooma and Mulwala were also reported felt in November.

On 31 December at 06:11 UTC an earthquake of magnitude ML 3.4 occurred near Michelago in southern New South Wales, where it was reported.

A mystery tremor struck the Hunter region about 11 pm EST on Tuesday 24 February. Many concerned residents rang emergency services but there was nothing recorded on the local area seismograph network in the Hunter. Seismologists concluded that F/A-18 Hornet fighters on training exercises in the region at the time might have been responsible but this was denied by RAAF officials.

Kevin McCue and Wayne Peck



Earthquake epicentres in Queensland 1998, magnitude $M_L \geq 2.5$

Figure 11

Queensland

Four of the eight earthquakes over magnitude 3 were in fact of magnitude 4 or more. A damage limiting feature of these earthquakes was that only one of the four was onshore, that of 13 February and it was widely felt though there were no reports of damage. The earthquake on 2 November offshore Central Queensland caused some surprise because, at magnitude 4.7 it was expected it would have been strongly recorded at Alice Springs on the array. In fact the signal to noise ratio was quite small, indicating a highly attenuating path.

1998-02-13	2320	150.675	25.645	4.0	Narayen	Widely felt
1998-06-30	0258	152.66	22.66	4.1	Off Rockhampton	Just a single felt report
1998-08-14	0827	151.20	28.25	2.5	Coolmunda Dam	Some reports from a very limited area
1998-11-02	1709	152.48	22.03	4.7	Off Rockhampton	Isolated felt reports.

Above is a list of the earthquakes reported felt in Queensland, at a time when earthquake monitoring undertaken by the University of Queensland on State Government contract was under review and actually ceased for more than a year.

Russell Cuthbertson

NETWORK OPERATIONS 1998

Several stations were removed during the year including the seismographs at Warburton (WBN) and Woolibah (WOOL) in Western Australia The old site KLG was reoccupied when WOOL was closed. A new site was selected near Marble Bar and a borehole drilled to set up a new IRIS station. The project is on hold until formal approval to use the land can be gained. With the change over from Optus satellite to Telstra cable communication, suitable lines were not available at Warburton. A new station with a single component vertical Willmore seismometer was established at Docker River to replace that at Warburton, the intention being to replace the Wilmore with a three component broad-band Guralp seismometer when one became available. Data recording commenced 01 December but the remote site was vandalised about 24 December effectively closing the station.

At Kakadu the remote site was totally destroyed by a bushfire on 21 June and the station had to be rebuilt. At Narrogin, modifications were made to the station in October by personnel from Albuquerque Seismological Laboratory. The digitisers (HRDCU and LRDCU) were replaced with one 12 channel digitiser module. The continuous broad band sampling rate is still 20 samples/second but triggered events are sampled at 40 samples/second. A Kinemetrics FBA 23 three component accelerometer, event triggered and sampling at 80 samples/second was installed. At Mundaring a larger hard disc was installed to give a greater buffer storage capacity.

A test station SYMN was established at the new AGSO office at Symonston in the ACT.

Calibration curves for the digital stations of the AGSO National Seismograph Network are presented in the 1995 Annual Report (McCue and Gregson, 1997). Corresponding curves for many of the analogue stations were presented in the 1990 Annual Report as separate figures for Eastern and Western Australian networks.

The States The ANU closed the rest of its network in south-eastern Australia including YOU, and the Seismology Research Centre added a new seismograph to their Victorian network at Hexham. There were no changes to the network in South Australia.

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

ACCELEROGRAPH DATA

In Western Australia and the Northern Territory
Seven earthquakes were recorded on the Cadoux accelerograph in 1998. Five were small (ML 2.5 or less), close (less than 10 km) Cadoux earthquakes. The largest of these, a magnitude ML 2.5 earthquake resulted in a peak ground acceleration of 372 mm/s^{-2}. The other two were for Yorkrakine earthquakes at a distance of 81 km. The largest of these had a magnitude ML 3.4 and resulted in a peak ground acceleration of 4 mm/s^{-2}.

Three Banda Sea earthquakes at distances between 650 km and 970 km, were recorded in 1998 on the Darwin accelerographs with peak ground accelerations of 6 mms^{-2} or less. On 25

March, a very deep magnitude 6.6 earthquake rocked the city gently and was recorded on the DRS accelerograph. There were no recordings on the Goomalling (GOK) or Perth accelerographs (KPK and EPS).

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 and Inlet Tower at Googong Dam NSW. The aging SMA-1s at the Animal Health Laboratory in Geelong, Victoria were replaced with Kelunjis by SRC seismologists. Two new accelerographs were set up at Wollongong by AGSO and the NSW Department of Public Works and Services, one on rock the other on soil foundations.

P Gregson, K McCue, G Gibson and W Peck

In South Australia
JUMP instruments in Adelaide and in the mid-north continued to provide data and were triggered on the earthquakes at:

Cleve on the Eyre Peninsula on 26 February magnitude ML 4.5, recorded on NAP, WHY and PTP, and

Nairne on 12 November magnitude ML 2.8, recorded at or near Adelaide on GHS and TUK.

David Love

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, 1998

Table 5 lists earthquakes that occurred throughout the world in 1998 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, 1998) and SEAN bulletin and are plotted in figure 2. The death toll was almost 9000, the two earthquakes in Papua New Guinea and Afghanistan causing most of the fatalities.

Papua New Guinea 17 July More than 2100 people were killed in Papua New Guinea following a major magnitude 7.0 earthquake and subsequent tsunami off the north coast on 17

July. The earthquake struck at dusk on a Friday evening before a long weekend and as a result, news of the tragedy and the disaster response were slow to emerge.

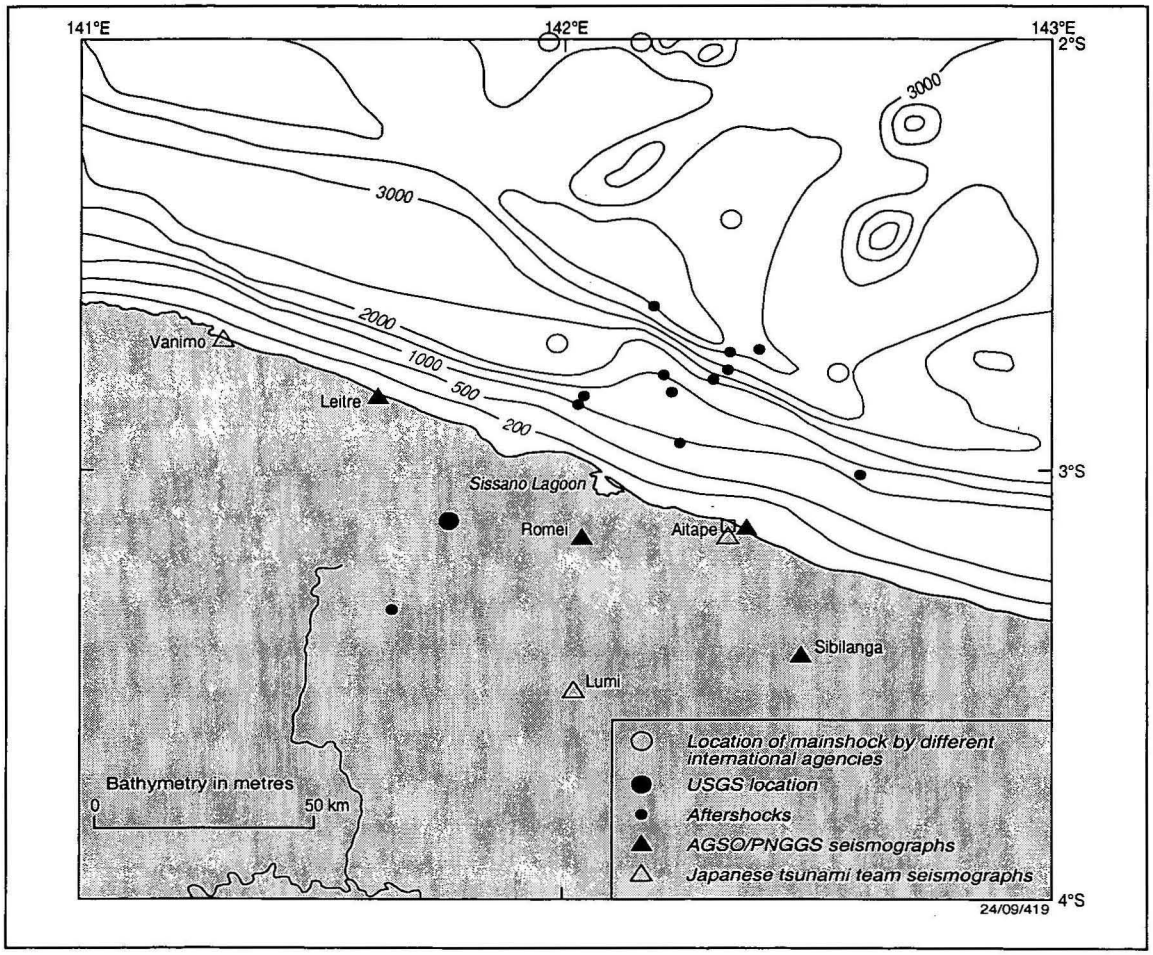


Figure 12 Mainshock and some aftershock locations near Sissano Lagoon, PNG

The earthquake rupture commenced about 50 km offshore near the New Guinea trench and generated a tsunami which struck the exposed coastline of the Sissano lagoon region some 10 minutes or so after the mainshock and about the time of a large aftershock. Reports of the relative timing of the mainshock, aftershock and tsunami arrival were contradictory which is understandable. In the 10 km wide zone fronting the lagoon, the tsunami reached 10 m height above mean sea level but rapidly decreased in height to either side. The series of large waves following the initial withdrawal of the sea swept all before them; villages, boats, trees and a bridge. The villagers had no escape from the coastal dune with only the ten or so minutes warning following the strong shaking of the earthquake and their only exit to the safety of high ground a 5 km trek to the eastern end of the beach. In retrospect this was a disaster waiting to happen, large earthquakes are relatively frequent along the north coast and several tsunamis have struck the shore; in 1907, 1930, 1935, and 1970, none though as large as this one (Everingham, 1977; Ripper and Letz, 1999).

AGSO with the assistance of AusAID, sent a team of AGSO and PNGGS seismologists to the area in late July to monitor aftershocks and report on the earthquake and tsunami. They met an International team assembling in Wewak to study the tsunami and its effects which enabled the two teams to coordinate their seismograph deployments.

The distribution of well located aftershocks shown above in a rectangular region offshore some 40 km x 30 km, indicates that the near horizontally dipping nodal plane striking parallel to the coast was probably the fault plane. The most likely cause of the tsunami was a non-uniform slip distribution on the offshore fault, 5m slip on the central 10 km section of the

fault, coupled with seafloor topographic focussing of the tsunami. There is considerable debate about the origin of the tsunami (Geist, 2000) which can be traced back to the original epicentre location onshore computed by the USGS. Their subsequent locations moved it progressively offshore into the region of the well located aftershocks. There has been no clear unequivocal evidence found to indicate that a submarine landslide or slump was the cause of the tsunami, no fresh backscarp or toe, no blocky sediment pile.

Antarctica 25 March Seismologists were still processing data from the Indonesian earthquake at 02:45 on 25 March which was felt in Darwin when the large P-waves from a great Antarctic earthquake were observed arriving at Mundaring by seismologist Lynn van Reeken who raised the alarm.

This intraplate earthquake on 25 March in the Southern Ocean off Antarctica was a great surprise to most seismologists. Rated magnitude Mw 8.1 it was the largest earthquake of the year and the largest ever seen in Antarctica. The previous largest known Antarctic earthquake had a magnitude of just 5.2 so both the likely mechanism and tsunami potential of this great earthquake were unknown. A tsunami watch for Australia issued by the Australian Tsunami Alert Service was called off at 9:30 pm EST when NTF staff detected no tsunami at the expected arrival time on a tide gauge they were monitoring in Tasmania.

The epicentre was not on a fracture zone or mid ocean ridge spreading segment and was more than 500 km NW of the Balleny Is hotspot; it was one earthquake that was unequivocably intraplate. The lack of past earthquakes is obviously not a sensible basis for neglecting the threat of earthquakes anywhere on the planet. So isolated was the epicentre that as far as is known, no human felt this great earthquake which is rather amazing.

Information including annual reports on tsunamis can be obtained from the Tsunami Newsletter (1998) or the ITIC homepage at: http://www.shoa.cl/oceano/itic/frontpage.html.

Kevin McCue

MONITORING OF NUCLEAR EXPLOSIONS

There were three nuclear explosions detected during 1998, all on the Indian Subcontinent. Other Nuclear Weapons States abided by an agreed moratorium on testing during the year. Details can be downloaded from the AGSO database on the web site (www.agso.gov.au), and are summarised as follows:

Pokaran India 11 May at 06:45:00 UTC
A single event was recorded throughout Australia with an equivalent body wave magnitude of mb 5.0 equivalent to a yield of 5 – 20 ktonnes of TNT. The NEIC estimate using worldwide data was mb 5.2 equivalent to a blast with a yield in the range 10 – 40 ktonnes of TNT.

Pokaran India 13 May at 10:13:42 UTC
Reports attributed to the Indian Government were that two sub kiloton devices were detonated however no trace could be found on Australian seismograms, nor on Pakistan seismograms at Nilore at a distance of 700 km.

Southwest Pakistan 28 May at 10:16:15 UTC
A single event was recorded across Australia with an equivalent body wave magnitude of mb 5.0 equivalent to a yield of 5 – 20 ktonnes of TNT. The NEIC estimate using worldwide data was mb 4.8. Reports attributed to the Pakistan Government indicated that five underground nuclear explosions were detonated on this day but only a single event was detected on Australian and overseas stations.

Southwest Pakistan 30 May at 06:45:54 UTC

A single event was recorded on some Australian stations with an equivalent body wave magnitude of mb 4.5, equivalent to a yield of under 10 ktonnes of TNT. The NEIC estimate using worldwide data was mb 4.7. It was clearly smaller than the earlier event.

David Jepsen and Spiro Spiliopoulos

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Table 1 Australian earthquakes 1998, magnitude ML ≥ 3.0

Source	Date UTC	Time UTC	Lat S	Long	Depth km	ML	Place
ADE	19980128	84506.5	-32.89	138.6	5	3.3	24 km NW Peterborough SA felt MM4
ADE	19980129	210605.1	-34.18	136.9	5	3	Spencer Gulf SA
AUST	19980130	165444.1	-13.25	143.18	10	3.5	C York Qld
MUN	19980131	132238.9	-21.214	120.399	5	3.7	68 km E Marble Bar WA
AUST	19980204	143626.8	-19.795	133.966	10	3.3	Tennant Creek NT
MUN	19980205	215907.1	-38.831	110.577	5	3	776 km SW Albany WA
MUN	19980208	44604.7	-17.831	122.259	5	3	16 km N Broome WA
MUN	19980211	85947.2	-23.558	115.263	5	3	117 km S Nanutarra WA
AUST	19980211	141719.3	-19.882	134.051	12	3.5	Tennant Creek NT
MUN	19980213	51049	-17.484	124.087	5	3.3	52 km E Derby WA
AUST	19980213	232051.5	-25.7	150.62	0	4	70 km west of Munduberra Qld.
AUST	19980214	182334.2	-35.372	148.604	0	4.2	Brindabella Mtns NSW, 60 km W Canberra. Felt throughout Canberra and minor damage at Argalong Station.
ADE	19980226	141304.2	-33.16	136.87	5	3.8	Eyre Peninsula SA near Cleve.
AUST	19980309	124042.9	-32.143	150.003	3	3.1	Cassilis NSW
ADE	19980311	32755.1	-36.615	140.447	10	3.4	Near Bordertown, Padthaway SA
MUN	19980312	124016.1	-23.75	113.308	5	3.2	130 km NNW Carnarvon WA
MUN	19980313	65733.4	-31.465	122.182	5	3.7	90 km NNE Norseman WA
MUN	19980322	175344.5	-31.516	122.164	5	4	85 km NNE Norseman WA
AUST	19980329	35017.6	-12.397	139.12	0	4.9	Gulf of Carpentaria Qld
AUST	19980329	134127.5	-12.406	139.256	10	3.6	Gulf of Carpentaria Qld
MUN	19980329	200647.3	-14.228	129.372	35	4.2	172 km NNE Kununurra WA
MEL	19980404	95542.7	-38.662	146.146	18	3.3	Fish Creek Vic
MUN	19980410	34645.2	-32.589	122.343	5	4.3	70 km SE Norseman WA
AUST	19980413	43302.4	-19.867	134.055	3	3	Tennant Creek NT
AUST	19980413	230313.2	-12.941	136.13	10	3.2	Gulf of Carpentaria NT
MUN	19980429	103408.4	-31.207	117.477	3	3	10km E Wyalkatchem WA
AUST	19980506	52933.5	-34.149	136.878	10	4.3	Spencer Gulf, SA
MUN	19980511	121126.6	-33.694	118.08	1	3.2	17 km SSW Nyabing WA
MUN	19980512	5900.9	-16.802	120.71	5	3	205 km NW Broome WA
AUST	19980515	235417.1	-26.094	130.941	5	3.4	NT/SA border
AUST	19980516	155541.4	-12.313	139.265	10	3.7	Gulf of Carpentaria Qld
MUN	19980518	214502.3	-24.705	111.366	5	3	235 km W Carnarvon WA
AUST	19980522	190114.4	-35.59	147.87	6	3.8	Near Cootamundra NSW, felt strongly and minor damage in farm buildings close to the epicentre
AUST	19980523	185026.2	-12.213	139.3	10	3.1	Gulf of Carpentaria Qld
ADE	19980530	190630.6	-37.872	139.826	23	3	Near Beachport SA
MUN	19980607	224256.2	-31.464	117.683	5	3.6	18 km N Kellerberrin WA
ADE	19980609	10050.9	-27.939	135.844	3	4.4	Oodnadatta SA
MUN	19980610	133103.3	-31.475	117.671	1	3	18 km N Kellerberrin WA
MUN	19980610	144602.8	-31.473	117.694	5	3	18 km N Kellerberrin WA
MUN	19980612	122837.2	-31.459	117.673	2	3.4	18 km N Kellerberrin WA
MUN	19980613	201329.6	-18.955	117.531	5	3.1	185 km Pt Hedland WA
AUST	19980616	151300.1	-23.651	134.465	7	3.2	Alice Springs NT. Felt in Alice Springs and by Park Rangers 50 and 100 km ENE Alice Springs.
MUN	19980622	94651.3	-21.724	119.719	5	4	63 km S Marble Bar WA

AUST	19980623	83837.9	-26.075	131.855	10	3.1	Uluru NT
AUST	19980625	73904.9	-19.818	133.881	1	4.1	Tennant Creek NT
MUN	19980627	70155.9	-30.815	121.605	5	3.5	15 km SE Kalgoorlie WA
AUST	19980630	25822.3	-21.253	152.65	3	4.1	Great Barrier Reef Qld
ADE	19980702	150901.2	-33.597	135.007	22	3	Elliston SA
MUN	19980713	53150.3	-15.904	120.981	5	3.1	265 km NW Broome WA
AUST	19980715	155155.4	-34.159	136.864	10	3.3	Spencer Gulf SA
AUST	19980716	71307.3	-37.296	155.626	0	3.5	Tasman Sea
AUST	19980716	214344.2	-35.101	139.741	0	3.1	Karoonda SA
MEL	19980717	12239.2	-36.367	147.942	21	4.3	Corryong Vic
MUN	19980717	184622.5	-26.502	127.845	11	3.4	132 km ESE Warburton WA
MUN	19980721	122355.9	-28.226	113.504	5	3	90 km SW Kalbarri WA
AUST	19980723	14912.2	-23.033	131.354	0	3	Near Yuendemu NT
MUN	19980731	4632.4	-24.301	125.694	5	3.2	220 km NW Warburton WA
AUST	19980803	134100.6	-19.898	134.02	2	3.5	Tennant Creek NT
AUST	19980804	14552.6	-13.211	132.534	0	3.4	Gimbat NT
AUST	19980811	182528.8	-32.178	144.355	0	3.8	Baden Park HS NSW
AUST	19980817	5825.8	-32.087	144.417	0	3	Baden Park HS NSW
MUN	19980817	24531.8	-17.662	123.565	5	3	40 km S Derby WA
AUST	19980817	45713.6	-29.111	135.104	0	3.6	Near Coober Pedy SA. Felt
MUN	19980819	23400	-17.039	120.093	5	3.1	250 km NW Broome WA
AUST	19980819	111244	-35.654	148.951	0	3	Orroral HS near Naas ACT. Felt
AUST	19980824	221708.4	-40.892	146.135	7	3	Bass Strait Tas
AUST	19980911	20757.3	-26.406	132.813	0	3.1	Musgrave Range SA
MUN	19980913	225101.1	-12.454	123.208	5	3.3	32 km SE Ashmore Is WA
MEL	19980915	132357.7	-38.405	147.236	0	3.4	Seaspray Vic
AUST	19980927	52019.3	-19.818	133.935	7	3.8	Tennant Creek NT
AUST	19980927	223208.3	-38.357	144.779	0	3.8	Near Portsea Vic
AUST	19981002	94343.4	-13.774	136.388	0	3.1	Groote Eylandt NT. Felt
AUST	19981008	120516.5	-39.455	145.81	10	3.3	Bass Strait
MUN	19981014	222612.1	-31.033	121.32	5	3.6	20 km ESE Coolgardie WA
AUST	19981016	134614.6	-34.669	147.385	16	3.9	Temora NSW. This earthquake was felt widely.
AUST	19981021	235937.2	-33.994	147.129	0	3	Near West Wyalong NSW
AUST	19981025	170155	-19.836	133.88	9	3.3	Tennant Creek NT
AUST	19981028	113329.8	-34.041	147.035	0	3.1	Near West Wyalong NSW
MUN	19981102	22618.1	-19.538	113.53	10	4.6	Off WA coast near Exmouth.
AUST	19981102	170938.1	-22.808	151.146	0	4.7	Off central Queensland coast. Felt
AUST	19981107	224250.5	-35.132	148.832	16	3.1	Wee Jasper NSW. Felt
MUN	19981112	191933.8	-13.05	121.83	6	4.5	Near Scott Reef, Indian Ocean
AUST	19981113	115437.4	-18.982	124.896	7	3.8	Great Sandy Desert WA
MUN	19981117	190203.3	-13.143	121.919	5	3.5	100 km N Scott Reef WA
AUST	19981203	130924.4	-19.75	133.842	7	3.1	Tennant Creek, NT
AUST	19981204	221232.1	-13.143	136.324	10	3	Arnhem Land, NT
ADE	19981217	235438.4	-32.382	138.371	8	3	Near Port Augusta SA
AUST	19981231	61136.3	-35.812	149.171	0	3.2	This earthquake was felt at Willandra and Burra NSW and in south Canberra and north Cooma .

Table 2. Large or Damaging Australian Earthquakes, 1788 - 1998

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		7.3		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	7.0	6.8		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	6.9	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 MacKay 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 MacKay WA
1978 05 06	1952 19	19.55	126.56		6.2		L MacKay 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

Table 3 Australian accelerograph data, 1998

Date UTC	*Time*	*Lat°S*	*Long°E*	*ML /mb*	*Recording Site * Epicentre*	*H/E ~ km s-p sec*	*Comp*	*T sec*	*Acc mms⁻²*
1 3	2042	30.80	117.17	1.8	CMC	6/6	PZ	0.037	1
							PN	0.021	1
							PE	0.019	2
							SZ	0.047	4
							SN	0.030	14
							SE	0.023	9
1 24	O204	6.75	129.62	mB 4.9	DPH	650	SZ	0.236	3
							SN	0.227	4
							SE	0.258	6
2 10	OO54	30.82	117.15	1.6	CMC	9/9	PZ	0.077	1
							PN	0.021	1
							PE	0.021	1
							SZ	0.028	3
							SN	0.028	10
							SE	0.020	7
2 14	18 23	35.37	148.60	4.2	Black Mtn Tower Base ACT	4.7s	SZ	0.08	1.5
							SN	0.08	1.9
							SE	0.08	1.6
					Black Mtn Tower Top	4.7s	SZ	0.2	3.6
							SN	0.2	3.9
							SE	0.2	3.4
					Googong Dam Tower NSW	6.1s	SZ	0.05	2.8
							SN	0.075	4.6
							SE	0.075	4.3
3 25	O245	7.35	128.68	mB 6.6	DRS	573	SZ	0.127	3
							SN	0.161	2
							SE	0.095	1
4 25	2219	30.81	117.09	1.8	CMC	3/3	PZ	0.020	5
							PN	0.020	4
							PE	0.020	9
							SZ	0.069	10
							SN	0.020	4
							SE	0.018	6
6 10	1331	31.48	117.68	2.0	CMC	81/81	PZ	0.113	0
							PN	0.113	1
							PE	0.113	0
							SZ	0.070	1
							SN	0.070	1
							SE	0.070	1
6 12	1228	31.46	117.67	3.4	CMC	81/81	PZ	0.114	2
							PN	0.114	1
							PE	0.114	1
							SZ	0.083	2
							SN	0.083	4
							SE	0.083	4
7 17	0122	36.37	147.94	4.3	Wambrook NSW	9.9s	SZ	0.07	1.4
							SN	0.14	2.2
							SE	0.06	3.1
					Aranda ACT	19.5	SZ	0.08	.25
							SN	0.2	.20
							SE	0.25	.22
					Inverness Vic		SZ		
							SN		
							SE		

Table 3 (cont.) Accelerograph data, 1998

8 19	11 12	35.65	148.95	3.0	Wambrook NSW	6.3s	SZ	0.06	.37
							SN	0.07	.37
							SE	0.06	.64
					Symonston ACT	4.4s	SZ	0.09	.33
							SN	0.025	.74
							SE	0.03	1.3
9 16	O553	7.93	123.63	mB 4.2	DRS	970	SZ	0.308	3
							SN	0.346	4
							SE	0.346	6
9 21	1144	30.80	117.08	2.5	CMC	4/4	PZ	0.020	11
							PN	0.020	9
							PE	0.020	14
							SZ	0.018	67
							SN	0.018	372
							SE	0.018	163
9 21	2258	30.79	117.08	1.7	CMC	4/4	PZ	0.028	2
							PN	0.028	2
							PE	0.280	2
							SZ	0.019	20
							SN	0.019	110
							SE	0.019	41
9 27	22 32	38.36	144.78	3.8	Surry Hills Vic	??	SZ	0.05	4.1
							SN	0.05	5.6
							SE	0.05	2.7
					Moonee Ponds Vic		SZ	0.08	3.7
							SN	0.08	9.4
							SE	0.08	6.3
10 16	13 46	34.67	147.39	3.7	Cotter Dam ACT	??	SZ	0.07	0.16
							SN	0.07	0.12
							SE	0.07	0.15
11 07	22 42	35.13	148.83	3.1	Cotter Dam ACT	2.4s	SZ	0.04	2.2
							SN	0.04	2.1
							SE	0.04	2.7
11 09	06 25	35.13	148.83	2.5	Cotter Dam ACT	2.4	SZ	0.04	1.0
							SN	0.04	1.4
							SE	0.04	1.2
12 31	06 11	35.81	149.17	3.2	Cotter Dam ACT	5.89 s	PZ	0.03	0.9
							PN	0.03	1.3
							SE	0.03	0.6
					Wambrook NSW	5.96s	SZ	0.07	1.7
							SN	0.07	3.3
							SE	0.03	2.9
					Dalton NSW	13.0s	SZ	0.03	0.59
							SN	0.08	2.2
							SE	0.03	2.0
12 31	08 15	34.55	148.84	2.5	Dalton NSW	4.4 s	SZ	0.05	.57
							SN	0.08	1.5
							SE	0.08	2.7

~ H/E is hypocetral/epicentral distance in km or distance over focal depth km

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

Table 4 Large or destructive World earthquakes, 1998

Source	*Date*	*UTC*	*Lat*	*Long*	*Depth*	*mb*	*Ms*	*Mw*
ISC	**19980104**	**61156.5**	**-22.231**	**170.909**	**76**	**6.1**	**6.9**	**7.4**

Loyalty Is. region.

PDE 19980110 035042 41.08 114.50 30 5.8 5.7
NORTHEASTERN CHINA. 70 people killed, 11 500 injured, over 70 000 houses destroyed, damage to the Great Wall in Hebei Province, felt Beijing.

QED 19980110 82005.2 14.225 -91.589 33 6.3 6.2 6.6
Guatemala. Sixteen people injured in Quazaltenango city and three people injured in San Marcos department. Damage in Quazaltenango, San Marcos and Solola departments.Landslides and power outages occurred at Quazaltenango. Felt in El Salvador, much of southern and western Guatemala and coastal areas of southeastern Mexico.

QED 19980130 121607.8 -24.118 -70.455 44 6.3 6.5 7.0
Near coast of Northern Chile. Minor damage in the Antofagasta area.

PDE 19980204 143321 37.08 70.09 33 5.6 6.1 6.0
AFGHANISTAN-TAJIKISTAN BORD REG. At least 2,323 people killed, 818 injured, more than 8000 houses destroyed.

PDE 19980220 121806 36.48 71.09 236 5.8 5.7 6.4
AFGHANISTAN-TAJIKISTAN BORD REG. One person killed, 8 injured

PDE 19980314 194027 30.15 57.60 9 5.9 6.9 6.6
NORTHERN IRAN. Five people killed, 50 injured, 2000 houses destroyed

QED 19980325 31224.7 -62.876 149.712 10 6.6 8.0 8.1
Southern Ocean Antarctica. This intraplate event caused a small tsunami and was the biggest earthquake this century not felt by humans.

PDE 19980326 162612 43.25 12.97 10 5.4 4.8
CENTRAL ITALY. One person died of a heart attack, additional damage after last year's earthquake of 26 September

QED 19980329 194816.0 -17.576 -179.061 527 6.5 6.2 7.2
FIJI ISLANDS REGION

PDE 19980410 150053 32.46 59.98 33 5.3 5.7 5.8
NORTHERN IRAN. At least 12 people killed, 10 injured

PDE 19980412 105533 46.25 13.65 10 5.3 5.7 6.0
AUSTRIA. One person died of a heart attack at Bovec, Slovenia

QED 19980503 233022.0 22.305 125.302 33 6.4 7.3 7.5
SOUTHEAST OF TAIWAN. Felt at Okinawa, Kyushu and Taiwan

QED 19980522 44850.2 -17.752 -65.418 24 6.0 6.6 6.5
CENTRAL BOLIVIA. 105 killed and about 200 injured in Aiquille-Totora area. Many buildings destroyed. Felt strongly in central Bolivia.

QED 19980530 62228.7 37.050 70.086 33 5.8 6.9 6.6
AFGHANISTAN - TAJIKISTAN BORDER REGION. At least 4700 people killed, 1500 injured and a number of villages completely destroyed in Takhar Province, Afghanistan.

PDE 19980627 135552 36.89 35.31 33 5.8 6.2 6.3
TURKEY. At least 145 people killed, more than 1500 injured.

PDE 19880709 051907 38.65 -28.63 10 5.7 6.0 6.2
AZORES ISLANDS. Ten people killed.

QED 19980716 115636.5 -10.978 166.095 110 6.3 7.1
SANTA CRUZ ISLANDS

PDE 19980717 045115 23.41 120.74 13 5.5 5.4 5.7
TAIWAN. Five people killed, 27 injured

AUST 19980717 84916.2 -2.800 142.000 5 5.9 7.1 7.0
OFFSHORE NEAR AITAPE PNG. At least 2100 people killed; hundreds injured; tsunami generated in the Sissano area; villages in the area were completely destroyed. AGSO and PNGGS seismologists installed a network of seismographs in the Aitape region to monitor aftershocks.

QED 19980729 71424.3 -32.324 -71.281 52 6.0 6.5
NEAR COAST OF CENTRAL CHILE. 2 people died; injuries in the Santiago area. Felt throughout much of central Chile.

QED 19980804 185918.2 -.551 -80.411 19 6.2 7.1 7.1
NEAR COAST OF ECUADOR. 3 people killed and 40 injured in the Bahia de Caraquez area. Damage and landslides

QED 19980820 64054.0 28.892 139.353 422 6.1 7.0
BONIN ISLANDS REGION. Felt.

PDE 19980827 090337 39.66 77.34 33 5.6 6.4 6.4
SOUTHERN XINJIANG, CHINA. At least 3 people killed, 7 injured

PDE 19980909 112759 40.04 15.98 10 5.2 5.2 5.6
SOUTHERN ITALY. One person killed by falling rock and another person died from a heart attack

QED 19980902 83727.2 5.453 126.746 33 6.4 6.7 6.8
MINDANAO PHIL. IS. Minor damage in the General Santos area. Felt strongly in southern Mindanao.

QED 19980903 173759.5 -29.308 -71.622 33 6.1 6.5 6.5
NEAR COAST OF CENTRAL CHILE. 2 people injured at La Serena. Felt widely in central Chile and also felt in Argentina.

QED 19980928 133429.7 -8.181 112.465 153 6.3 6.5
JAWA INDONESIA. 1 person killed, 200 homeless, 38 buildings collapsed and 62 damaged in the Malang area. Felt in central and eastern Jawa, Bali, Lombok and Sumbawa.

QED 19981109 53844.0 -6.895 128.981 33 6.4 7.0 7.0
BANDA SEA. Felt strongly on Ambon. Also felt at Darwin Australia

PDE 19981113 130111 27.79 53.61 33 5.3 5.1 5.4
SOUTHERN IRAN. Five people killed, 105 injured.

PDE 19981119 113815 27.31 101.03 33 5.2 5.6 5.6
SICHUAN, CHINA. Five people killed, 1543 injured.

QED 19981129 141031.4 -2.051 124.925 33 6.5 7.7 7.8
CERAM SEA. At least 34 people killed on Mangole and 153 people injured on Mangole and Taliabu. 7 people killed, 8 injured and several buildings damaged at Manado, Sulawesi. A timber factory sustained extensive damage, dozens of houses destroyed and landslides blocked a highway on Mangole.

PDE 19981211 201624 36.51 71.02 223 5.0 5.7
AFGHANISTAN-TAJIKISTAN BORD REG. Five people killed.

Table 5a The 10 Largest Earthquakes in the World Since 1900

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 Islands	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 5b Most Destructive Known Earthquakes on Record

(50,000 deaths or more)

(Listed in order of greatest number of deaths)

(From http://neic.usgs.gov/neis/eqlists/eqsmosde.lis)

Date	Location	Deaths	Mag	Comments
January 23, 1556	China, Shansi	830,000		
July 27, 1976	China, Tangshan	255,000	8.0	
August 9, 1138	Syria, Aleppo	230,000		
May 22, 1927	China, near Xining	200,000	8.3	Large fractures.
December 22, 856+	Iran, Damghan	200,000		
December 16, 1920	China, Gansu	200,000	8.6	Major fractures, landslides.
March 23, 893+	Iran, Ardabil	150,000		
September 1, 1923	Japan, Kwanto	143,000	8.3	Great Tokyo fire.
December 28, 1908	Italy, Messina	70,000 to 100,000 (estimated)	7.5	Deaths from earthquake and tsunami.
September, 1290	China, Chihli	100,000		
November, 1667	Caucasia, Shemakha	80,000		
November 18, 1727	Iran, Tabriz	77,000		
November 1, 1755	Portugal, Lisbon	70,000	8.7	Great tsunami.
December 25, 1932	China, Gansu	70,000	7.6	
May 31, 1970	Peru	66,000	7.8	$530,000 damage, great rock slide, floods.
1268	Asia Minor, Silicia	60,000		
January 11, 1693	Italy, Sicily	60,000		
May 30, 1935	Pakistan, Quetta	30,000 to 60,000	7.5	Quetta almost completely destroyed.
February 4, 1783	Italy, Calabria	50,000		
June 20, 1990	Iran	50,000	7.7	Landslides.

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

APPENDIX 1

ISOSEISMAL MAPS

Eight of the earthquakes during 1998 were sufficiently widely felt that questionnaires were distributed and the returned forms collated to draw up isoseismal maps; Brindabella NSW, Cleve SA, Padthaway SA, Cootamundra NSW, Corryong Vic, Orroral Valley ACT, Temora NSW, Michelago NSW

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).

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.

Isoseismal Map of the Brindabella earthquake NSW

14 February 1998

This earthquake occurred at 5:30 am ESST on 15th February. The few residents of homesteads in the Brindabella Mountains were reportedly shaken out of their beds; at Argalong Station a window was broken and minor non-structural cracking of the walls of an outhouse was reported. The noise of things shaking woke many Canberra and Tumut residents and at Burrinjuck Dam the shaking woke most people. It was felt as far as Harden-Murrumburrah to the northwest and Cooma to the south.

A bushwalker and his family camped at the summit of Mt Gingera were surprised by the intensity of shaking, frightening the children. An extract from the Canberra Times (16 February 1998) is shown below.

Accelerographs at Googong Dam and in the Black Mountain Tower were triggered as reported elsewhere in this report.

There were no aftershocks recorded in Canberra.

Earthquake shakes Canberra region

By IAN WARDEN

"I was terrified! It was like the earth was opening under us and that we were going to go under," a still-trembling Guillermina Barlin, of Brindabella Homestead, recalled with horror after yesterday morning's earthquake.

The earthquake, measuring 4.2 on the Richter scale, made the earth move for Canberrans right across the city but made it rock and roll for the Barlins.

Kevin McCue, of the Australian Geological Survey Organisation's Seismological Centre, went with several other colleagues to work at the centre in dawn because of the earthquake that, he said later, shook Canberra at precisely 5.33.34am.

Mr McCue said he was professionally and personally "absolutely broken hearted" that he had not felt the earthquake in Aranda (he was alerted by other means).

He said the quake, centred in a largely unpopulated area close to the Brindabella Homestead, about 28km south-west of Wee Jasper, about 60km from Canberra, had certainly been "very widely felt" in Canberra. Realising where the earthquake was focused he had telephoned the Brindabella Homestead at once to check that all was well.

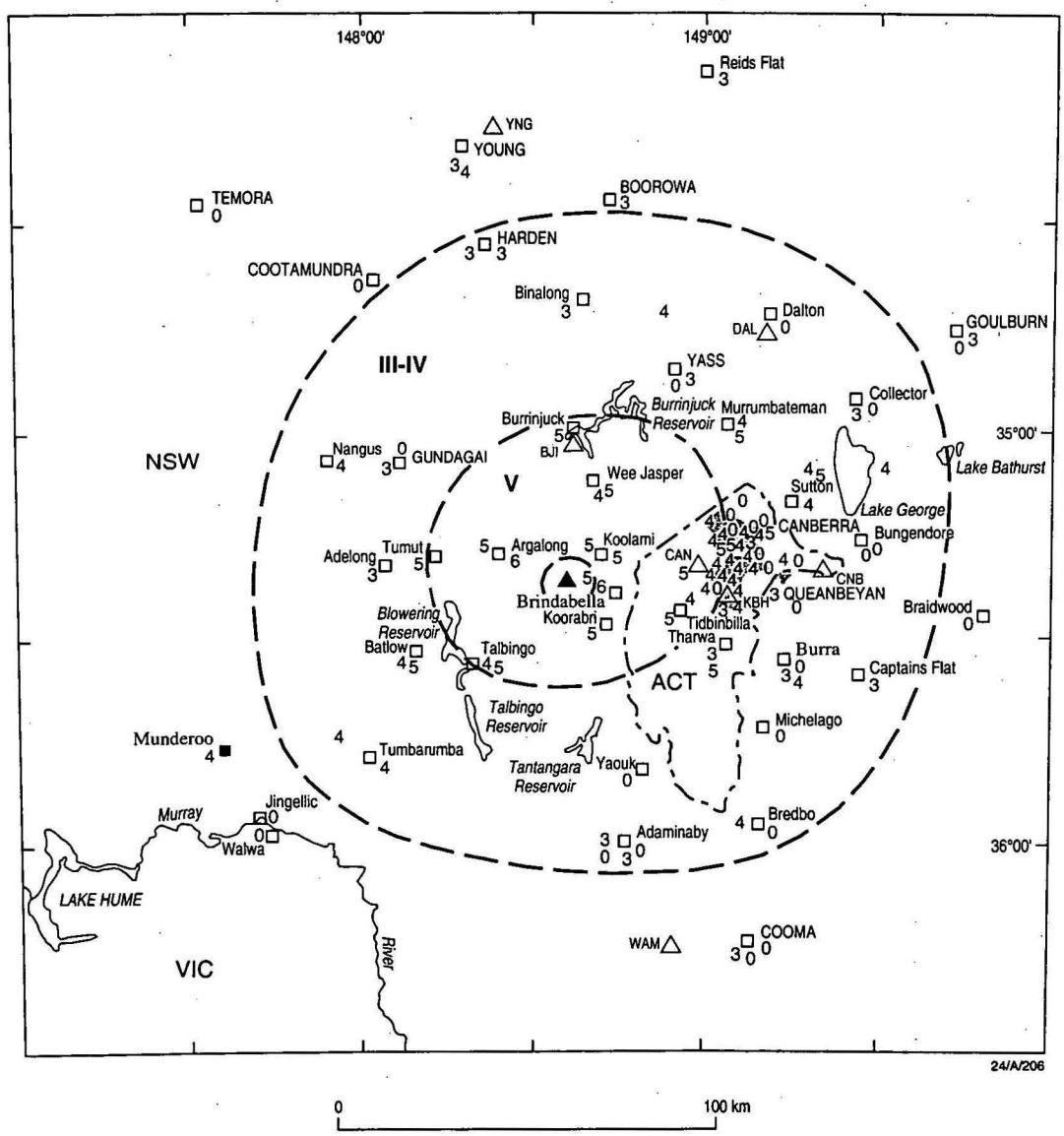
Mr McCue said the epicentre was just west of the homestead. As well as in Canberra, the

Continued on Page 2

The Seismological Centre's seismogram recording of yesterday's earthquake. The time is recorded at the bottom of the graph in universal coordinated time — the old Greenwich Mean Time.

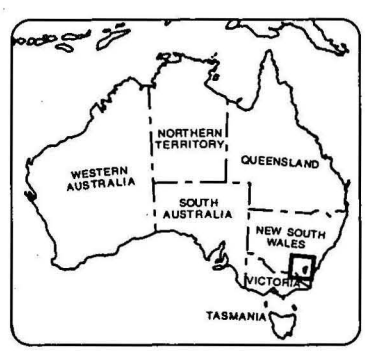
Contributors: This map was compiled by Kevin McCue.

ISOSEISMAL MAP OF THE BRINDABELLA EARTHQUAKE, NSW
14 FEBRUARY 1998



DATE: 14 February 1998
TIME: 18:23:34.2 UTC
MAGNITUDE: ML 4.2±0.2
EPICENTRE: 35.37°S 148.60°E
DEPTH: 0 km

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



Isoseismal Map of the Cleve earthquake South Australia

26 February 1998

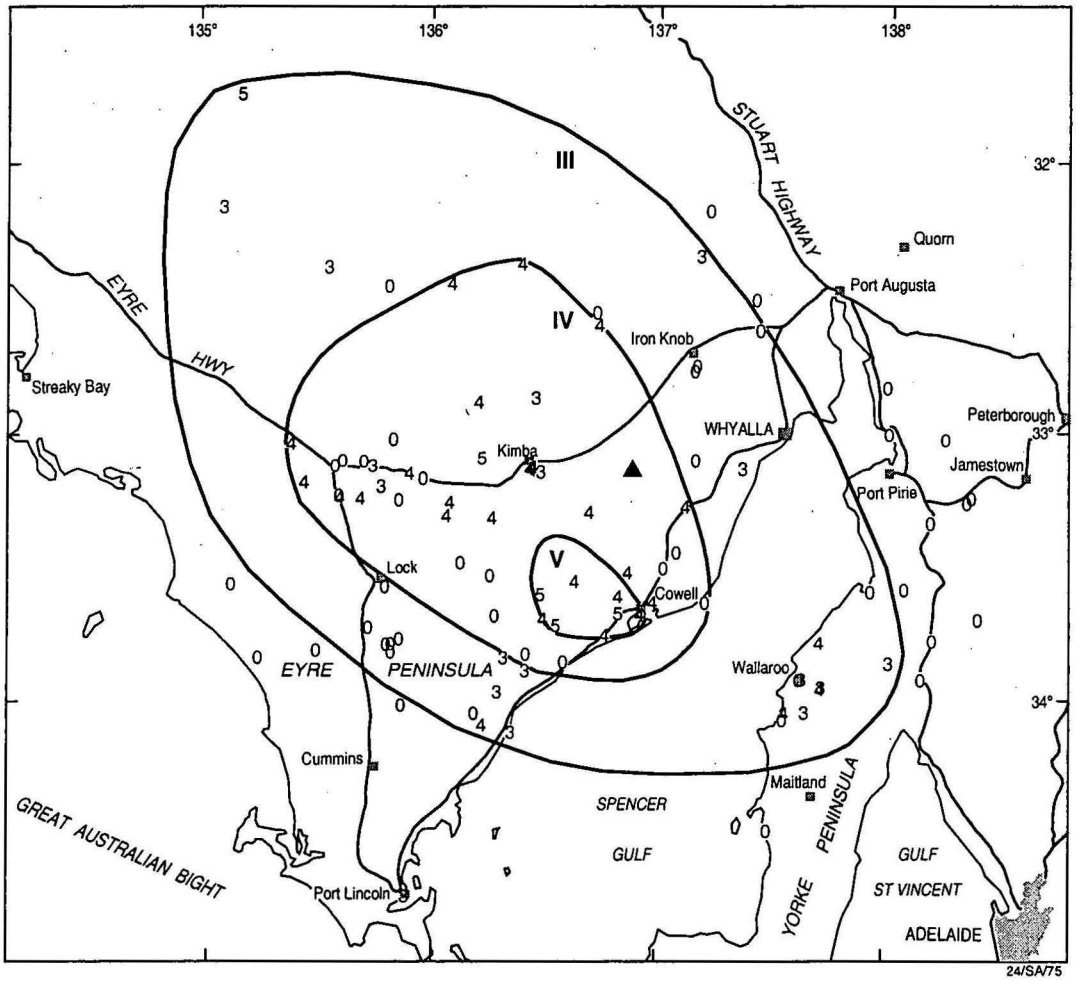
This earthquake occurred at 12:43 am on Friday 27 February local time. The epicentre was about 40km NNE of Cleve. It was felt strongly by people in the area, waking residents with a loud rumbling, shaking doors and windows quite strongly.

A questionnaire was distributed for an isoseismal map. Radio reports also asked people in remote areas to contact us if they felt the event. 155 questionnaires were sent out. From 101 replies and a number of phone calls the map was constructed. It is surprising how far to the north west that the event was felt, compared to other directions. Given the night hour, it is difficult to construct a good isoseismal map, particularly at the lower intensities. As there were 4 recorders within 100km the depth of 28 km is more reliable than usual.

This earthquake was the largest on Eyre Peninsula since about 1980. The magnitude was initially estimated at 4.1, however inclusion of all stations, digital and analogue, suggests that the magnitude was probably around 4.5, which would accord better with the results of the isoseismal map. A duration magnitude of 3.6 was computed, which is particularly low. All 3 JUMP accelerometers (Joint Urban Monitoring Program) in the Whyalla, Port Pirie areas triggered.

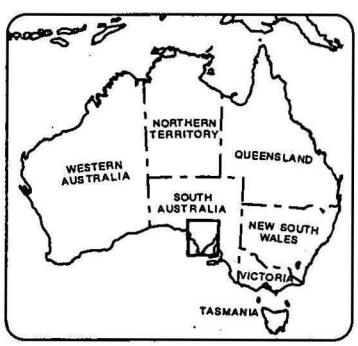
Contributors: This map was compiled by David Love.

ISOSEISMAL MAP OF THE CLEVE EARTHQUAKE, SA
26 FEBRUARY 1998



DATE: 26 February 1998
TIME: 14:13:04 UTC
MAGNITUDE: 3.8 ML
EPICENTRE: 33.16°S 136.87°E
DEPTH: 5 km

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



Isoseismal Map of the Padthaway earthquake, South Australia

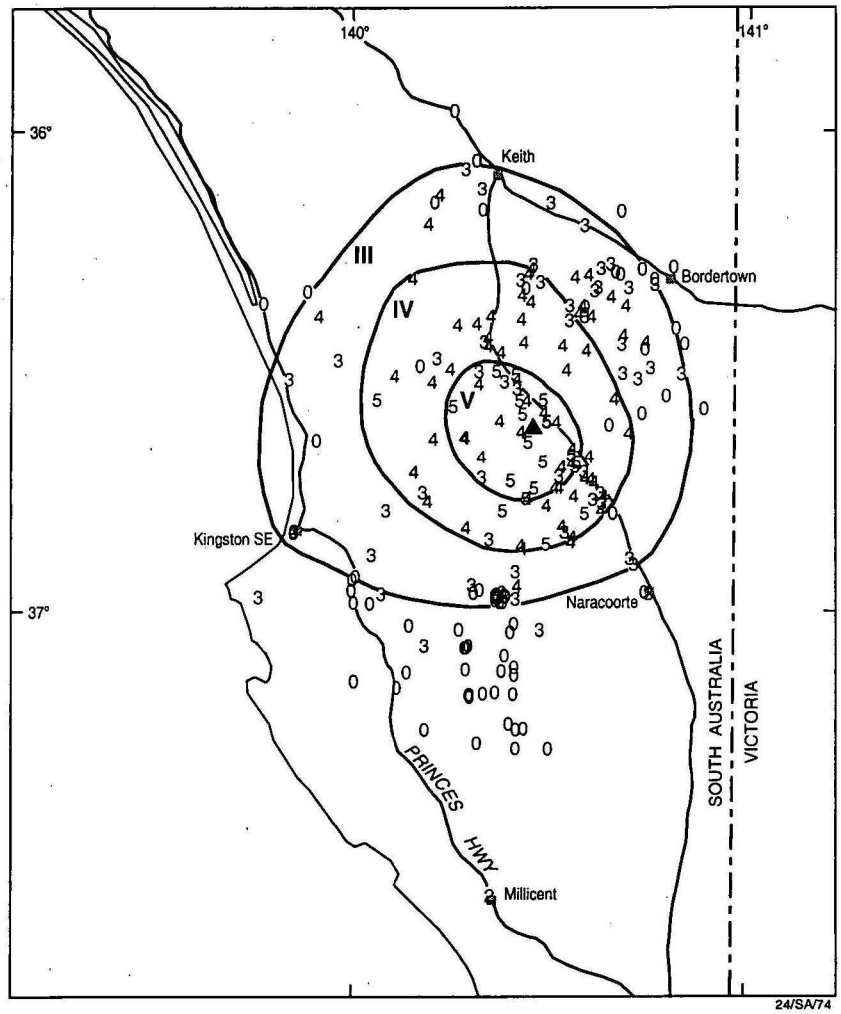
11 March 1998

This earthquake occurred at 1:58pm on Wednesday 11 March local time. The epicentre was about 10km SW of Padthaway in the South East. People near the epicentre heard a loud noise similar to an explosion, or to the sound of heavy vehicles in the vicinity. A jolt or heavy shaking making windows and doors rattle accompanied the noise.

The time of day was good for isoseismal reporting, and the area is fairly well populated. Thus a questionnaire was distributed to construct an isoseismal map. 460 forms were sent, more than usual, but using a cheap roadside delivery method in a number of areas. 239 replies were received, and most of these were used in the map. About 60% of the replies were plotted to Section and Hundred (land subdivision) descriptions, meaning that they were usually accurate to within 200m. The result is quite a detailed map, despite the relatively low magnitude of 3.7.

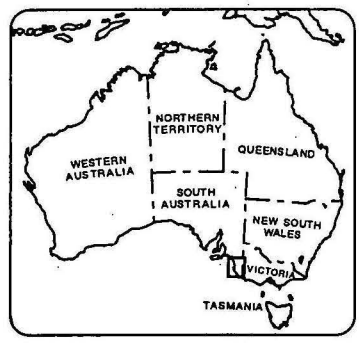
Contributors: This map was compiled by David Love

ISOSEISMAL MAP OF THE PADTHAWAY EARTHQUAKE, SA
11 MARCH 1998



DATE: 11 March 1998
TIME: 03:27:55 UTC
MAGNITUDE: 3.4 ML
EPICENTRE: 36.62°S 140.45°E
DEPTH: 5 km

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



Isoseismal map of the Cootamundra earthquake New South Wales

22 May 1998

An earthquake shook central NSW at 5:01 am on Saturday morning 23 May (EST), waking residents of Cootamundra, many of them frightened out of bed to investigate its cause. The computed epicentre was 16 km WNW of Cootamundra in the triangle it forms with Stockinbingle and Bethungra where it was equally strongly felt. A few farmers in the epicentral region reported minor damage, cracks in unreinforced masonry walls, garage doors stuck and tiles off walls. Some had crockery thrown off shelves, another reported that pavers around the pool were displaced.

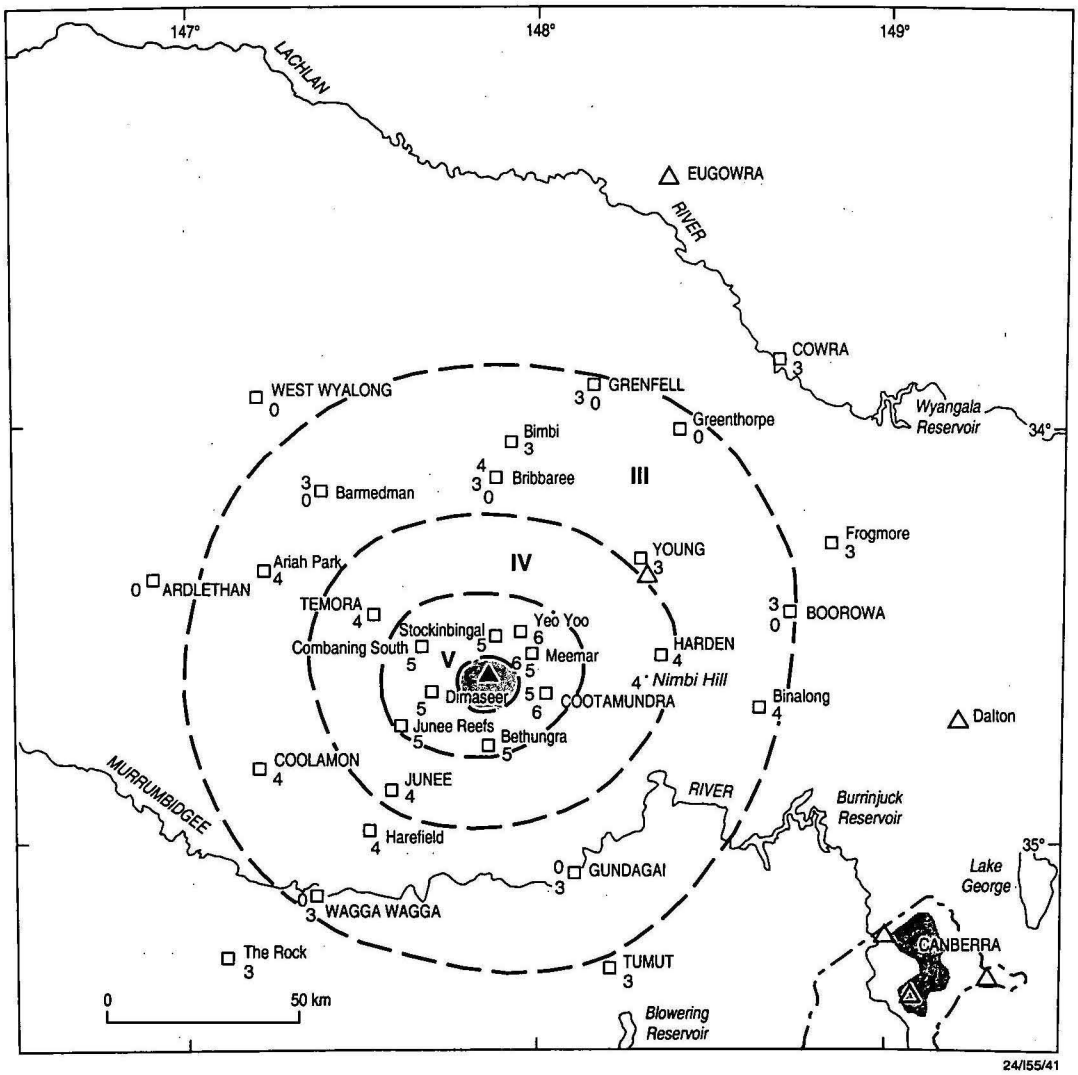
In Junee, touch lamps were reported to have been turned off by the shaking. The earthquake was felt over a radius of about 80 km, from Cowra in the northeast to Tumut in the south and an isoseismal map has been drawn up from all the reports.

A similar sized earthquake occurred nearby at Temora on 11 October 1992. An extract from the AGSO earthquake database shows that 120 small earthquakes with magnitude 2.5 or more have occurred within about 90 km of Cootamundra since 1960 when the ANU installed a seismographic network in the Snowy Mountains and Dalton area.

Date: 23 May 1998
Time: 05:01:14 EST
Location: 34.59 ± 0.07, 147.87 ± 0.07
Magnitude: 3.8 ML (Richter)

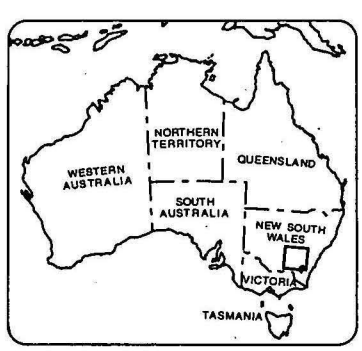
Contributors: This map was compiled by Kevin McCue.

ISOSEISMAL MAP OF THE COOTAMUNDRA EARTHQUAKE, NSW
22 MAY 1998



DATE: 22 May 1998
TIME: 19:01:14.4
MAGNITUDE: ML 3.8
EPICENTRE: 34.6°S 147.9°E
DEPTH: 6.0 km

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



Isoseismal map of the Corryong earthquake

Victoria

17 July 1998

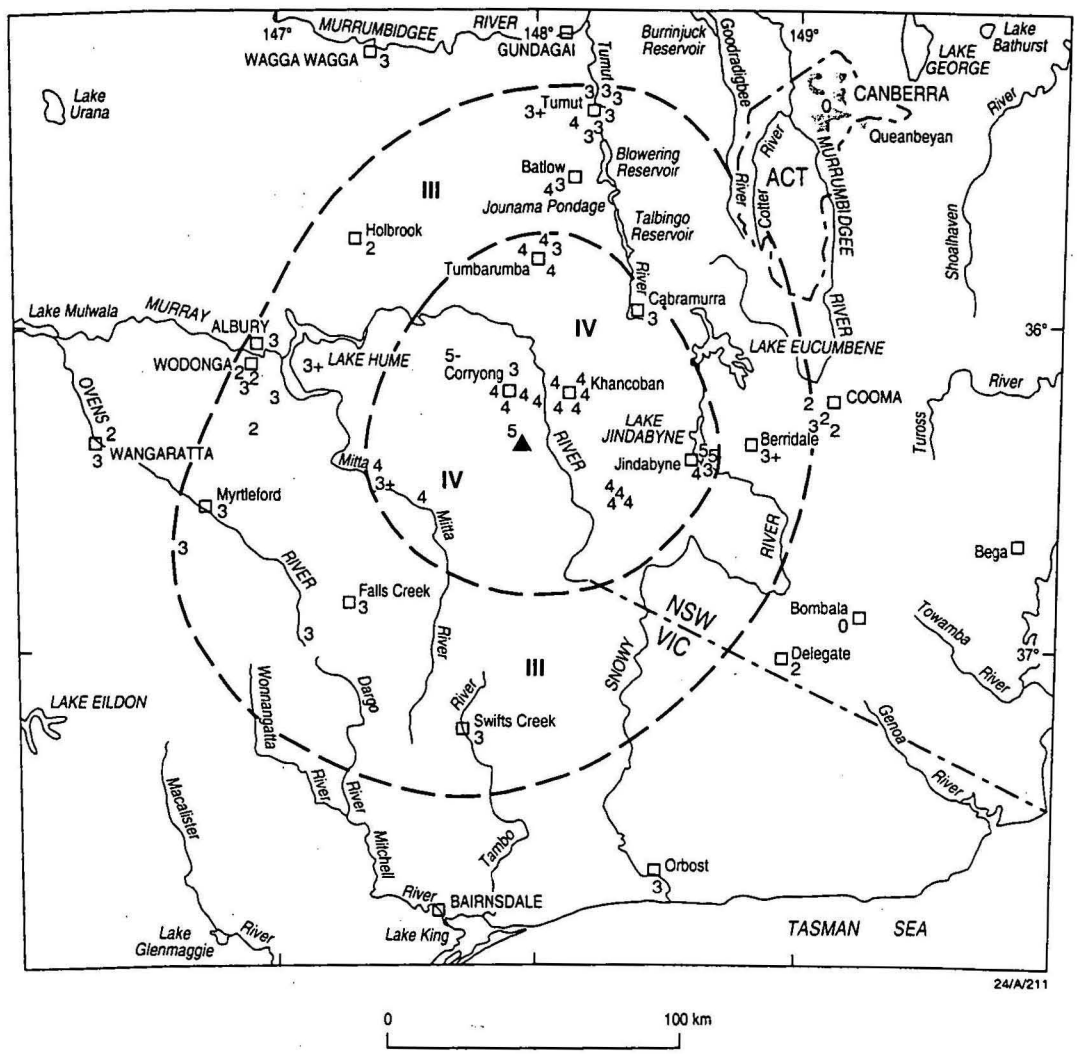
This magnitude 4.3 earthquake struck the Riverina district at 11:22 am EST. The epicentre was near Corryong which had last been shaken by a similar sized earthquake on 9 March 1982. Engineers at the nearby Hume and Blowering Dams carried out a full inspection of facilities as part of their safety emergency plan and maintained a watch for several days (Daily Advertiser, 18 July 1998) though no problems were experienced.

The earthquake was felt widely in Victoria and New South Wales and many people completed questionnaires through the SRC and AGSO web sites. The isoseismal map shows it was felt from Tumut in the north to Orbost in the south and Wangaratta in the west to Cooma in the east. There was apparently no damage, the epicentre sufficiently distant from the urban area of Corryong to attenuate the shaking below the damage threshold.

Accelerograms of the earthquake were recorded at Wambrook NSW and Inverness Victoria as reported elsewhere in this report.

Contributors: This map was compiled by Kevin McCue and Wayne Peck

ISOSEISMAL MAP OF THE CORRYONG EARTHQUAKE, VICTORIA
17 JULY 1998



DATE: 17 July 1998
TIME: 01:22:39.2 UTC
MAGNITUDE: 4.3 ML
EPICENTRE: 36.37°S 147.94°E
DEPTH: 21 km

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

Isoseismal map of the Orroral Valley earthquake

ACT

19 August 1998

Many people were already asleep when this small earthquake occurred in the Namadgi National Park in the ACT at 9:12pm EST on 19 August, so there were fewer reports than might have been expected. The epicentre was about 15km southeast of Corin Dam and some 30 km south of Canberra's southern suburbs. A very few people in Canberra's northern suburbs reported feeling a slight shake whereas those in Tharwa and the southern suburbs reported strong shaking, fortunately for just a few seconds. Garran residents are reported to have run out into the street in alarm. A selection of some of the hundred or so reports submitted to AGSO are summarised below.

Kambah: Felt by all in the house, windows rattled, strong vibration felt within the house. Also heard loud rumbling sound.

Curtin: Felt by all five of us and sounded like a low rumble as if a very large truck was going past.

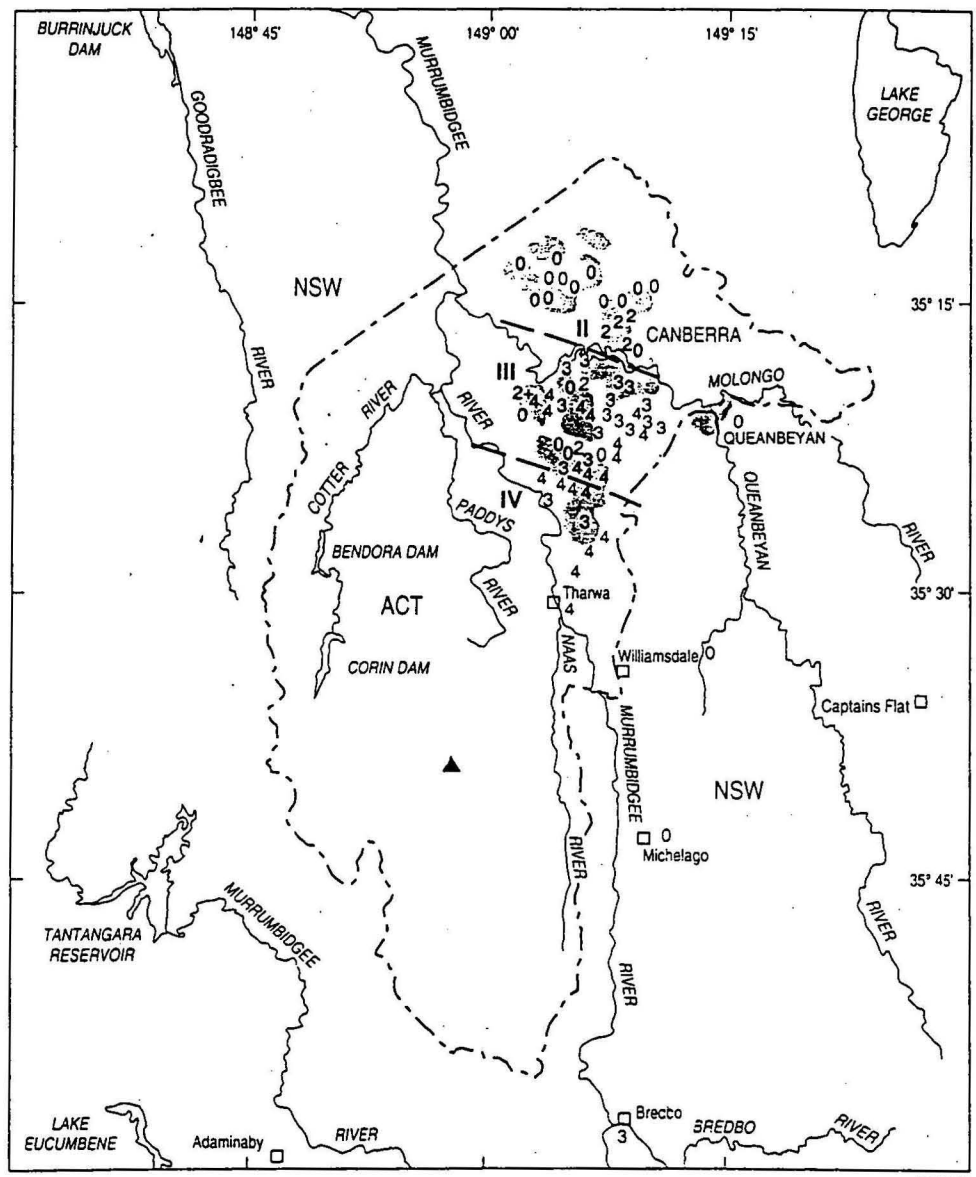
Gordon: We heard it coming then it shook the house but the windows didn't rattle, the furniture, book shelf did.

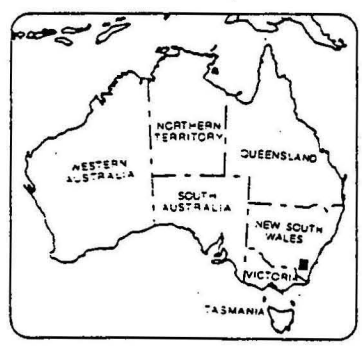
Wanniassa: Huge 20 sec shudder – the ground vibrated and made a thundering noise, wasn't aware of the windows rattling but my daughter's bed shook.

Tharwa: Heard then felt big rumble, everything rattled, foundations shook.

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

ISOSEISMAL MAP OF THE ORRORAL VALLEY EARTHQUAKE, ACT
19 AUGUST 1998





DATE: 19 August 1998
TIME: 11:12:44 UTC
MAGNITUDE: 3.0 ML
EPICENTRE: 35.65°S 148.95°E
DEPTH: 1 km

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

Isoseismal map of the Temora earthquake

NSW

16 October 1998

Riverina jolted by late night tremor was the headline of a Special Late Edition of The Daily Advertiser, a Wagga Wagga newspaper, on Saturday 17 October. The Wagga Police duty officer said the phones were flat out for about half an hour following the earthquake. He reported that: *another officer and myself were at the station when the quake hit. It did sound as if a train or a truck had hit something.* Wagga is nearly 50 km from the computed epicentre! One person from Turvey Park who was interviewed for the newspaper article said the quake *nearly bounced me off the lounge chair. I was watching TV, it frightened the living daylights out of me. I thought something must have hit the house. My lounge chair started jumping and I nearly ended up on the floor.*

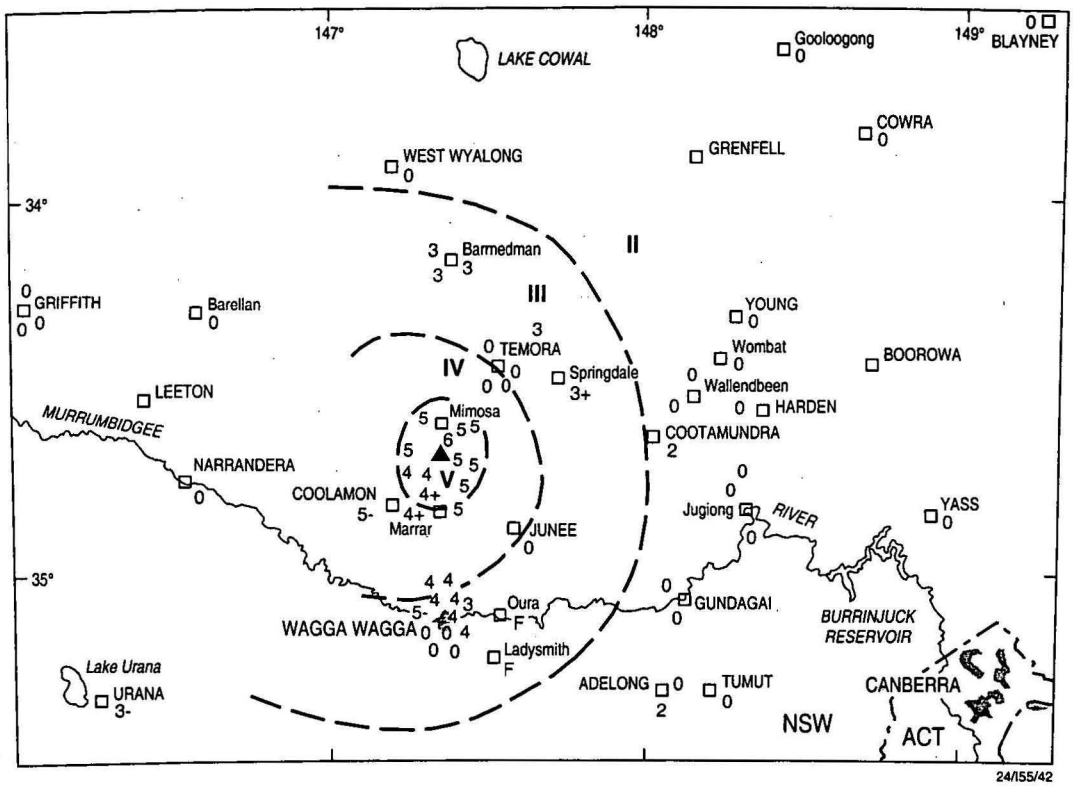
The newspaper reported other interviews. An elderly Coolamon resident thought her house was going to collapse and was quite distressed. Another spokesman from Marra said: *the jolt was quite severe. We have never felt anything like that before. Initially we thought it was a jet passing over the top of our house but then we realised it was something a lot more serious.*

This was the second earthquake in the Riverina in 1998 to have caused widespread interest and several people commented on the relative intensity of the May and October earthquakes; at Barmedman *it was much louder and not as severe as the May event.* The earthquake magnitude was 3.7 and it was felt over a radius of about 70 km from the epicentre south of Marrar. Reports included minor cracking of old brick and pise walls (in one case extension of cracks from the October 1992 earthquake) and damage to a water tank at Mimosa. The origin time at 11:46 pm EST when most people were already sleeping probably reduced the response.

An accelerograph at the Lower Cotter Dam near Canberra triggered in the earthquake, the record is shown in a later section, the maximum acceleration or pga was just 0.15 mg in both vertical and horizontal directions.

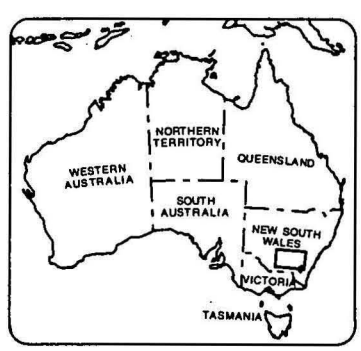
Contributors: This map was compiled by Y Li, A J McEwin and K McCue

ISOSEISMAL MAP OF THE TEMORA EARTHQUAKE, NSW
16 OCTOBER 1998



DATE: 16 October 1998
TIME: 13:46:13.1 UTC
MAGNITUDE: 3.7 ML
EPICENTRE: 34.70°S 147.36°E
DEPTH: 2 km

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



Isoseismal map of the Michelago earthquake

NSW

31 December 1998

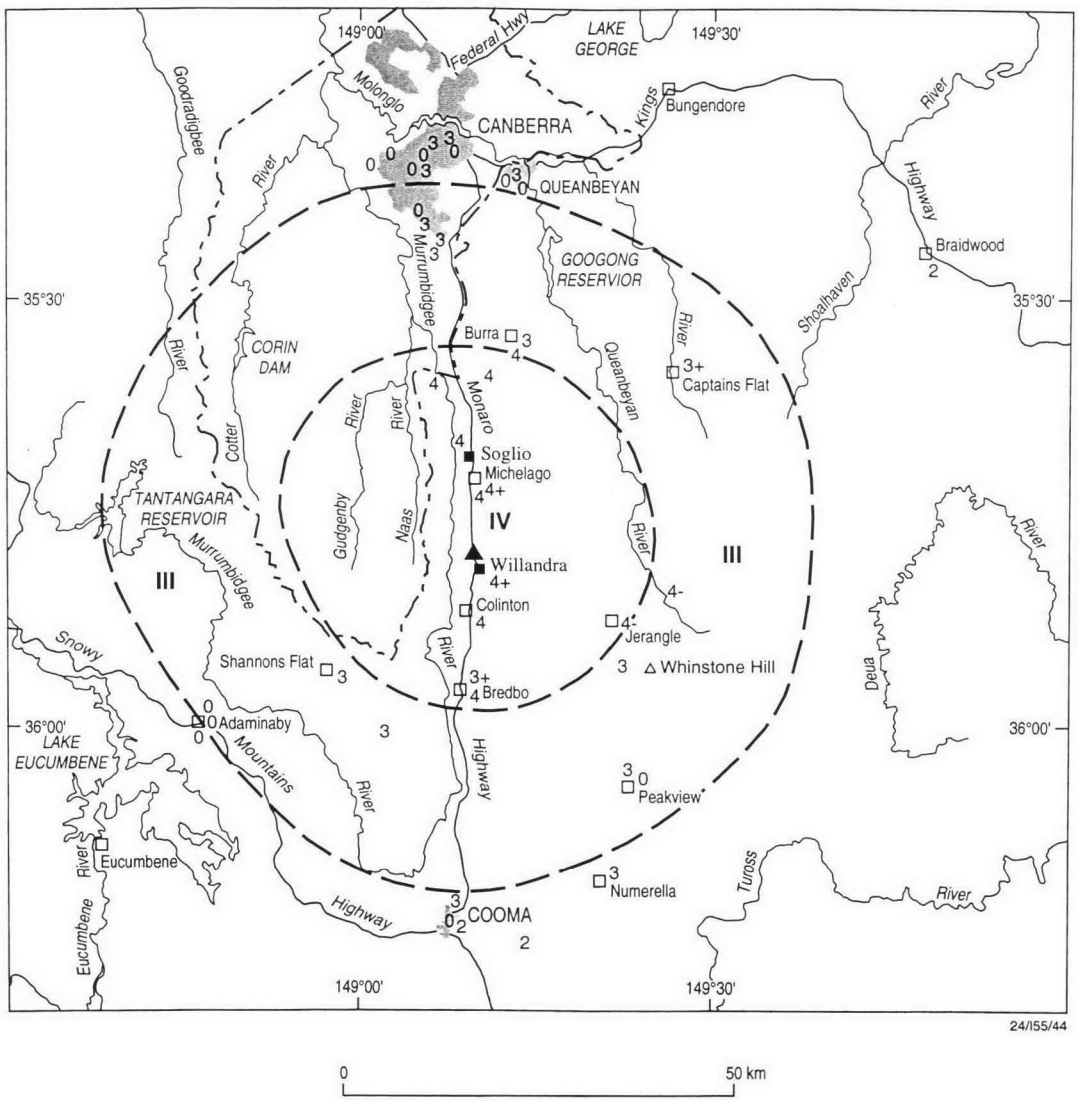
The epicentre of this magnitude 3.2 earthquake was between Bredbo and Michelago and there were numerous reports from Canberra and Cooma residents disturbed by the shaking. Most of the assigned intensities were gleaned from telephone queries, sufficient to draw up the isoseismal map opposite.

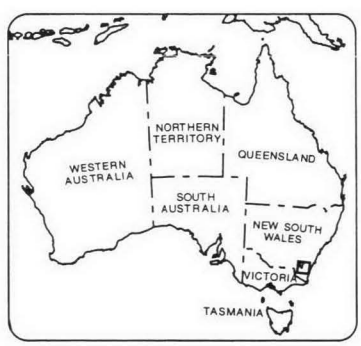
Three accelerographs triggered on the earthquake; the closest at Wambrook, another at the Lower Cotter dam, the other at Dalton. These records give useful correlation between the assigned intensity and recorded ground shaking (note the time shown on these records has not been corrected).

This was the 5th earthquake felt in Canberra in 1998, something of a record though the intensities were no greater than MM4-5 during the February Brindabella earthquake. Larger regional earthquakes have shaken Canberra more strongly in the past 100 years, earthquakes located near Dalton in 1934 and 1949 and near Bowral in 1961 which caused minor damage in Canberra suburbs.

Contributors: This map was compiled by Kevin McCue

ISOSEISMAL MAP OF THE MICHELAGO EARTHQUAKE, NSW
31 DECEMBER 1998





DATE:	31 December 1998
TIME:	06:11:36.3 UTC
MAGNITUDE:	3.2 ML
EPICENTRE:	35.81° S 149.17° E
DEPTH:	5 km

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

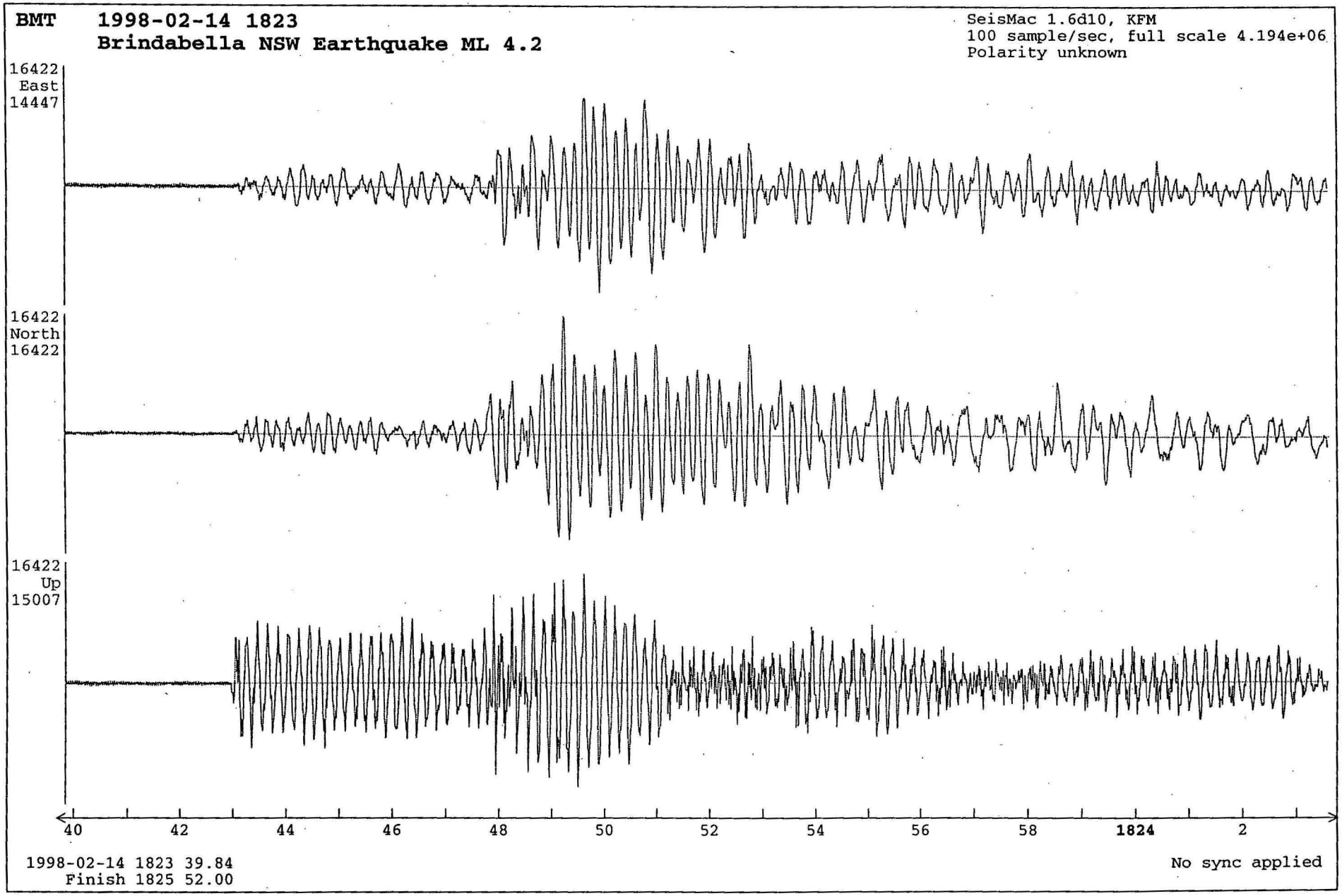
APPENDIX 2

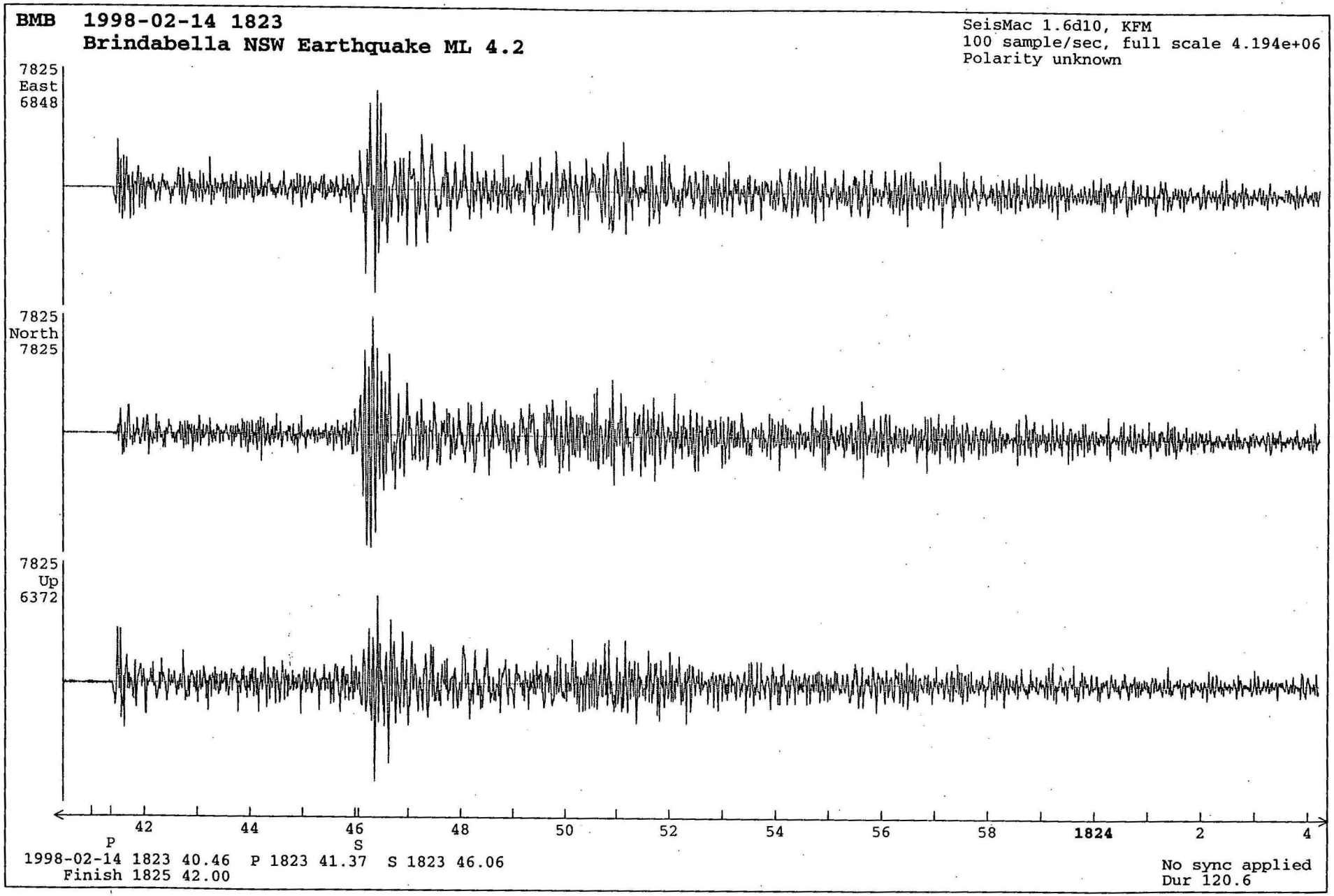
AUSTRALIAN ACCELEROGRAMS 1998

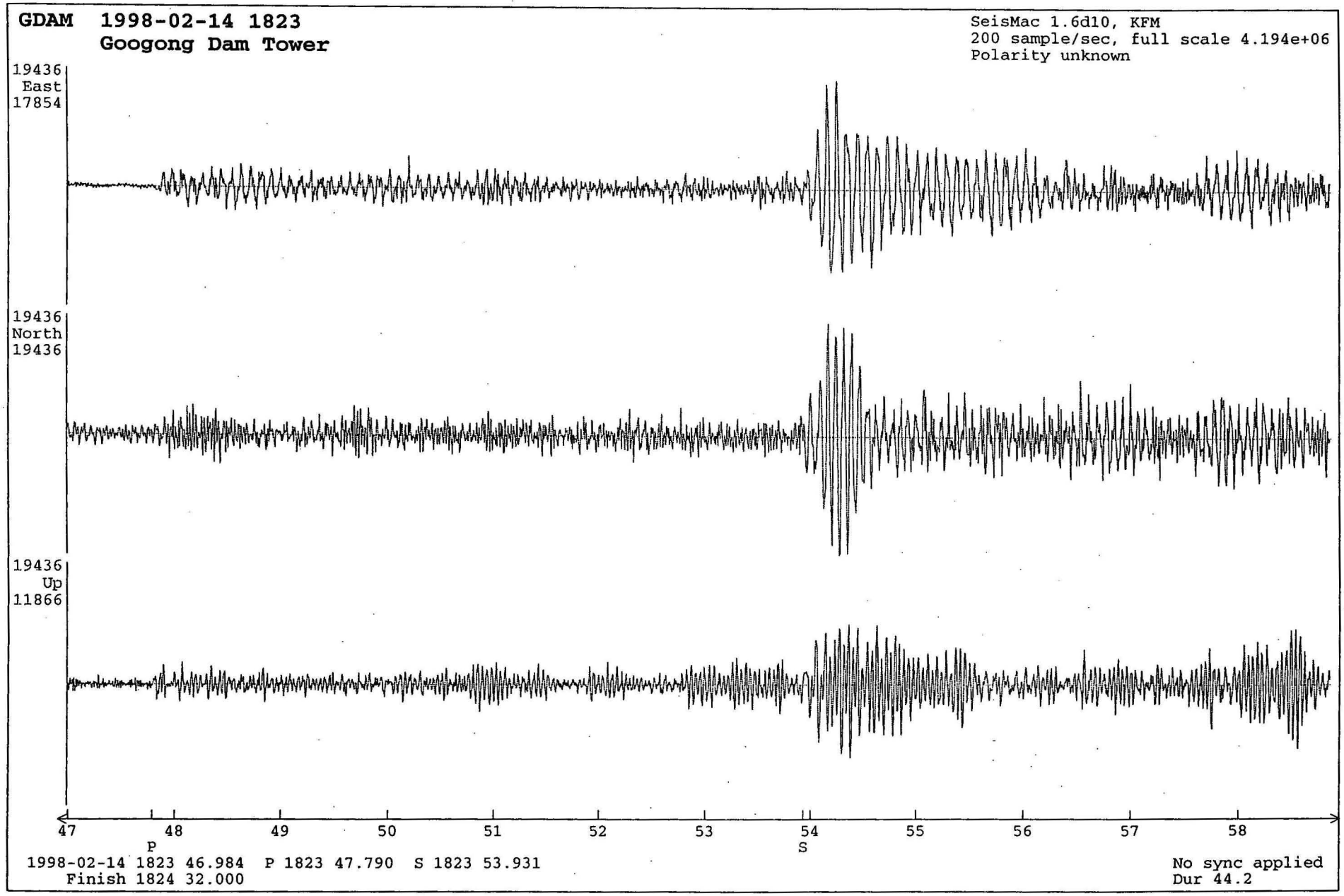
As a result of the Joint Urban Monitoring Program (JUMP) devised at a meeting of Commonwealth, State and Territory representatives in Canberra in February 1990, two accelerographs were installed in most urban communities with a population in excess of 50 000 people. This initiative has resulted in a substantial collection of precious strong motion records which are required for hazard analyses, the building code spectrum and research into the mechanism of the earthquakes and the attenuation of shaking caused by them.

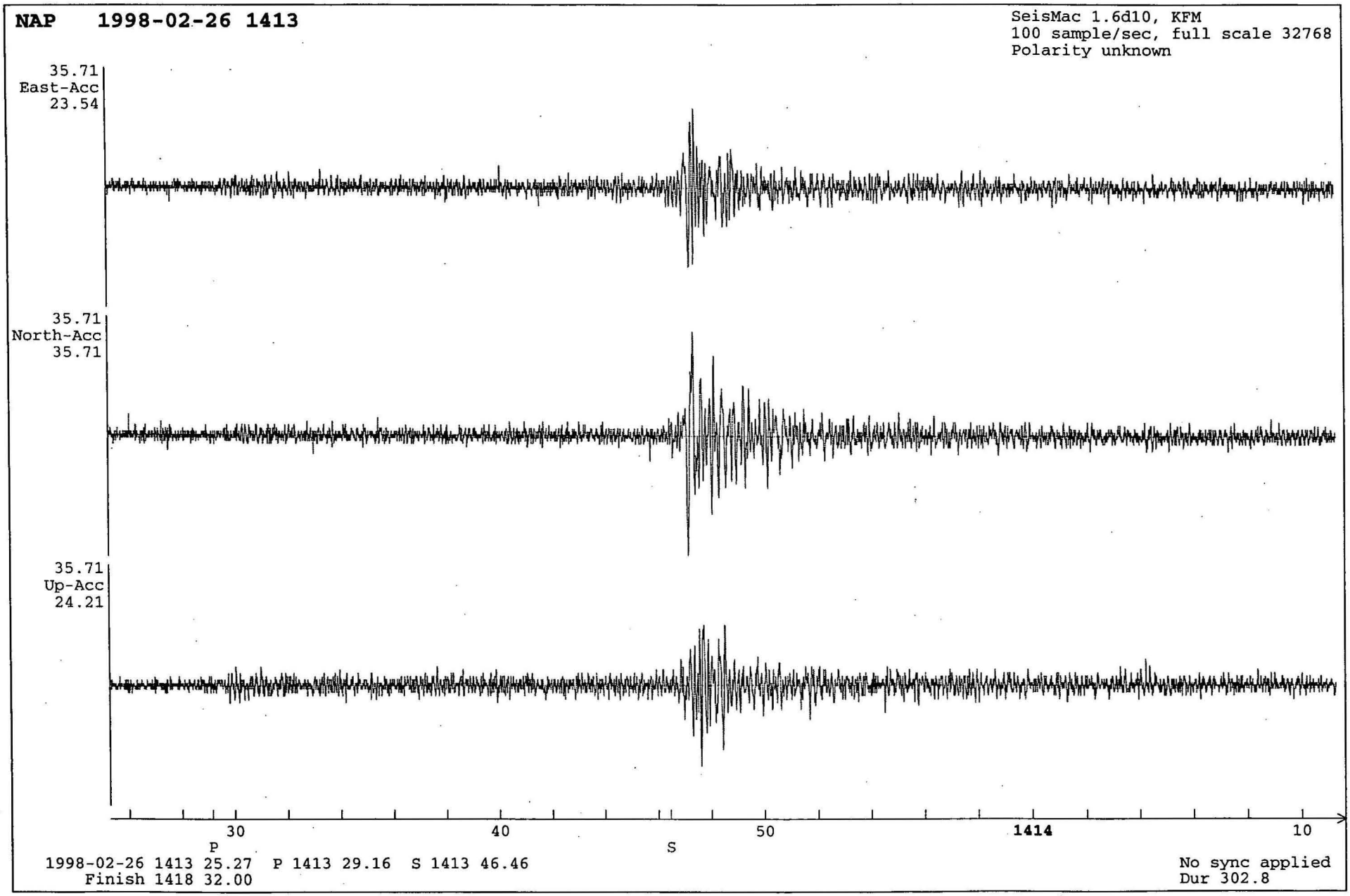
The more important records obtained in 1998 are illustrated here (for site details see McCue & others, 1999).

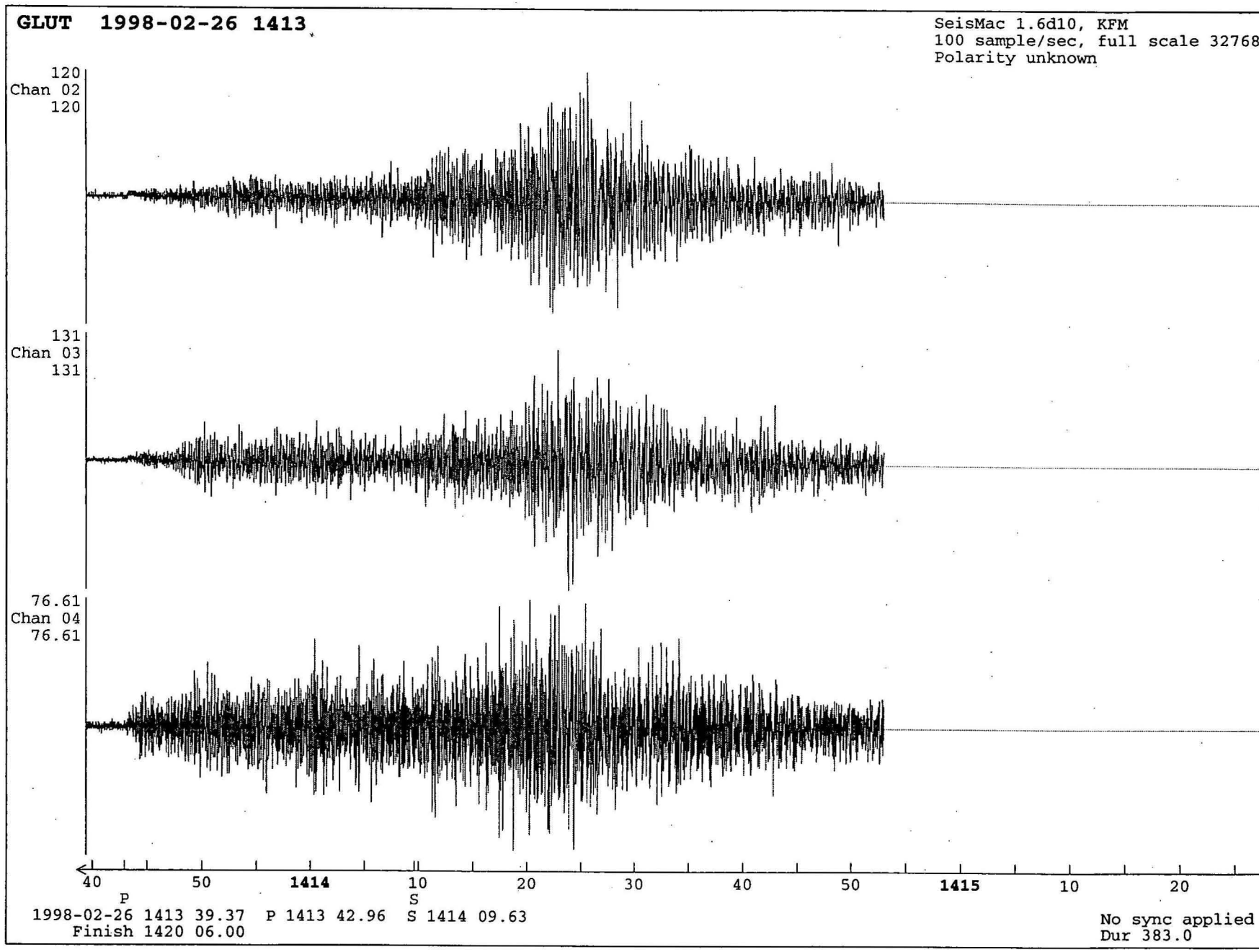
Location	*Earthquake region*	*(Recording sites)*
Googong Dam	Brindabella NSW	(GGD)
Black Mtn		(BMB)
Cotter Dam	Temora NSW	(COTA)
Wambrook	Michelago NSW	(WAMB)
Cotter Dam		(COTA)
Dalton		(DALT)

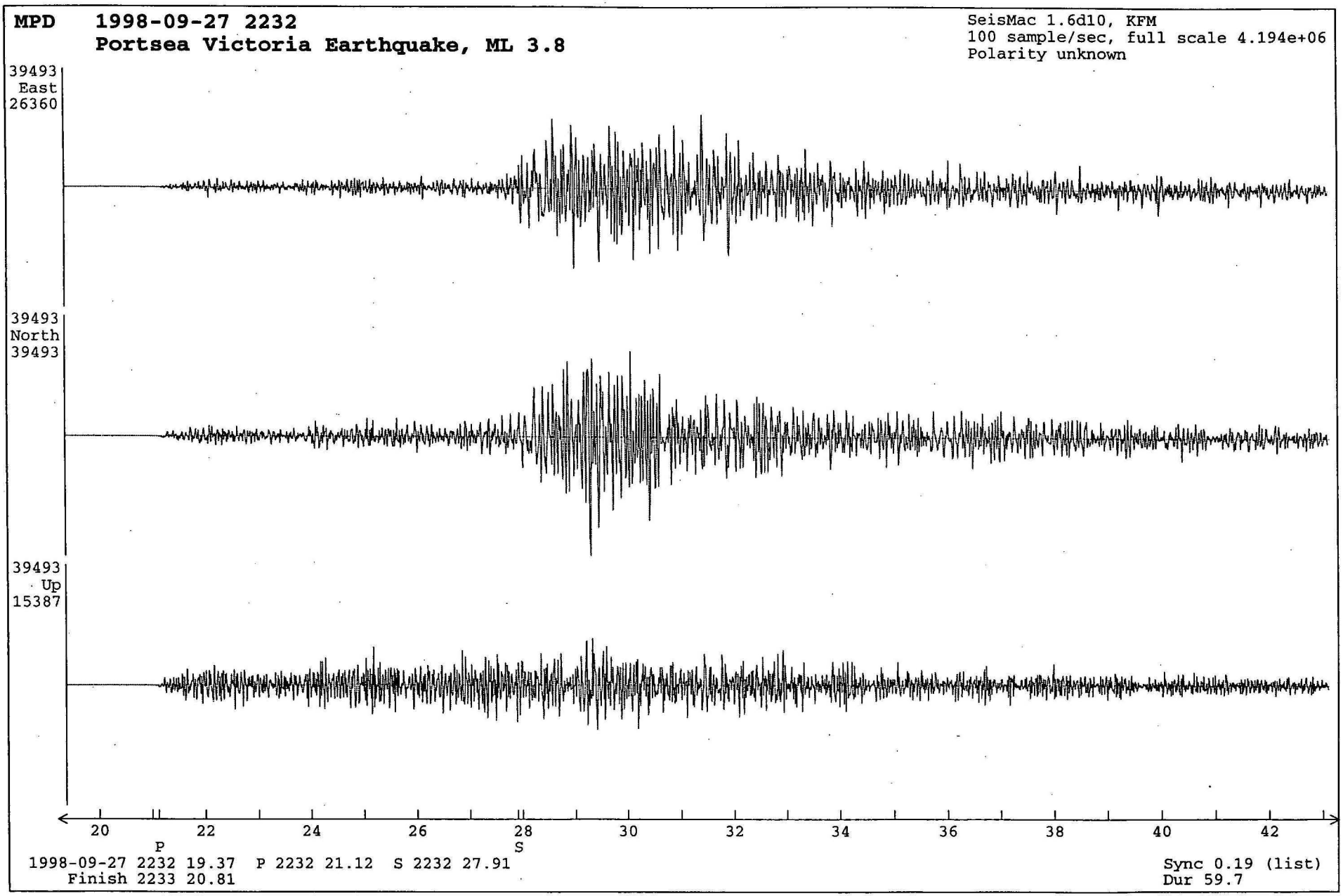

BMT 1998-02-14 1823
Brindabella NSW Earthquake ML 4.2
SeisMac 1.6d10, KFM
100 sample/sec, full scale 4.194e+06
Polarity unknown
16422
East
14447
16422
North
16422
16422
Up
15007
40
42
44
46
48
50
52
54
56
58
1824
2
1998-02-14 1823 39.84
Finish 1825 52.00
No sync applied

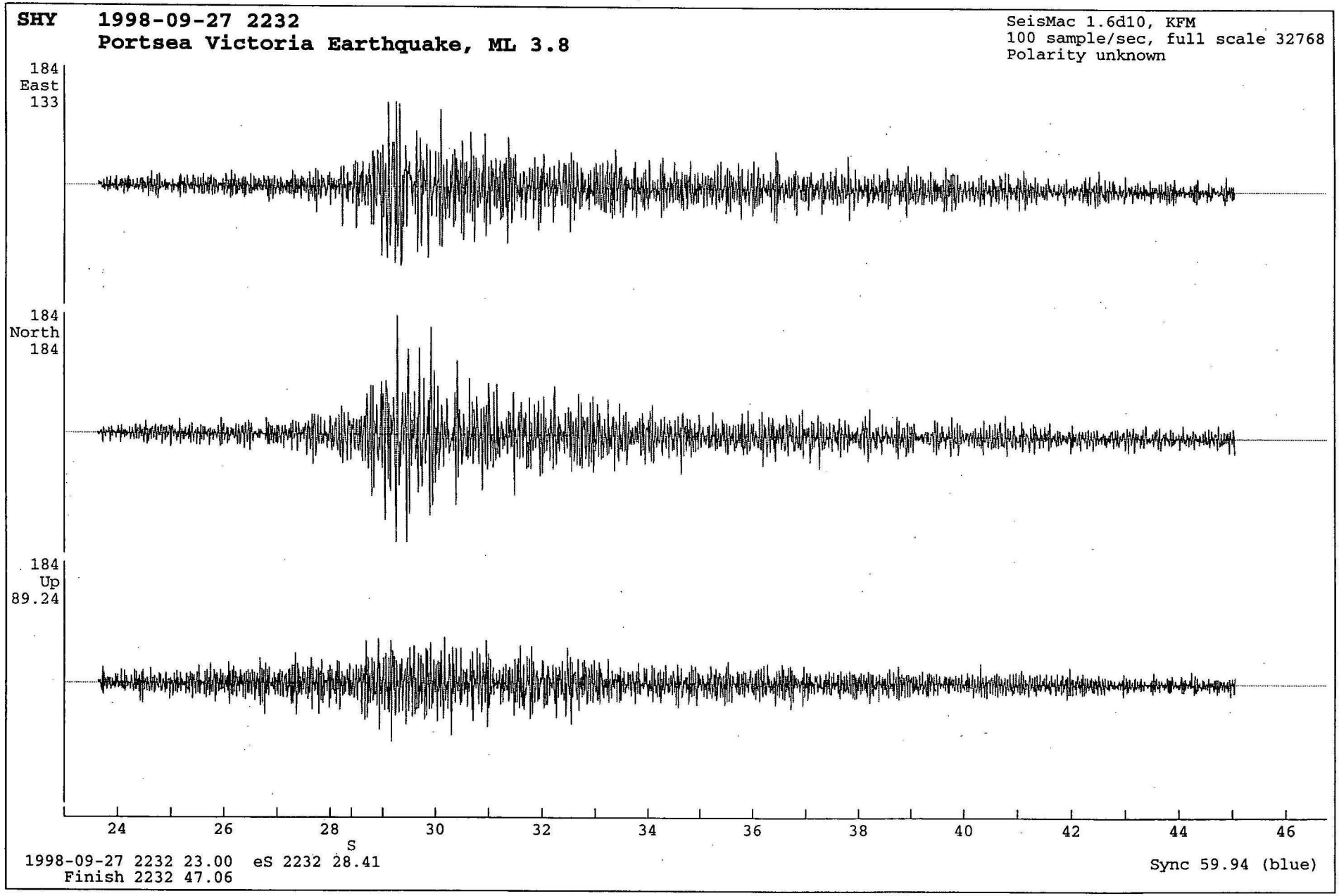

BMB 1998-02-14 1823
Brindabella NSW Earthquake ML 4.2
SeisMac 1.6d10, KFM
100 sample/sec, full scale 4.194e+06
Polarity unknown
7825
East
6848
7825
North
7825
7825
Up
6372
42
44
46
48
50
52
54
56
58
1824
2
4
P
S
1998-02-14 1823 40.46 P 1823 41.37 S 1823 46.06
Finish 1825 42.00
No sync applied
Dur 120.6

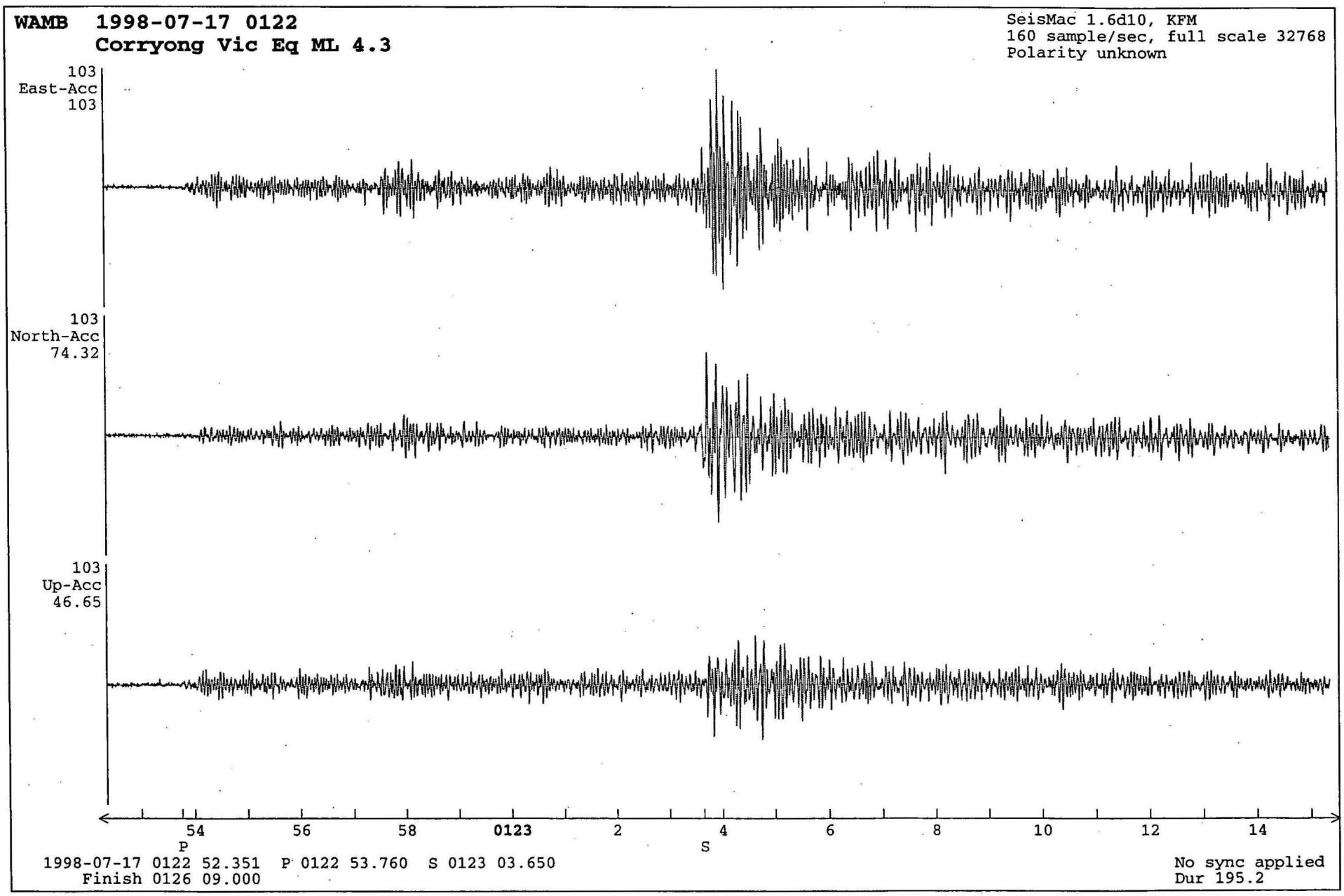

GDAM 1998-02-14 1823
Googong Dam Tower
SeisMac 1.6d10, KFM
200 sample/sec, full scale 4.194e+06
Polarity unknown
19436
East
17854
19436
North
19436
19436
Up
11866
47
48
49
50
51
52
53
54
55
56
57
58
P
S
1998-02-14 1823 46.984 P 1823 47.790 S 1823 53.931
Finish 1824 32.000
No sync applied
Dur 44.2

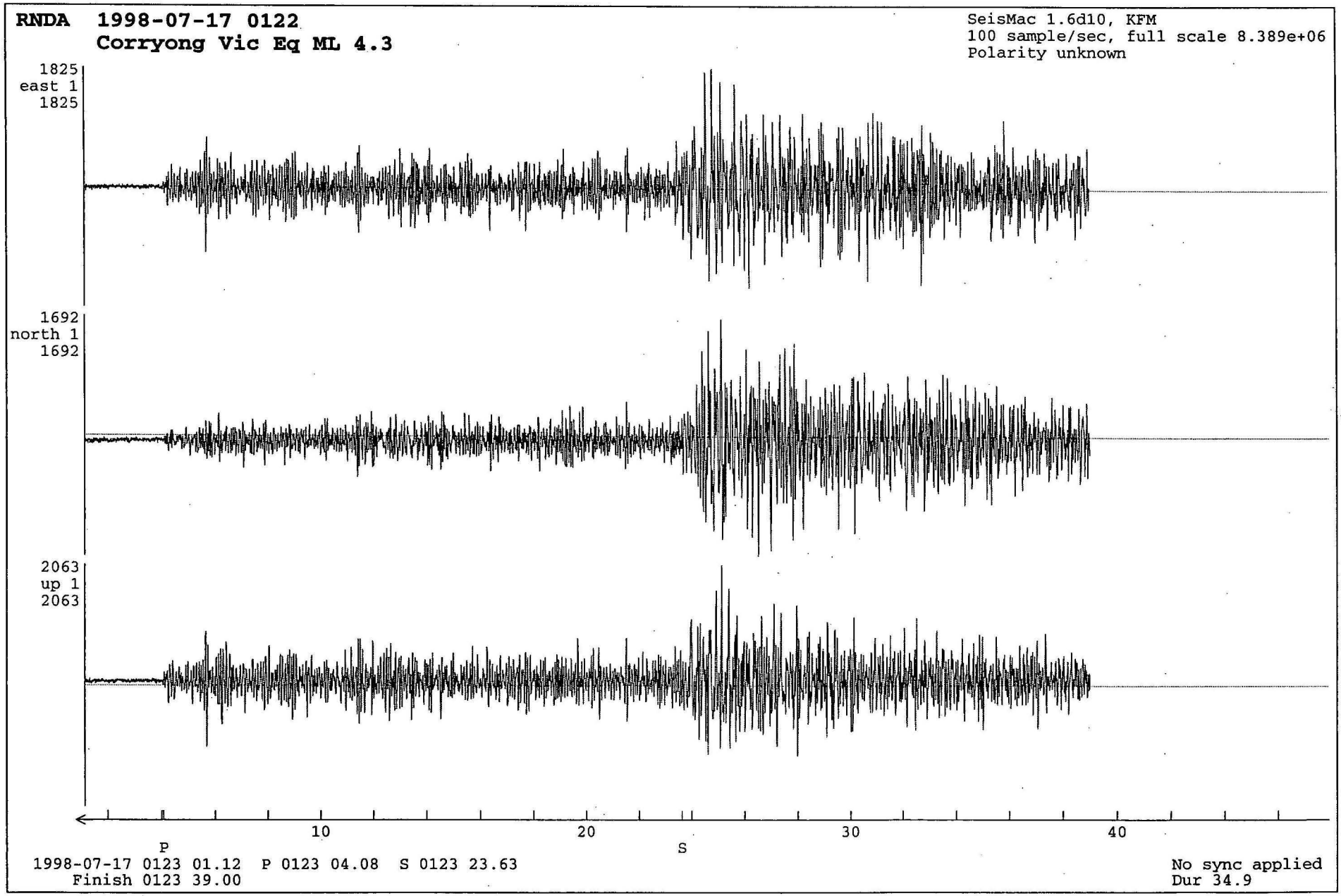

NAP 1998-02-26 1413
SeisMac 1.6d10, KFM
100 sample/sec, full scale 32768
Polarity unknown
35.71
East-Acc
23.54
35.71
North-Acc
35.71
35.71
Up-Acc
24.21
30
40
50
1414
10
P
S
1998-02-26 1413 25.27 P 1413 29.16 S 1413 46.46
Finish 1418 32.00
No sync applied
Dur 302.8

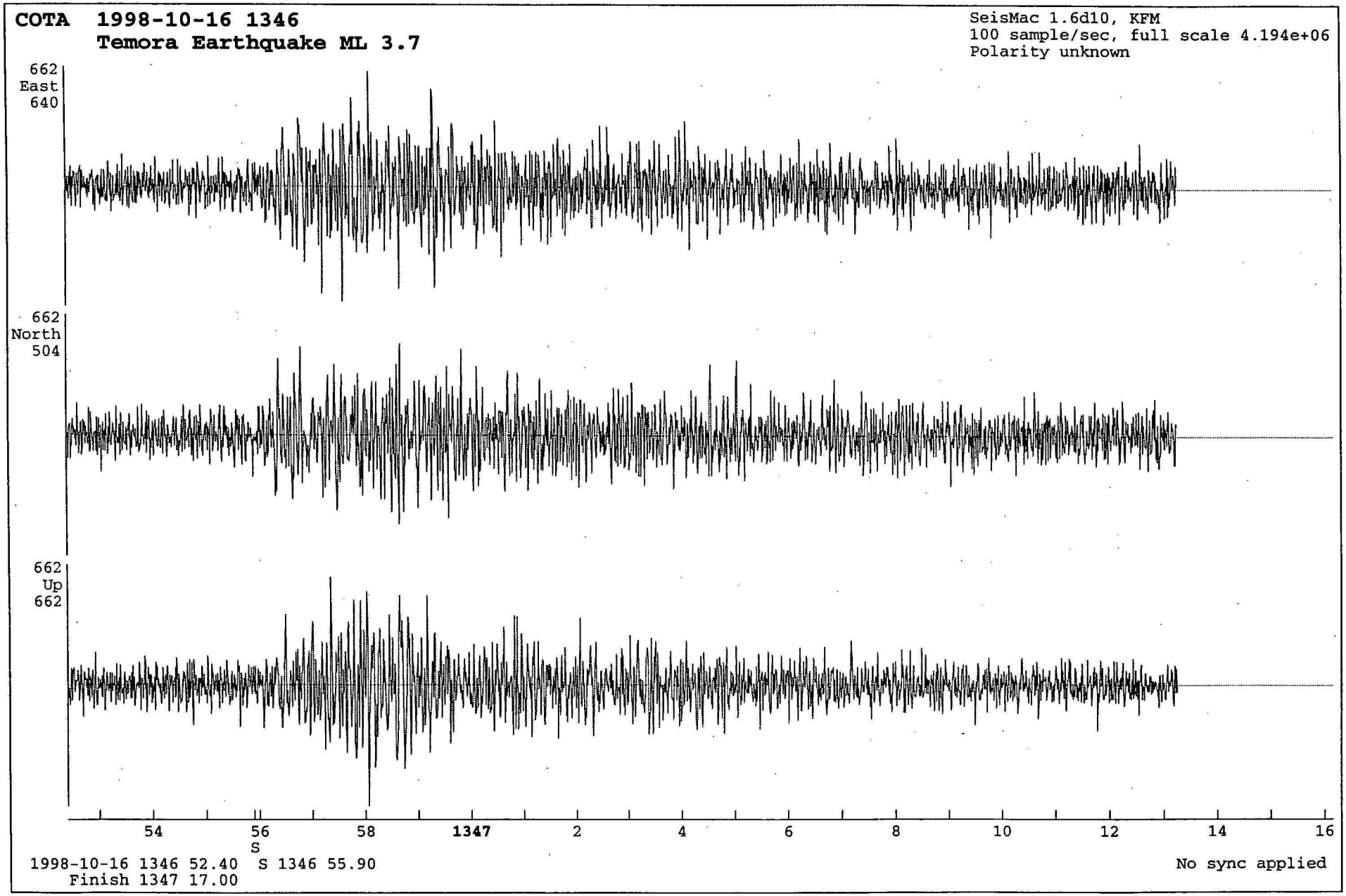

GLUT 1998-02-26 1413
SeisMac 1.6d10, KFM
100 sample/sec, full scale 32768
Polarity unknown
120
Chan 02
120
131
Chan 03
131
76.61
Chan 04
76.61
40
50
1414
10
20
30
40
50
1415
10
20
P
S
1998-02-26 1413 39.37 P 1413 42.96 S 1414 09.63
Finish 1420 06.00
No sync applied
Dur 383.0

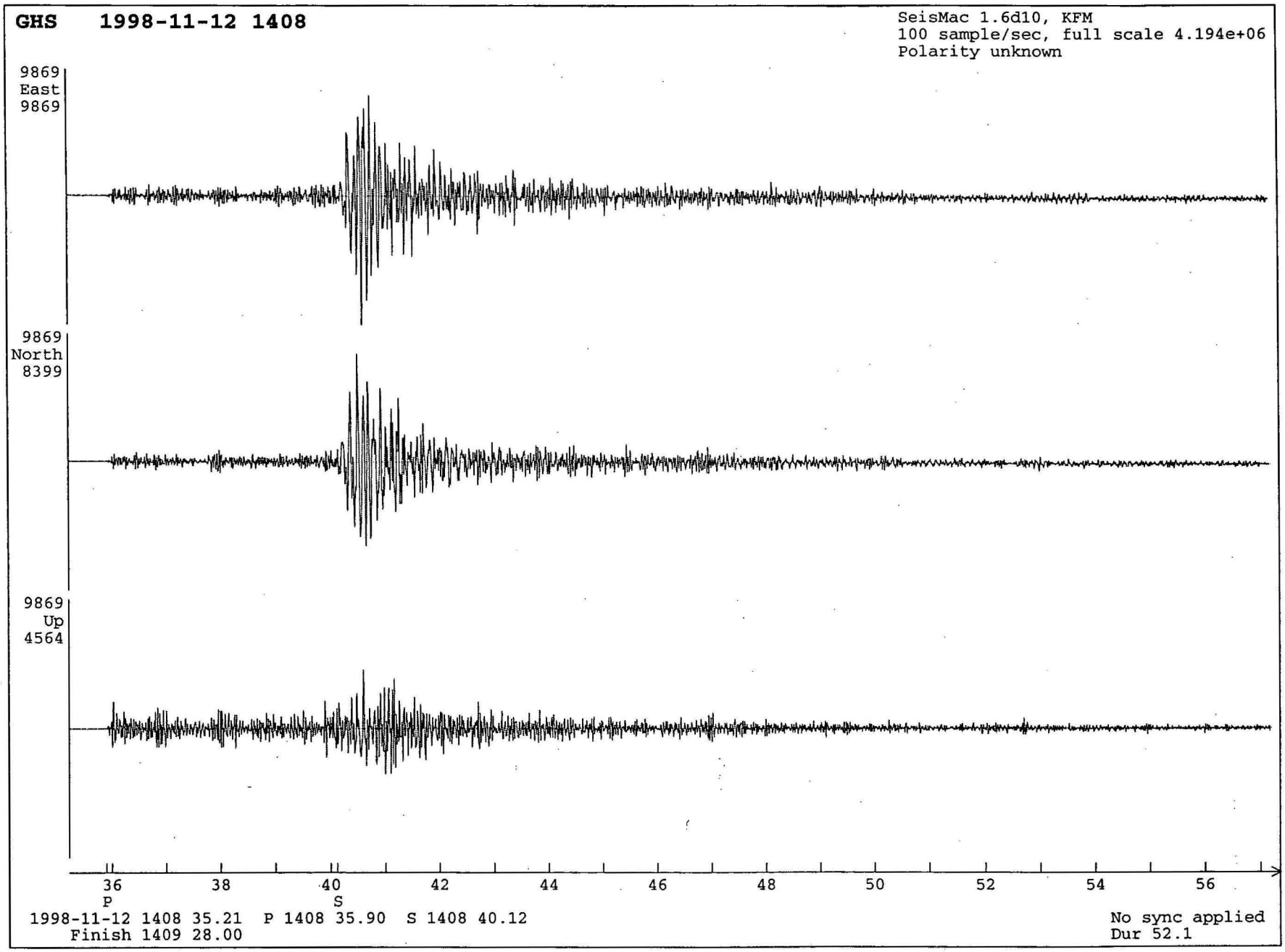

MPD 1998-09-27 2232
Portsea Victoria Earthquake, ML 3.8
SeisMac 1.6d10, KFM
100 sample/sec, full scale 4.194e+06
Polarity unknown
39493
East
26360
39493
North
39493
39493
Up
15387
20
22
24
26
28
30
32
34
36
38
40
42
P
S
1998-09-27 2232 19.37 P 2232 21.12 S 2232 27.91
Finish 2233 20.81
Sync 0.19 (list)
Dur 59.7

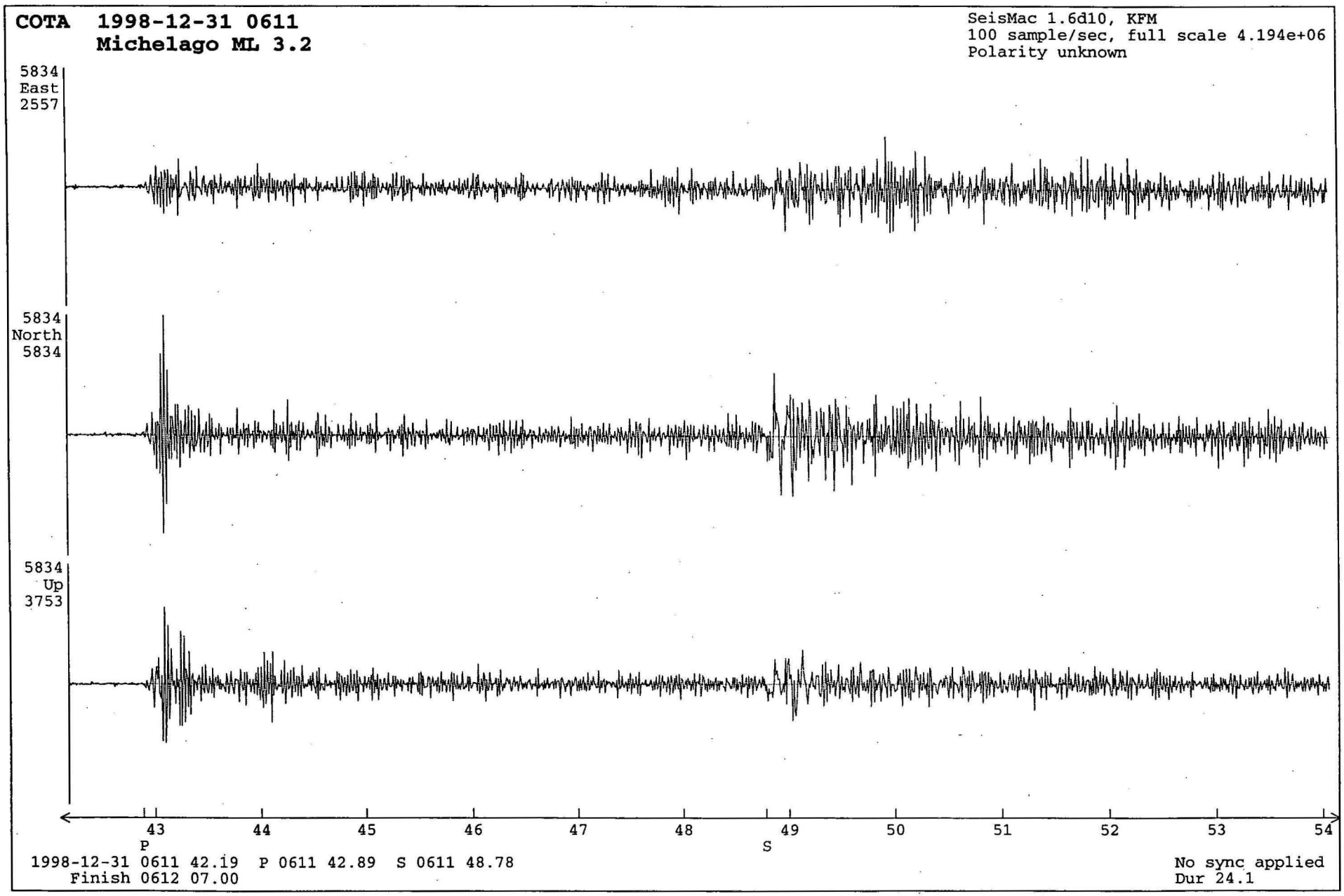

SHY 1998-09-27 2232
Portsea Victoria Earthquake, ML 3.8
SeisMac 1.6d10, KFM
100 sample/sec, full scale 32768
Polarity unknown
184
East
133
184
North
184
184
Up
89.24
24
26
28
30
32
34
36
38
40
42
44
46
S
1998-09-27 2232 23.00 eS 2232 28.41
Finish 2232 47.06
Sync 59.94 (blue)

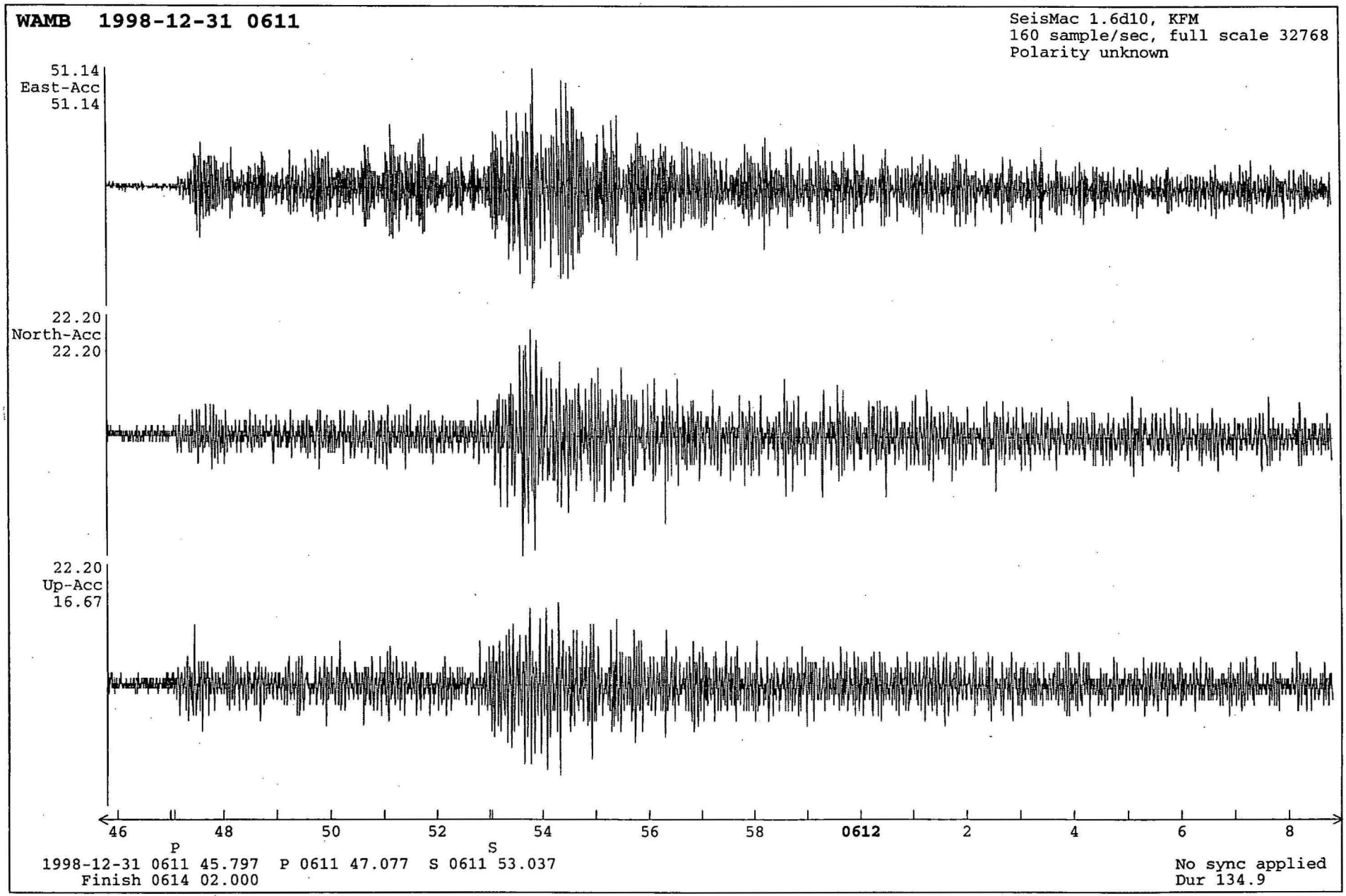

WAMB 1998-07-17 0122
Corryong Vic Eq ML 4.3
SeisMac 1.6d10, KFM
160 sample/sec, full scale 32768
Polarity unknown
103
East-Acc
103
103
North-Acc
74.32
103
Up-Acc
46.65
54
56
58
0123
2
4
6
8
10
12
14
P
S
1998-07-17 0122 52.351 P 0122 53.760 S 0123 03.650
Finish 0126 09.000
No sync applied
Dur 195.2


RNDA 1998-07-17 0122
Corryong Vic Eq ML 4.3
SeisMac 1.6d10, KFM
100 sample/sec, full scale 8.389e+06
Polarity unknown
1825
east 1
1825
1692
north 1
1692
2063
up 1
2063
10
20
30
40
P
S
1998-07-17 0123 01.12 P 0123 04.08 S 0123 23.63
Finish 0123 39.00
No sync applied
Dur 34.9


COTA 1998-10-16 1346
Temora Earthquake ML 3.7
SeisMac 1.6d10, KFM
100 sample/sec, full scale 4.194e+06
Polarity unknown
662
East
640
662
North
504
662
Up
662
54
56
S
58
1347
2
4
6
8
10
12
14
16
1998-10-16 1346 52.40 S 1346 55.90
Finish 1347 17.00
No sync applied


GHS 1998-11-12 1408
SeisMac 1.6d10, KFM
100 sample/sec, full scale 4.194e+06
Polarity unknown
9869
East
9869
9869
North
8399
9869
Up
4564
36
38
40
42
44
46
48
50
52
54
56
P
S
1998-11-12 1408 35.21 P 1408 35.90 S 1408 40.12
Finish 1409 28.00
No sync applied
Dur 52.1


COTA 1998-12-31 0611
Michelago ML 3.2
SeisMac 1.6d10, KFM
100 sample/sec, full scale 4.194e+06
Polarity unknown
5834
East
2557
5834
North
5834
5834
Up
3753
43
44
45
46
47
48
49
50
51
52
53
54
P
S
1998-12-31 0611 42.19 P 0611 42.89 S 0611 48.78
Finish 0612 07.00
No sync applied
Dur 24.1


WAMB 1998-12-31 0611
SeisMac 1.6d10, KFM
160 sample/sec, full scale 32768
Polarity unknown
51.14
East-Acc
51.14
22.20
North-Acc
22.20
22.20
Up-Acc
16.67
46
48
50
52
54
56
58
0612
2
4
6
8
P
S
1998-12-31 0611 45.797 P 0611 47.077 S 0611 53.037
Finish 0614 02.000
No sync applied
Dur 134.9

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

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

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 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 $\Delta = 20–160°$, 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. This is a most convnient 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:

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

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.

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