3 Earthquake History, Regional Seismicity and the 1989 Newcastle Earthquake (C. Sinadinovski, T. Jones, D. Stewart, and N. Corby)

3.1 Seismology

Australia has a relatively low rate of seismicity due to its location towards the centre of the Indo-Australian Tectonic Plate. Earthquake activity is much higher around the margins of the Indo-Australian Plate, for example in places such as Indonesia, Papua New Guinea and New Zealand. Nevertheless, many historic earthquakes have occurred in Australia and Geoscience Australia's database (QUAKES) contains information on tens of thousands of historic earthquakes in the Australian continent. Most of these, however, have been in areas of low population density.

Australian earthquakes are termed 'intraplate' earthquakes because of their distance from the more active plate boundary. Models to explain the origins of Australian earthquakes need much more development and, in the interim, the occurrence and nature of Australian earthquakes is incompletely understood and poorly described. This incomplete understanding leads to uncertainties in descriptions of the earthquake hazard facing the Newcastle and Lake Macquarie study area.

Prior to events such as the 1968 Meckering earthquake (M6.9) and the 1989 Newcastle earthquake (M5.6), Australia was thought to be relatively safe from this particular natural disaster. As shown in Table 3-1 several damaging earthquakes have impacted upon Australian communities in the last 50 years. The 1989 Newcastle earthquake dominates the damage and casualty statistics.

The 1989 Newcastle earthquake prompted a re-examination of earthquake activity in the Hunter region. Prior to this event, the earthquake history of the region was forgotten, lost or ignored, apart from perhaps the memory of 1925 Boolaroo earthquake in older residents. For example, the effects of the 20 June 1868 Maitland earthquake had been documented (Clarke, 1869) but had passed into insignificance. Following the 1989 event, research revealed a significant history of moderate magnitude earthquakes in the Hunter region (Hunter, 1991).

At least five earthquakes of magnitude 5 or greater have occurred in the Hunter region since European settlement in 1804 (Table 3-3). Some of these earthquakes caused damage in areas that, at the time, were sparsely populated. Similar events, were they to occur today in populated areas, would certainly cause significant damage. Even small earthquakes have caused damage in the Sydney Basin. For example, two earthquakes of magnitude 4.3 in Lithgow in 1985 and 1987 caused minor damage to masonry walls and chimneys (McCue, 1995).

Strong earthquakes have the potential to cause damage at considerable distances from their sources. Consequently, our study of historical seismicity has considered earthquakes occurring within approximately 200 km of Newcastle (Figure 3.1). This area extends from Kempsey in the north to Nowra in the south. The geology of this area includes, in broad terms, parts of the Sydney Basin, the New England Orogen to the north, and the Lachlan Fold Belt to the south-west (Appendix D). The significant[3] historical earthquakes that occurred in this part of New South Wales and that were felt in Newcastle are listed in Table 3-3. Geoscience Australia's QUAKES database contains information on about 125 historical earthquakes in this region (Appendix B).

Information on these earthquakes has come from two sources. Information on earthquakes which occurred before seismographs were installed in New South Wales has come entirely from the historical records of the felt effects of these earthquakes; ie newspaper reports, personal letters, and journal reports. It should be emphasised that the epicentres of these pre-instrumental events could be incorrect by 25 km or more due to uncertainties in interpreting Modified Mercalli Intensities from usually very sparse macroseismic data. Additionally, the Richter magnitudes of these pre-instrumental events have been estimated from the radius of perceived ground shaking, again from the macroseismic data, and therefore the computed magnitudes also contain uncertainties.

[3] *Significant earthquakes have been defined as those earthquakes which caused ground shaking intensities in populated areas of MM V or more on the Modified Mercalli Scale of Intensity. Appendix A, (Dowrick, 1996) gives a full description of the Modified Mercalli Scale*

Table 3-1: Most-damaging Australian earthquakes, 1950-2002

Date (local)	**Location**	**Magnitude**	**Insured damage**	
			Contemporary dollars	**2002 dollars**[4]
01/03/1954	Adelaide SA	5.4 ML	$5.6 M	$64 M
22/05/1961	Robertson/Bowral NSW	5.6 ML	$0.5 M	$4.7 M
14/10/1968	Meckering WA	6.9 ML	$1.5 M[5]	$12 M[5]
10/03/1973	Picton NSW	5.5 ML	$0.5 M	$3.3 M
02/06/1979	Cadoux WA	6.0 Ms	$3.5 M[5]	$12 M[5]
22/01/1988	Tennant Creek NT (3 events)	6.2, 6.3, 6.5 Mw	$1.1 M	$1.7 M
28/12/1989	Newcastle NSW	5.6 ML	13 killed, $862 M[5]	$1,124 M[5]
06/08/1994	Ellalong NSW	5.4 ML	$36 M[5]	$44 M[5]

More recently, information on earthquakes, such as their location, depth, Richter magnitude, and time of occurrence, has come from analysis of recordings from seismographic networks. Instrumental monitoring of the region began with the establishment of the Riverview College seismograph station in Sydney in 1909. The ability to detect and locate Hunter earthquakes using a sole, distant station located in a noisy city was poor, and only those Hunter earthquakes with moderate or large magnitudes were recorded reliably. The instrumental locations of Hunter earthquakes determined from the Riverview seismograph alone contain large uncertainties. In 1958, the Research School of Earth Sciences at the Australian National University began operating its south-east Australia network. Seismographs were installed in the region from Sydney to the Snowy Mountains and seismic events in the Newcastle-Hunter region with magnitudes of approximately ML 3.0 and greater were located routinely using data from these stations. Uncertainties in the epicentral locations are typically at least ± 10 km. Uncertainties in earthquake depths are higher.

The detection and location capabilities for earthquakes with local magnitudes greater than about 2 (detection) and 2.5 (location) improved with the establishment of a seismograph network in the Hunter area by GA, Newcastle City Council and Kiwanis International in 1990. The Hunter network includes seismographs in Merewether, North Lambton, Chichester Dam and Quorrobolong. Hunter Water Corporation and Cessnock City Council have also supported the operation of this network. A seismograph at Mangrove Creek Dam in the Central Coast also telemeters data to GA in real time. Accelerographs (earthquake strong motion recorders) have been installed at North Lambton and Newcastle No. 2 Sports Ground. The operation of the Mangrove Creek Dam seismograph and the Newcastle accelerographs is funded by the NSW Department of Public Works and Services.

Even with improved earthquake detection capability for the Newcastle area, errors in epicentral locations and depths are still significant. The instrumental coverage to the west in the Upper Hunter valley and north in the New England Tableland is still poor. To the east, ocean prevents the deployment of instruments. Uncertainties in epicentral locations of ± 10 km (within 95% confidence levels) are still common. The uncertainties limit attempts to associate Hunter earthquake activity with geological structures, because the errors in location could be of the order of the dimensions of the structure itself.

A simple statistical test (Stepp, 1972) was applied to the earthquake catalogues to determine the time period over which the catalogues were complete for various earthquake magnitudes. The results for the TSMZ are shown in Table 3-2.

[4] *Source: ABS, 2002,Longer Term Series, CPI All Groups, Weighted Average of Eight Capital Cities*

[5] *Source: Insurance Disaster Response Organisation, www.idro.com.au*

Table 3-2: Completeness intervals for the Tasman Sea Margin Zone

Earthquake Magnitude	Period of completeness
3.2	01 January 1970
4.0	01 January 1960
5.0	01 January 1910

3.1.1 Isoseismal Maps

Reports of damage and other "felt" effects are quantified in terms of assigned intensities (Modified Mercalli Intensity MM values – see Appendix A). The compiled isoseismal maps for each earthquake (contour map of the individual intensities MM, based on the above data) provide part of the data for this study. Isoseismal maps were published in three BMR/AGSO Atlases (Everingham et al., 1982; Rynn et al., 1987; McCue, 1995).

Isoseismal maps show the distribution of the shaking effects of earthquakes, and provide valuable information for estimates of earthquake risk. They are of particular significance in Australia, where instrumental strong-motion data are scarce and difficult to obtain. Isoseismal maps for Australian earthquakes have appeared in a large variety of publications, and some maps have been republished in small groups when used in specific earthquake risk studies Isoseismal maps for the two most recent strong earthquakes in the Hunter are shown in Figure 3.2 and Figure 3.3. Other isoseismal maps are shown in Appendix B.

In the isoseismal map of the 1989 Newcastle earthquake (Figure 3.2) the maximum intensity was assessed at MM VIII (McCue et al., 1990). Modern structures in the epicentral region and downtown Newcastle suffered considerable damage including the Pasminco zinc refinery, the then unopened John Hunter Hospital, Newcastle Technical College and The Junction Motel. Of course special reasons can be found for their failure, and many other structures were undamaged, but the ground motion was undeniably strong. The Newcastle earthquake was felt at MM IV-V in Sydney and clearly in Canberra, especially in tall buildings. The radius of perceptibility was about 310 km, corresponding to a Richter magnitude of 5.6. The shape of the contours is similar to those of other Hunter Valley earthquakes in 1868 and 1925 (see Appendix B) but the 1989 earthquake is the largest since it was felt over a wider area.

The Ellalong earthquake occurred at 1103 UTC on 6 August 1994 about 12 km south-west of Cessnock NSW. Its magnitude was ML 5.4 (Jones et al., 1994) and its computed depth was 1.4 ± 2.3 km. The earthquake was the largest in eastern Australia since the ML 5.6 1989 Newcastle earthquake and its epicentre was only 30 km west of the epicentre of the 1989 earthquake. The two events had similar reverse faulting mechanisms with horizontal north-east – south-west pressure axes. The isoseismal map of the 1994 Ellalong earthquake (Figure 3.3) indicates that maximum intensities of MM VII were observed near the epicentre and the radius of the MM VI isoseismal is about 8 km. A maximum peak ground velocity of more than 160 mm/s was recorded by a mine vibration monitor within a few kilometres of the hypocentre and a maximum vertical acceleration of 0.34 g was calculated from the same record.

Because of the sparseness of instruments to record strong ground motion in Australia we will have to rely for many years on the careful analysis of felt intensities to assess earthquake risk. Therefore it is essential that a comprehensive and reliable source of these data is maintained. New isoseismal maps of past and future earthquakes, and possible revisions of existing isoseismal maps, will be included in annual GA seismological reports.

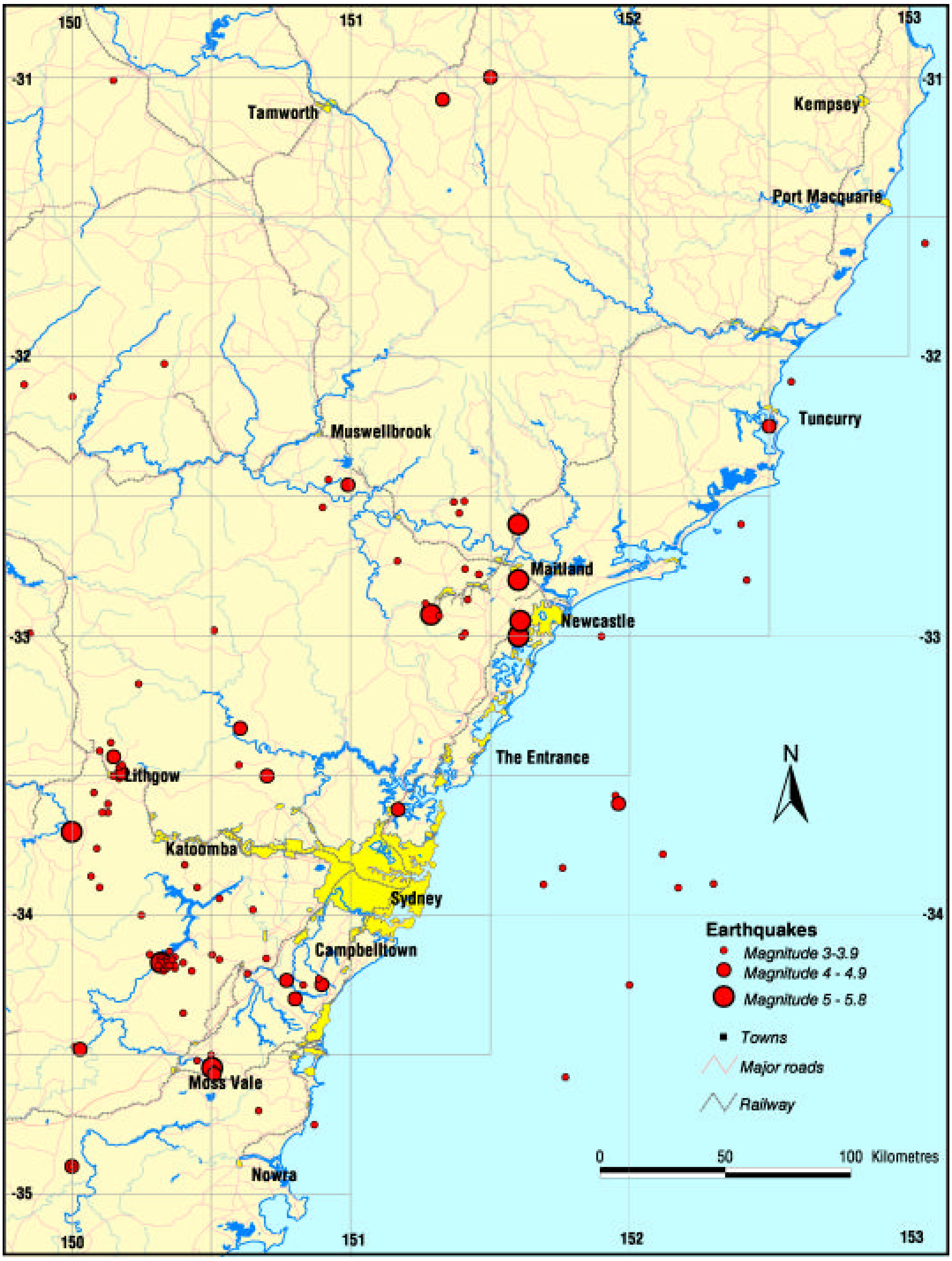

Figure 3.1: Earthquake epicentres within about 200 km of the study region

Table 3-3: Significant earthquakes in the study area

Date	Time (UTC[6])	Lat (°S)	Long (°E)	Place	M_L[7]	I_{max}[8]	Comments	Source
02/07/1837	12:20	(33.0)	(152.0)	Near Newcastle	(5.0)	V	Felt in Newcastle MM V	Hunter, 1991
27/01/1841	21:55	32.8	151.6	Near Newcastle	4.9	V	Felt in Newcastle MM V	McCue, 1995
27/10/1842	19:30	32.6	151.6	Near Paterson	5.3	V	Felt in Newcastle MM V	McCue, 1995
18/06/1868	14:00	32.8	151.6	Maitland	5.3	VI	Felt in Newcastle MM V - VI; damage reported	McCue, 1995
18/10/1872	18:50	33.7	149.8	Jenolan Caves	5.3	VI	Felt in Newcastle MM IV - V	McCue, 1995
10/06/1916	00:17	32.25	152.5	Seal Rocks	4.6	VI-VII	Felt in Newcastle MM IV-V	McCue, 1995
15/08/1919	10:21	33.5	150.7	Kurrajong	4.6	V	Felt in Newcastle MM II-III	Everingham et al., 1982
18/12/1925	10:47	33	151.6	Boolaroo	5.3	VI	Felt in Newcastle MM VI; damage reported	Rynn et al., 1987
21/05/1961	21:40	34.55	150.503	Robertson-Bowral	5.6	VII	Felt in Newcastle MM III - IV	Everingham et al., 1982
09/03/1973	19:09	34.17	150.32	Picton	5.5	VII	Felt in Newcastle MM III	Everingham et al., 1982
15/11/1981	16:58	34.25	150.9	Appin	4.6	V	Felt in Newcastle MM III	Everingham et al., 1982
13/02/1985	08:01	33.49	150.18	Lithgow	4.3	VI	Felt in Newcastle MM III	McCue, 1995
20/02/1986	21:43	33.33	150.604	Upper Colo	4.0	IV	Felt in Newcastle MM II	McCue, 1995
24/06/1987	15:04	33.43	150.149	Lithgow	4.3	VII	Not felt in Newcastle	McCue, 1995
27/12/1989	23:26	32.95	151.607	Newcastle	5.6	VIII	Felt in Newcastle MM VIII; damage and casualties	McCue, 1995
08/06/1994	11:03	32.92	151.288	Ellalong	5.4	VII	Felt in Newcastle MM IV - VI	Jones et al., 1994
17/03/1999	01:58	34.23	150.77	Appin	4.8	V	Not felt, Newcastle	McCue et al., in press

[6] *UTC = Universal Coordinated Time = Australian Eastern Standard Time minus 10 hrs*

[7] *M_L = Richter (or local) magnitude*

[8] *I_{max} = maximum seismic intensity measured on the Modified Mercalli Scale*

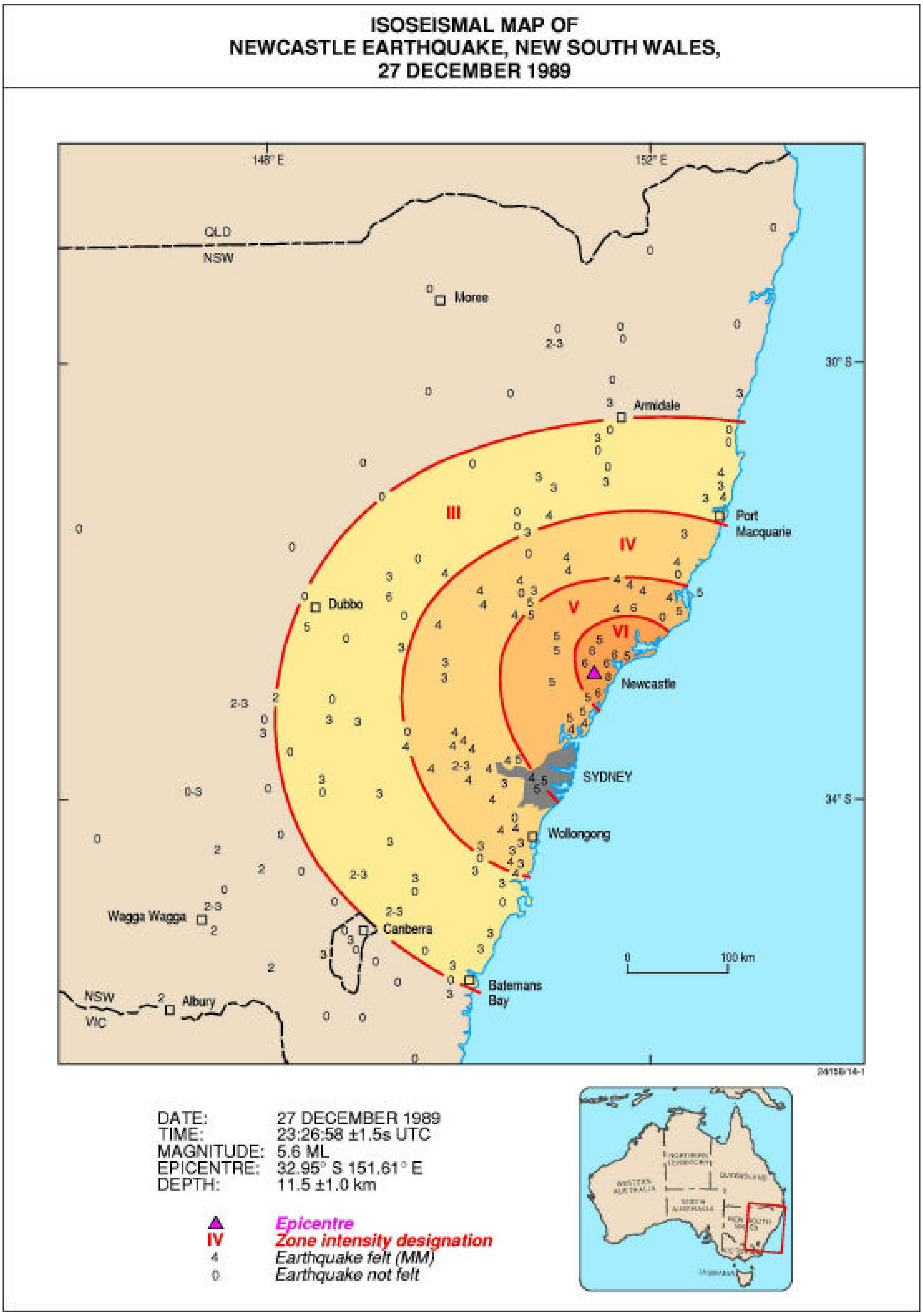

Figure 3.2: Isoseismal map of the Newcastle earthquake, New South Wales, 27 December, 1989 (UTC). Note that this event occurred on the 28 December local time

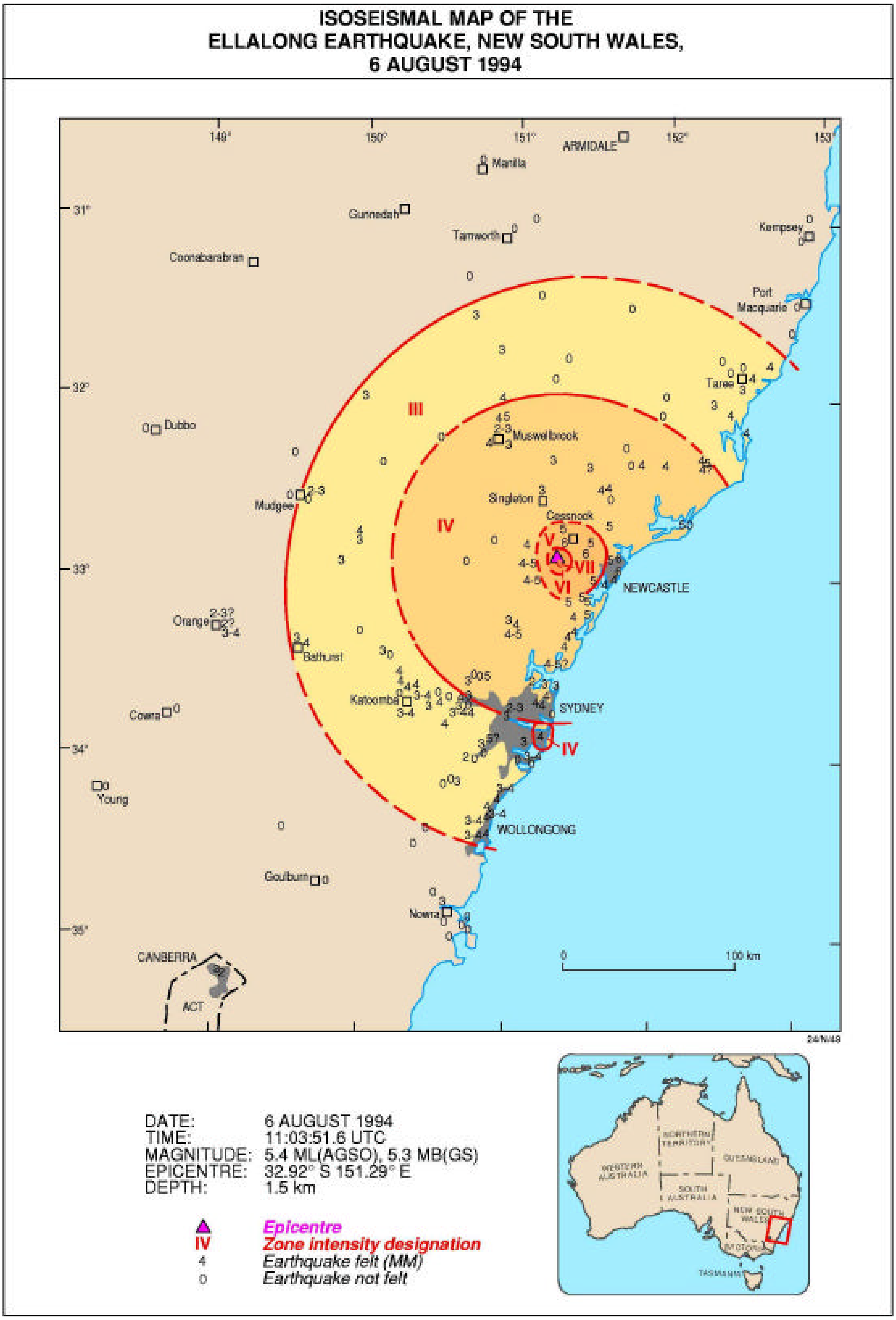

Figure 3.3: Isoseismal map of the Ellalong earthquake, New South Wales, 6 August 1994

3.2 The 1989 Newcastle Earthquake

The Richter magnitude 5.6 earthquake which occurred in Newcastle/Lake Macquarie on 28 December 1989 is termed the 1989 Newcastle earthquake. Unfortunately, there were no strong motion recordings of the earthquake close to the heavily damaged areas. However, the mainshock was followed on 29 December 1989 by several aftershocks, one of which was recorded on an array of seismographs installed that day in the Newcastle area. The recordings of the aftershock were used to synthesise the 1989 earthquake ground motion, resulting in estimates of around 0.24g for peak ground acceleration at a weathered rock site west of the Newcastle CBD (Wesson, 1996; Sinadinovski et al., 1996).

The 1989 Newcastle earthquake is described in detail below. The risk models used in this study are also validated in the following Chapters by way of comparison to the 1989 event.

The Newcastle 1989 earthquake claimed 13 lives and caused extensive devastation to buildings and other structures. This level of damage was unusual for such a moderate-magnitude earthquake. The level of damage appears to be partly due to the presence of regolith, as well as the location and condition of particular building types.

Inferences concerning wave propagation effects associated with the damage caused on 28 December 1989 depend on the estimated geographic location, focal depth, and mechanism of the earthquake. Of the hypocentral parameters, only the focal depth of the mainshock, 11.5 ± 0.5 km, is well constrained, by core-phase observations at the Eskdalemuir array in Scotland. With the focal depth thus constrained, the computed epicentre is near Boolaroo, at 32.95°S 151.61°E, some 15 km west-south-west of central Newcastle, with error-ellipse semi-axes of 16 km east-west and 6 km north-south (McCue et al., 1990). Other solutions, such as the epicentre calculated at ANU (Kennett, 1992) put it offshore, 11 km east of Boolaroo, but still within the error ellipse of the GA instrumental solution.

An aftershock related to the main 1989 event occurred at 0908 hours (UTC) on 29 December 1989. It was of local magnitude 2.9 and was felt in several suburbs of the City, with an intensity of MM II - III. By itself, the mainshock hypocentral determination does not give meaningful spatial resolution of the epicentre in relation to the area with highest seismic intensity. However, a precise hypocentre determined for the aftershock on 29 December is within a few kilometres of the computed mainshock focus, providing strong evidence that the mainshock epicentre was near Boolaroo rather than Newcastle. The aftershock, recorded by a local array of ten seismographs installed after the mainshock, had a calculated focal depth of 13.7 ± 2.0 km. Given the similarity of mainshock and aftershock focal depths, the general tendency of early aftershocks to cluster on mainshock ruptures or their edges, and the relatively small rupture dimension (a few km) expected for an earthquake of this magnitude, the Boolaroo epicentre is selected as the most likely position for the 1989 event.

A focal mechanism solution was constructed based on the first motions of ground movements recorded on seismographs. The focal mechanism determined for the mainshock is thrust, with a north-easterly and near-horizontal axis of maximum compressive stress. The north-west striking focal planes have dips of 75° to the north-east and 32° to the south-west. The plane dipping steeply to the north-east is preferred as the fault plane on the basis of geomorphic evidence. Rupture on the north-east dipping plane would direct maximum shear-wave energy toward Newcastle, and so it is possible that the apparent seismic intensity anomaly is due in part to the radiation pattern.

The 1989 Newcastle earthquake was felt from Albury, Cooma and Bermagui, in the south; to Temora and Narromine in the west; and Coonabarabran, Inverell, Armidale, Coffs Harbour, in the north (up to 550 km from Newcastle). The duration of felt shaking in Newcastle was 5 to 6 seconds. The area sustaining structural damage extended from Newcastle to Liverpool (Sydney) in the south (138 km); Scone in the north-west (145 km); and Gladstone (near Kempsey) in the north (320 km). A local intensity map of the 28 December 1989 (local date) earthquake for the Newcastle and Lake Macquarie area is shown in Figure 3.4 (Rynn et al., 1992).

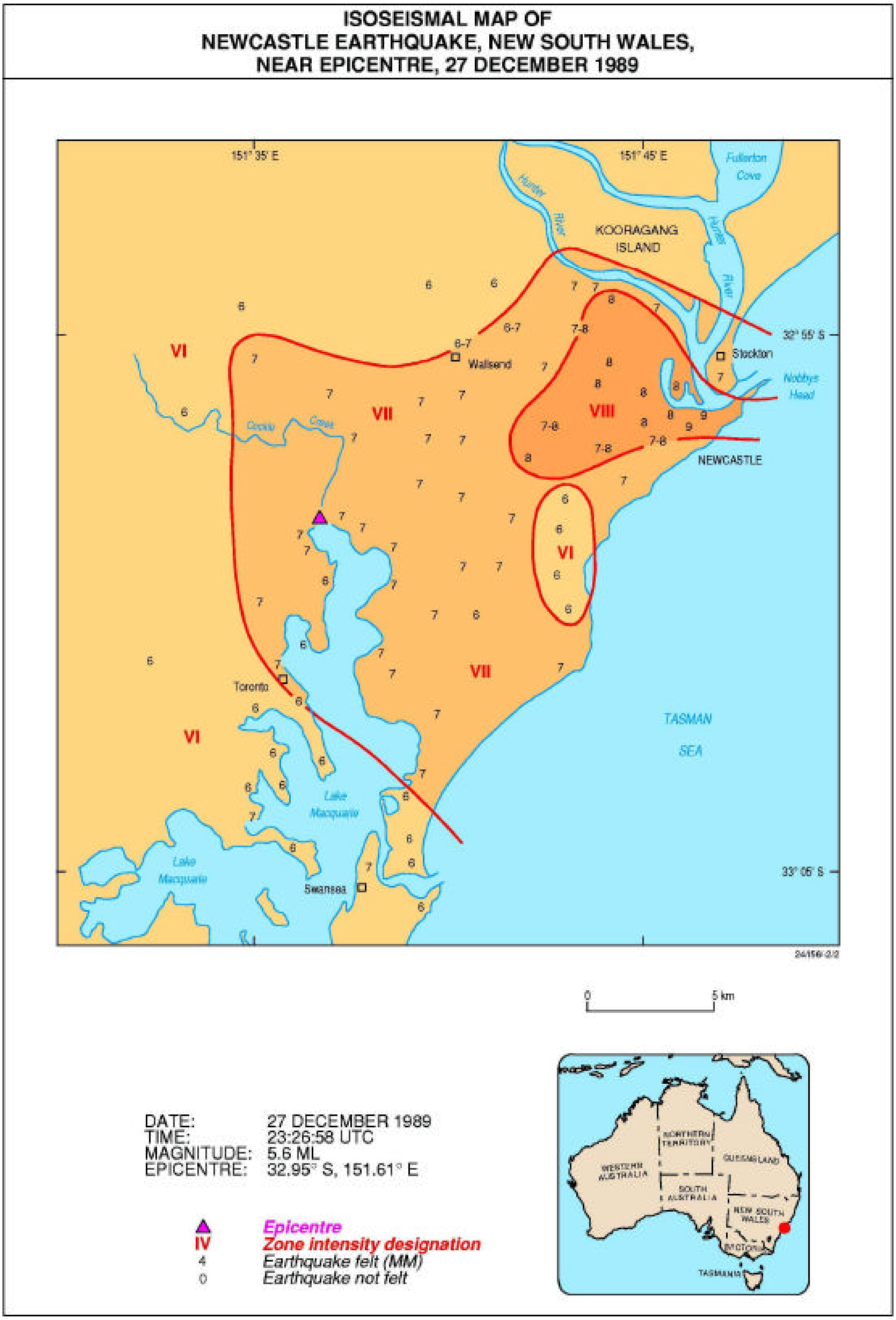

Figure 3.4: Intensity map for the Newcastle and Lake Macquarie area of the 27 December (UTC) 1989 earthquake (after Rynn et al., 1992)

Unusual phenomena at sea in the Newcastle area were reported. Several large ships east of the port of Newcastle, and boats on Lake Macquarie, reported high-frequency vibrations of the vessels at the time of the earthquake. Surfboard riders at beaches south of Newcastle reported two large waves appearing out of a fairly calm ocean, and seafloor movements were reported by skin divers.

There were several reports of people seeing earthquake waves travelling across the ground in suburbs of Newcastle such as Hamilton. However, there was no ground deformation, surface rupture/faulting; mine subsidence or observed liquefaction.

Newcastle was in chaos immediately following the earthquake as office workers poured out of buildings into rubble-strewn streets. Police cordoned off city streets and evacuated buildings in the central business district. Disaster response was hampered by disrupted telephone service, damage to critical buildings and blocked road access.

Several major hospitals sustained serious damage which caused disruption to medical services and, in the case of Royal Newcastle Hospital, resulted in the evacuation of patients because of fears of the effect of aftershocks on already damaged buildings. Because of the deaths and large number of injuries, hospitals implemented emergency plans to cope with the disaster.

Fires are often a major threat after an earthquake. This fortunately was not the case in Newcastle, and only one fire was reported. At the TAFE College at Tighes Hill a spill occurred in the chemistry building, resulting in a fire.

There were 13 deaths and at least 150 injuries. Tens of thousands of buildings were damaged. The insured losses were estimated at $862 million in 1990 dollars[9].

3.2.1 Principal Information Sources

Following the 1989 Newcastle Earthquake a considerable body of descriptive and interpretative material was prepared by a wide group of writers, investigators and professionals. This body of material has formed the platform from which the present project was built and is reviewed in this Chapter. Some of the most important sources are mentioned below, and sections of some documents are quoted in Appendix I. The primary information sources are:

1) "The Unexpected Catastrophe, 1989 Newcastle Earthquake Information Resource", CD Database produced by Newcastle Regional Library 1999, ISBN 0646375539 (Newcastle Regional Library, 1999). This excellent compilation holds written, visual and audio material collected by the Library, collated and edited by Ajita Lewis of the library.

2) "Newcastle Earthquake Study", The Institution of Engineers, Australia, 1990 - Edited by Dr R. E. Melchers of the Department of Civil Engineering & Surveying, The University of Newcastle. (Melchers, 1990).
The Institution of Engineers, Australia, recognising that valuable evidence of how buildings in Australia react under earthquake stress would soon be lost as restoration work commenced, took the lead in commissioning this remarkable document which was produced only months after the event. It contains powerful and pertinent recommendations, many of which still need action. The Institution approached the NSW Government who engaged the CSIRO and the University of Newcastle to undertake this study.

3) "Damage and Repair of Public Buildings", Earthquake Reconstruction Project, Newcastle Regional Office of the NSW Public Works Department, 1992
This valuable report records inspections of over 1,000 public buildings and the repair of over 600 State Government buildings. (NSW PWD, 1992)

4) "A Report on Earthquake Zonation Mapping of the City of Newcastle for Newcastle City Council", May 1995, by the Centre for Earthquake Research in Australia. (CERA, 1995)
This study was fully funded by the Council of the City of Newcastle, and was compiled by Dr Jack Rynn, then of the University of Queensland. The report has been considered by Council and its staff but has not been made available publicly.

[9] *Source: Insurance Disaster Response Organisation, www.idro.com.au*

5) "The earth was raised up in waves like the sea… EARTHQUAKE TREMORS FELT IN THE HUNTER VALLEY SINCE WHITE SETTLEMENT", Cynthia Hunter, 1991 (Hunter, 1991)
This book has researched written records of the time and presents a historical summary by Cynthia Hunter of the experience of earthquakes in the Hunter region over the last two hundred years. It records events back to 1788 in Sydney and 1801 in the Hunter.

6) "Factors Influencing the Structural behaviour of Residential Buildings in Newcastle Following the December 1989 Earthquake" (Irwin Johnston and partners NSW Pty Ltd and D J Douglas and partners Pty Ltd, 1991), The Insurance Council of Australia and GIO commissioned this report to examine the factors affecting damage to small buildings, both at the time and in the period following the earthquake.

7) Proceedings of the annual seminars of the Australian Earthquake Engineering Society (AEES).(IEAUST, 1986; McCue and Hince, 1992; Wilson et al., 1993; McCue, 1994; Griffith and Butler, 1996; Cuthbertson et al., 1997; Gregson et al., 1998)

3.2.2 Building Damage States in the 1989 Newcastle Earthquake

Newcastle City Council holds databases containing information of damage from the 1989 earthquake to more than 3,500 buildings. These databases are an extremely valuable historic record of most of the structures that suffered major damage in the 1989 earthquake, and the degree of damage that they underwent.

The damage rating used by Council assessors and others is described in Table 3-4. A map of the colour coded damaged buildings was prepared from the Newcastle City Council databases. This map is shown in Figure 3.5. For information on the geological site classes which underlie this figure, refer to Chapter 4.

The Newcastle City databases contain considerable detail. However, in this report, the data have not been used to compare the simulations of damage in the 1989 earthquake with the observed data. One of the main problems with the data is that either no information was recorded on the building type or, if it was, it was recorded in a way that did not allow us to easily compare it with the construction types used in our simulation models (see Chapter 6).

Another difficulty for us was that the damage ratings were difficult to compare with the damage states used in our simulations (see Chapter 6).

Table 3-4: Building damage classification system from the 1989 Newcastle earthquake

Building classification	Description
Red	Immediate Public Danger
Amber	Severe Damage, Possible Danger, Access Required
Blue	Damaged but Habitable
Green	Minor Damage

In conclusion the 1989 Newcastle earthquake presented a unique opportunity to learn about the effects and impacts of earthquakes on Australian communities. With regard to this study, it represented an opportunity to verify the modelling techniques used (Chapter 6).

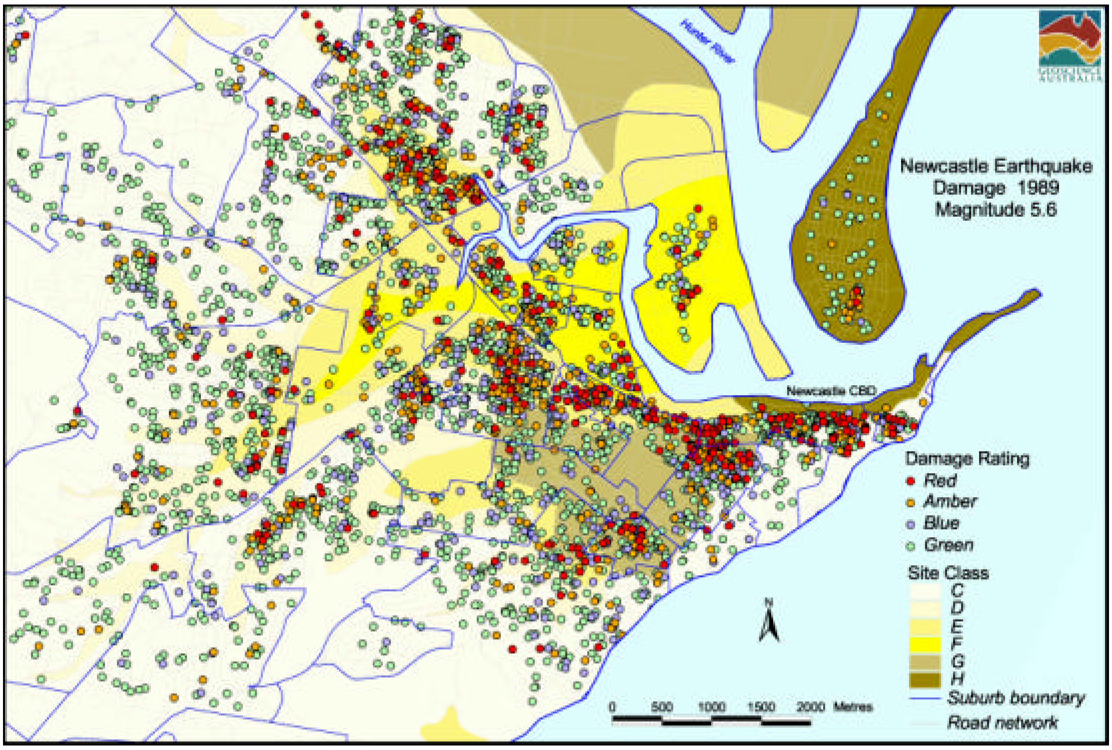

Figure 3.5: Recorded damage distribution in the Newcastle area, according to Newcastle City Council colour coded damage ratings for the 1989 earthquake