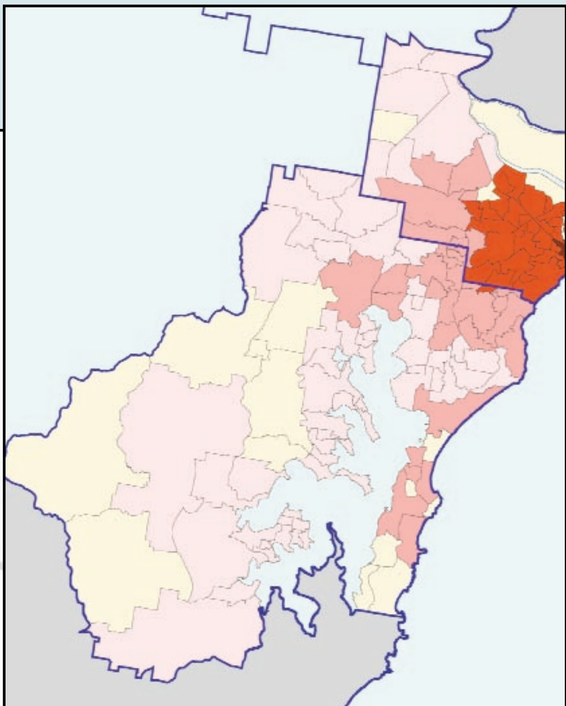
Earthquake Risk in *Newcastle* & LAKE MACQUARIE



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Edited by Trevor Dhu and Trevor Jones

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DEPARTMENT OF INDUSTRY, TOURISM & RESOURCES

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EARTHQUAKE RISK IN NEWCASTLE AND LAKE MACQUARIE

Edited by Trevor Dhu and Trevor Jones

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Hunter District Emergency Management Committee

City of Lake Macquarie

1 Summary (T. Jones and T. Dhu)

This Chapter summarises the important results of the earthquake risk assessment of Newcastle and Lake Macquarie. The summary presents the essential aspects of the risk assessment techniques used, the important results and conclusions, and suggests options to mitigate the earthquake risk in Newcastle and Lake Macquarie.

1.1 Background

At 10.27 am on the 28 December 1989 an earthquake measuring 5.6 on the Richter scale shook Newcastle, Australia's sixth most populous city. This moderate-magnitude earthquake claimed 13 lives and caused extensive damage to buildings and other structures. This event clearly demonstrated that moderate-magnitude earthquakes, which frequently occur in Australia, have the potential to dramatically impact Australian communities.

Natural hazards devastate Australian communities almost every year. In response to the danger posed by these natural hazards, Geoscience Australia developed the Cities Project. This initiative began in 1996 and is focused on research to measure and mitigate risks faced by Australian urban communities from a range of natural hazards including earthquakes. The ultimate objective is to improve the safety of communities, and consequently make them more sustainable and prosperous.

1.2 Introduction

In addition to the devastating 1989 Newcastle earthquake, at least four other earthquakes of magnitude 5 or greater have occurred in the surrounding Hunter region since European settlement in 1804. 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. The frequency with which these events have occurred in the Hunter region suggests that earthquakes pose a genuine threat to the communities there.

This study presents the most comprehensive and advanced earthquake risk assessment undertaken for any Australian city to date. It has focused on the economic losses caused by damage to buildings from earthquake ground shaking, and not on the impacts from other, secondary hazards such as soil liquefaction and surface faulting. The study has adopted a probabilistic approach that makes allowances for the variability that is inherent in natural processes as well as the uncertainty in our knowledge.

The results from this project will assist decision-makers involved in local and state government, policy development, the insurance industry, engineers, architects, and the building and finance industries to manage potential damage and loss of life from earthquakes in Newcastle and Lake Macquarie. The results also have implications for the earthquake risk facing larger Australian cities such as Sydney, Melbourne and Adelaide. This is due to a number of factors, including similarities between the earthquake hazard in Newcastle and Lake Macquarie and other parts of Australia, and similarities between the urban environments, particularly the composition of the building stock.

We emphasise that this report should be regarded as the best and most recent assessment of earthquake risk in Newcastle and Lake Macquarie. However, we acknowledge that there are limitations in the models and data we have used, and that we have an incomplete understanding of the natural variability inherent in ground shaking and building response.

The results, interpretations and conclusions could change with the incorporation of new data and with different model assumptions.

Therefore, the reader should not take action based on information in this report alone.

1.3 Methodology

The general risk assessment philosophy adopted by the Cities Project has been developed from the joint Australia/New Zealand Risk Management Standard, (AS/NZS4360, 1999). It can be expressed conceptually as follows:

Risk = Hazard * Elements at Risk * Vulnerability of the Elements at Risk

For the specific case of earthquake risk assessments, this process can be described by the flowchart in Figure 1.

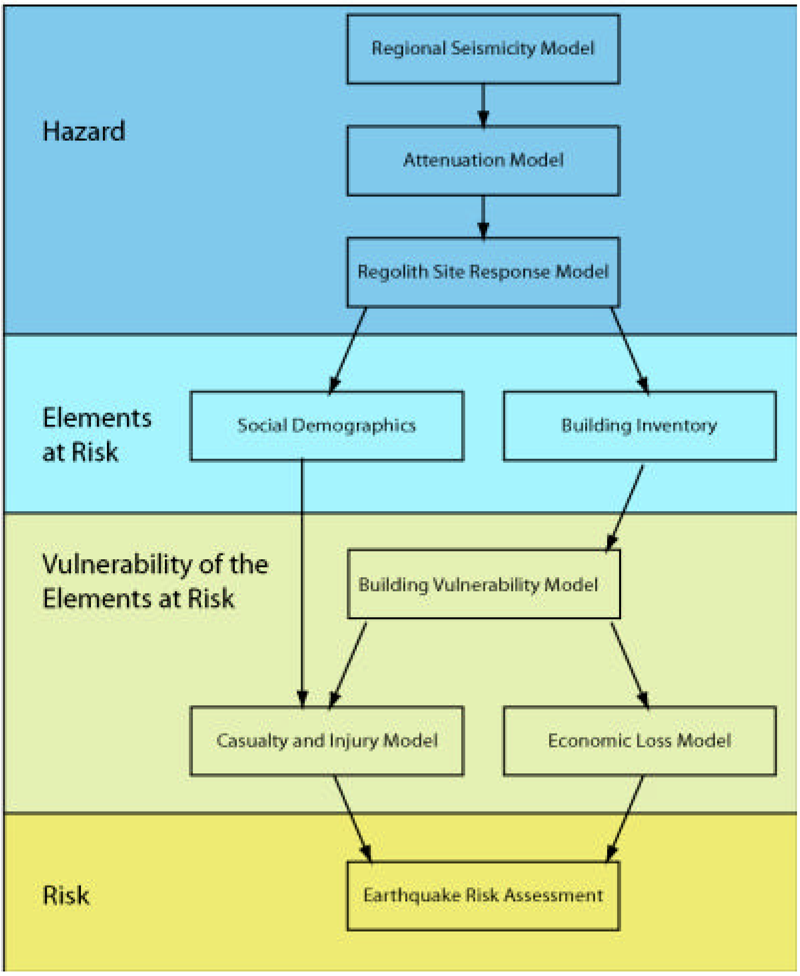

Figure 1.1: Flowchart describing the earthquake risk assessment process as applied to Newcastle and Lake Macquarie

A brief overview of the key assumptions and models used in the Newcastle and Lake Macquarie earthquake risk assessment is provided below. For a detailed description of the adopted methodology, the reader is directed to Chapters 3 to 6.

1.3.1 Earthquake Hazard

The earthquake hazard in a region can be described in terms of *the level of ground shaking that has a certain chance of being exceeded in a given amount of time*. For example, it is common to describe earthquake hazard in terms of the level of ground shaking that has a 10% chance of being exceeded in 50 years. In order to calculate the earthquake hazard, three key models are needed, specifically:

- a *regional seismicity model*, which describes the chance of an earthquake of a given magnitude occurring in a year;
- an *attenuation model*, which describes generally how earthquake ground shaking or intensity decreases with distance away from the earthquake source, and;

- a *site response model*, which describes how local regolith (soils, geological sediments and weathered rock) will affect the ground shaking experienced during an earthquake.

The *regional seismicity model* was created from historical seismicity and an interpretation of the earthquake occurrence on local geological structures. The model describes the chance of occurrence of earthquakes with moment magnitudes ranging from 4.5 through to 6.5, as these were thought to be the events likely to inflict damage on the study region.

The *attenuation model* of Toro et al. (1997) was used in this study. This attenuation model was developed for central and eastern North America, a region of the world that is thought to have similar attenuation characteristics to Australia. However, it must be emphasised that no explicit study has been conducted on the suitability of this model for Australian conditions.

The *site response model* was developed from detailed geotechnical data which were acquired primarily in the Newcastle municipality, and to a lesser degree the Lake Macquarie municipality. These data were used to classify the study region into six different site classes. State-of-the-art modelling techniques were then used to determine how ground shaking on regolith (soils, geological sediments and weathered rock) would differ from ground shaking on an unweathered rock outcrop.

1.3.2 Elements at Risk

Geoscience Australia undertook a comprehensive field survey in order to document the characteristics of buildings in the study region that contribute to the building's vulnerability during an earthquake. This survey obtained vital information such as wall construction type and building usage for approximately 6,000 buildings in the study region. In addition to surveying a sample of the general building stock, an effort was made to survey all essential service facilities such as hospitals, and ambulance and fire stations.

1.3.3 Vulnerability of the Elements at Risk

Earthquake vulnerability models are used to estimate the level of damage caused by a given level of ground shaking for a wide variety of building types. For the purposes of this study, building damage due to earthquake ground shaking was calculated using the method described in Kircher et al. (1997). The vulnerability models were developed specifically for Australian building types. This approach allows the calculation of damage on the basis of building type. For example, given a certain level of ground shaking, the damage to an unreinforced masonry structure would be different from the damage to a timber-framed structure.

Models based on work from the Federal Emergency Management Agency (FEMA) in the United States were used to convert estimates of building damage into estimates of economic loss. In this study, economic loss is defined in terms of the restoration cost of local buildings and their contents. The models from FEMA were calibrated using the cost of restoration for local buildings. FEMA models were used to calculate casualty losses in terms of injuries and lives lost.

1.3.4 Earthquake Risk

As mentioned previously, the earthquake risk to the study region is a combination of the earthquake hazard, the elements at risk and the vulnerability of those elements to earthquake ground shaking. In this study, these three components have been combined by:

- conducting computer simulations of approximately 1,200 earthquakes across the study region, each with its own magnitude and probability of occurrence based upon the regional seismicity model;
- using the attenuation and site response models to determine the level of ground shaking from every simulated earthquake at each of the surveyed buildings;
- using the vulnerability models to calculate the damage and economic loss to every building from each earthquake, as well as the related casualties, and;
- aggregating the losses across all the buildings in the study region to produce an estimate of loss for each of the 1,200 simulated earthquakes.

1.3.5 Incorporation of Variability

Any attempt to model natural processes or phenomena should incorporate some of the variability that is inherent in nature. For example, in this work we have classified the entire study region into six different regolith site classes. However, it is unrealistic to believe that every point within a single regolith site class will respond to an earthquake in precisely the same manner. Similarly, it is unrealistic to believe that every timber-framed building in the study area will suffer the same amount of damage given a certain level of ground shaking.

A detailed description of how natural variability has been incorporated into this study can be found in Chapters 3 to 6. However, in essence, the natural variability was incorporated by allowing the model parameters to vary in the simulations. One result of incorporating this variability is that two buildings of the same type, which experience the same level of ground shaking, may suffer different levels of damage. Similarly, the site response and attenuation models were allowed to vary in each earthquake simulation.

1.3.6 Verification of the Risk Assessment Methodology – The 1989 Newcastle Earthquake

A computer simulation of the 1989 Newcastle earthquake was used to test the risk assessment methodology used in this work. The results of the simulated earthquake were compared against records of the actual damage experienced during the 1989 event. For a detailed comparison of the simulated results with those recorded after the event, the reader is directed to the attached main report. When considered on a broad scale, the results of this comparison are very encouraging. For example, the simulated economic loss for the study region in 1989 dollars was of the order of $1.1 billion. This simulated economic loss is for both insured and uninsured properties. In comparison, in the aftermath of the 1989 earthquake, the insured losses in 1989 dollars were estimated to be $862 million[1].

1.4 Earthquake Risk Assessment Results

1.4.1 Earthquake Hazard in the Newcastle and Lake Macquarie Region

Earthquake hazard is typically measured in terms of the level of ground shaking that has a certain chance of being exceeded in a given time period. The Australian earthquake loading standard, AS1170.4-1993, presents earthquake hazard in terms of an ‘acceleration coefficient’ that has a 10% chance of being exceeded in 50 years. This acceleration coefficient is considered to be equivalent to peak ground acceleration. A comparison of the earthquake hazard from AS1170.4-1993 with the equivalent hazard calculated in this study is presented in Figure 1.2 and Figure 1.3. Both maps have the same trend of increasing hazard towards the north-east of the study region. The hazard calculated within this study is typically greater than the hazard suggested by the Australian earthquake loading standard.

The hazard maps presented in Figure 1.2 and Figure 1.3 were calculated using a measure of ground shaking (i.e. peak ground acceleration) that would be experienced on a rock outcrop. However, the buildings in Newcastle and Lake Macquarie are not built on rock, but rather on varying thicknesses of regolith. Note also that the damage experienced by buildings is often influenced not only by the peak ground acceleration, but also by the level of ground shaking at a specific period of vibration. For example, low- to medium-rise structures are typically more vulnerable to ground shaking that has a period of vibration of approximately 0.3 s than they are to peak ground acceleration. Figure 1.4 presents an estimate earthquake hazard on regolith based on the response of idealised low- to medium-rise structures. This figure clearly demonstrates that the soils and geological sediments from rivers, streams, wetlands and barrier sands have a greater level of hazard than the weathered rock material which covers the rest of the study region.

Medium- to high-rise structures are typically more vulnerable to ground shaking that has a period of vibration of approximately 1 s. Figure 1.5 presents the earthquake hazard on regolith based on the response of idealised medium- to high-rise structures. In this figure, the highest hazard can be seen to be associated with the coastal and riverine deposits in the eastern and north-eastern parts of the study region.

[1] *Insurance Disaster Response Organisation, 2002, www.idro.com.au.*

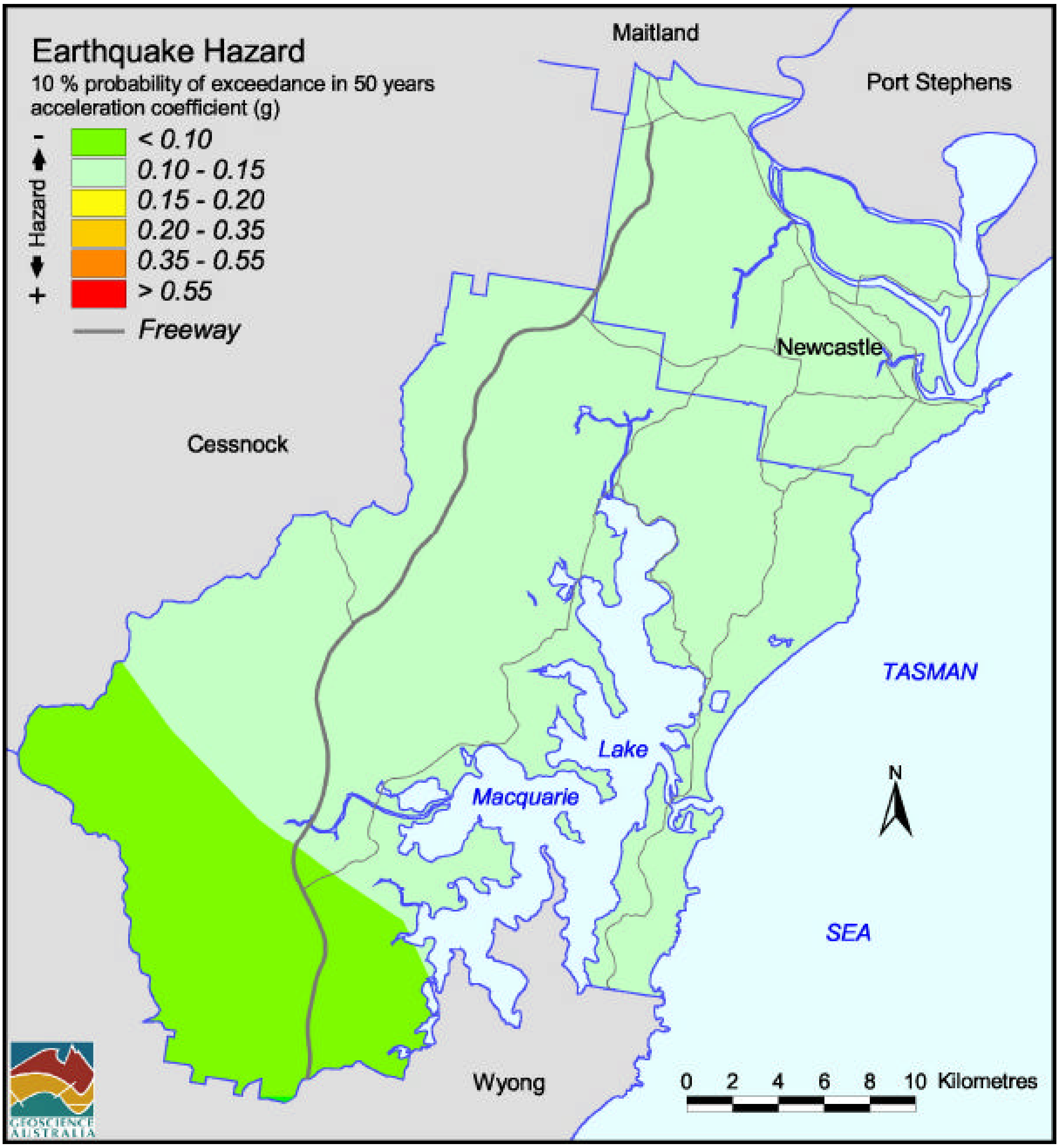

Figure 1.2: Earthquake hazard on rock in Newcastle as suggested by the Australian earthquake loading standard, AS1170.4-1993. Earthquake hazard is defined as the acceleration coefficient (considered equivalent to peak ground acceleration) that has a 10% chance of being exceeded in 50 years

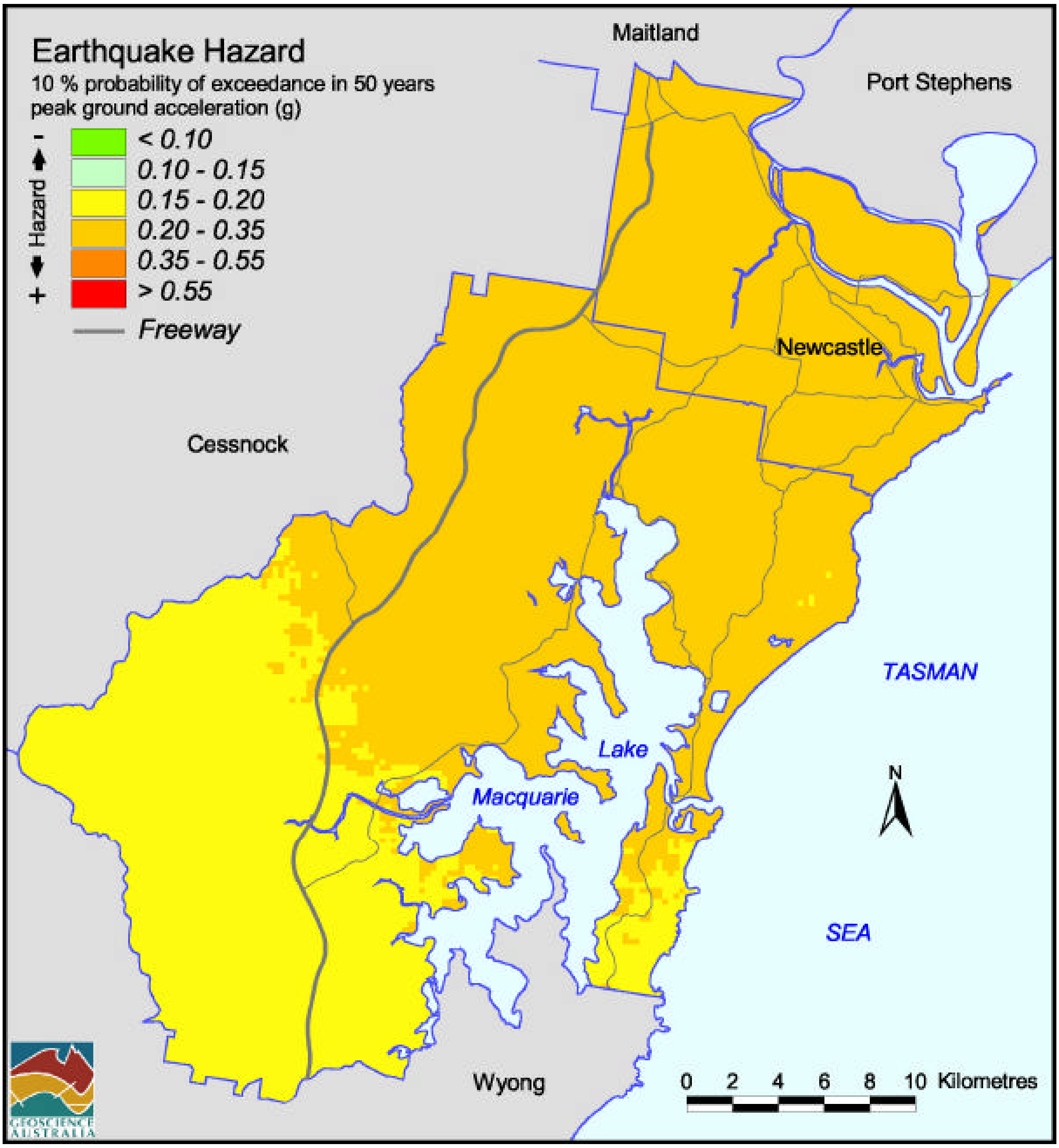

Figure 1.3: Earthquake hazard on rock in Newcastle as suggested by the hazard assessment conducted for this study. Earthquake hazard is defined as the peak ground acceleration that has a 10% chance of being exceeded in 50 years

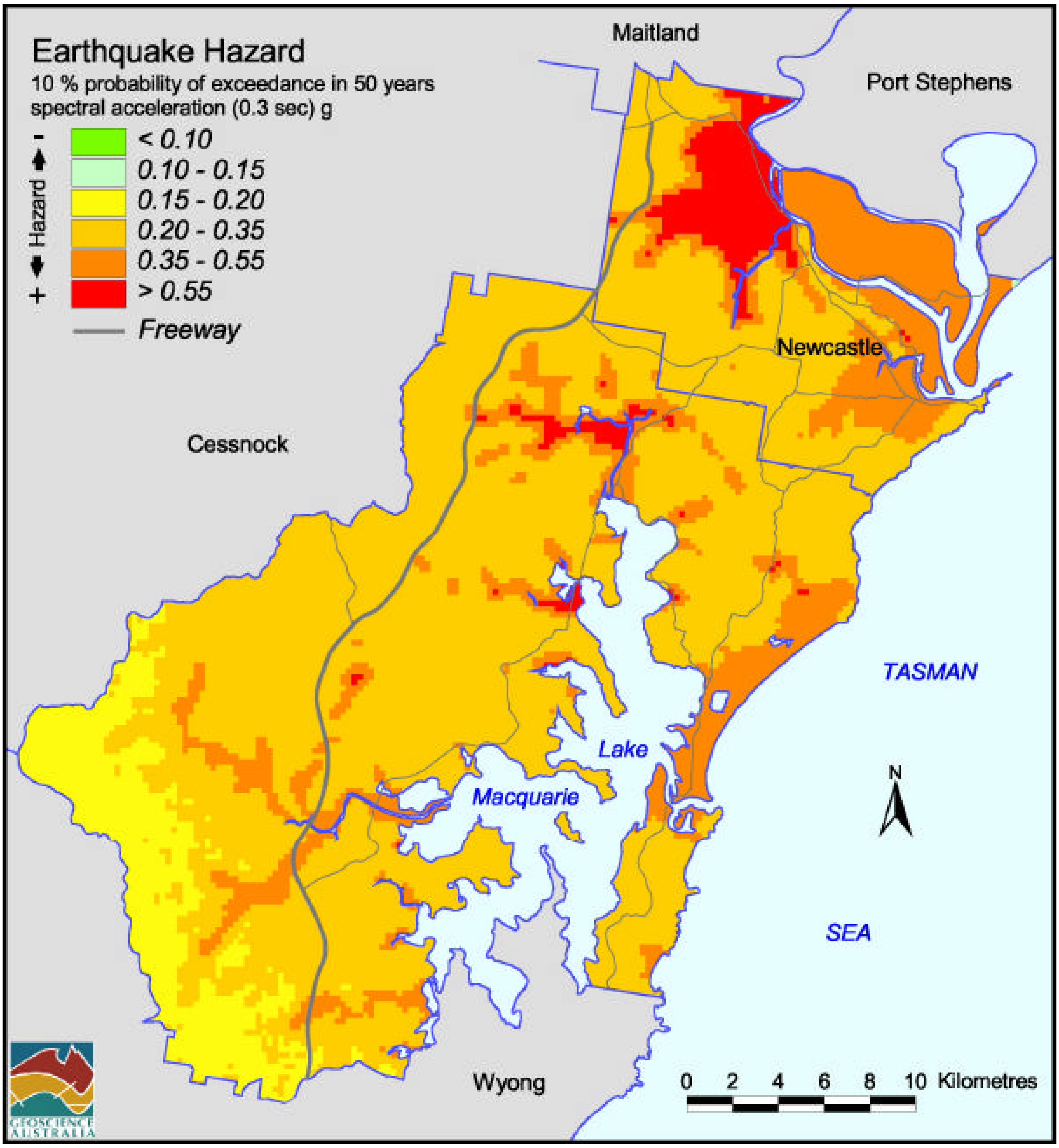

Figure 1.4: Earthquake hazard map on regolith with a 10% chance of being exceeded in 50 years. Hazard is defined by the response of idealised low- to medium-rise buildings with a natural period of 0.3 s. Note that the soils and geological sediments from rivers, streams, wetlands and barrier sands have a greater level of hazard than the weathered rock material which covers the rest of the study region

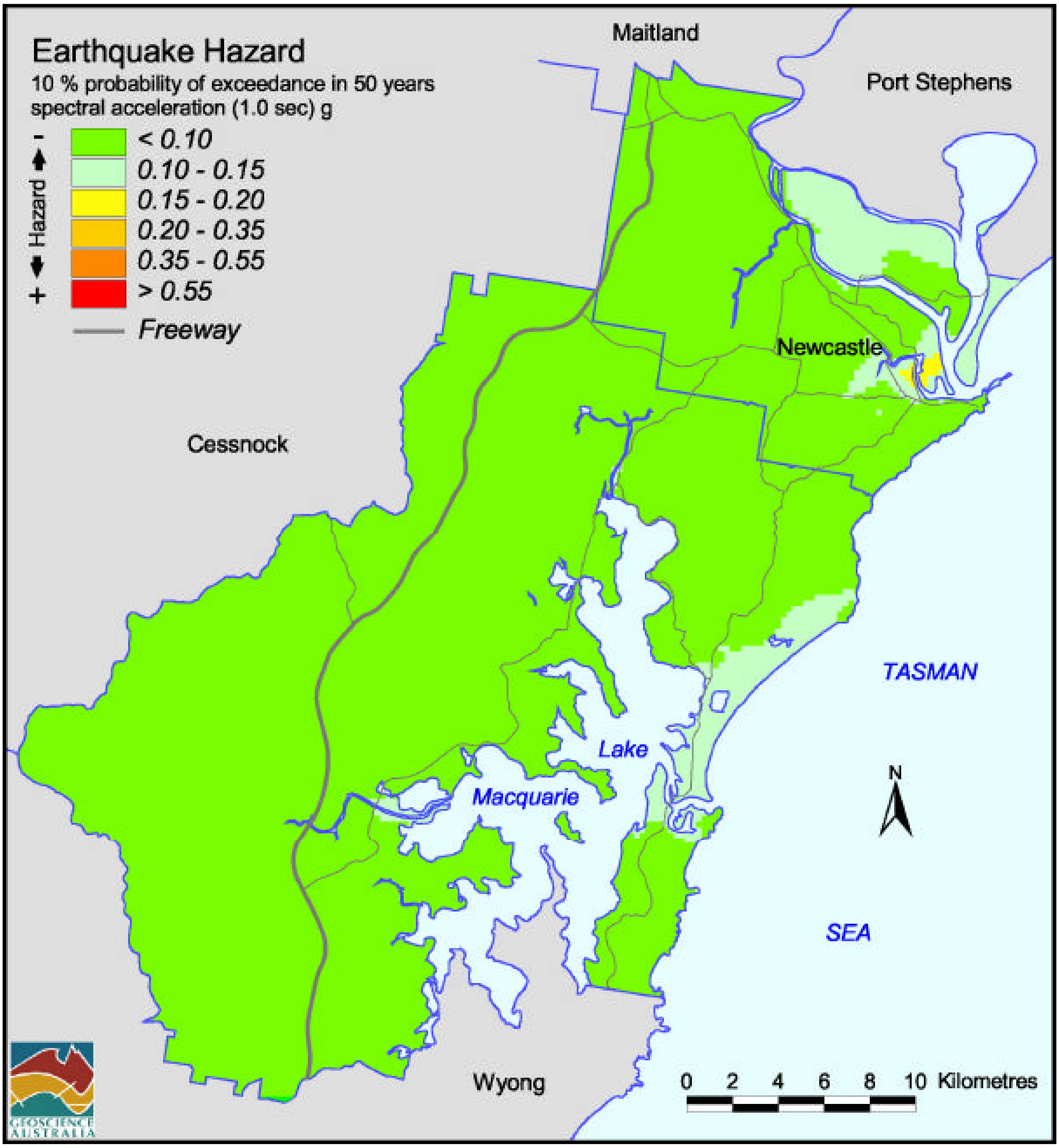

Figure 1.5: Earthquake hazard map on regolith with a 10% chance of being exceeded in 50 years. Hazard is defined by the response of idealised medium- to high-rise buildings with a natural period of 1 s. Note that the highest hazard is associated with the coastal and riverine deposits in the eastern and north-eastern parts of the study region

1.4.2 Earthquake Risk in the Newcastle and Lake Macquarie Region

The earthquake risk to a region can be described in many ways. However, a common expression is in terms of a risk curve (also called a probable maximum loss or PML curve). A risk curve for the study region is presented in Figure 1.6. This curve describes the probability of the study region incurring various minimum levels of economic loss within a single year. Economic loss is expressed as a percentage of the total value of all buildings and their contents in the study region. For example, the Newcastle 1989 event had a simulated loss on the order of 7.2% of the total value of the building stock and associated contents. Locating this point on the risk curve suggests that this level of loss has a probability of about 0.0006 of being exceeded in any single year. This annual probability corresponds to a return period of around 1,500 years for the 1989 Newcastle earthquake, and for other events that would have a similar impact on Newcastle and Lake Macquarie.

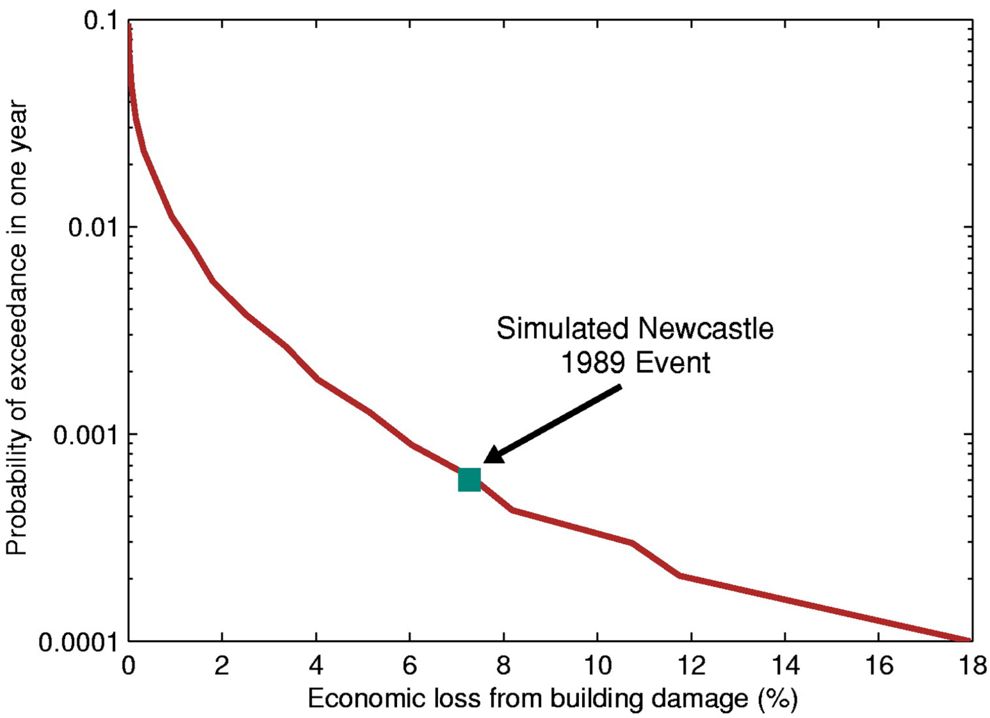

Figure 1.6: Risk curve (probable maximum loss curve) for the Newcastle and Lake Macquarie region. Economic loss is expressed as a percentage of the total value of all buildings and their contents in the study region

The majority of the earthquake risk in the study region is from events that have probabilities of occurrence in the range of 0.02 to 0.001 (return periods of 50 - 1,000 years). This suggests that the risk to the region is primarily from relatively infrequent events with low or moderate impacts. In contrast, very frequent events will have low impacts, and consequently they pose little risk to Newcastle and Lake Macquarie.

Very high impact events can also occur in the region. However, because these events are rare they only contribute relatively small amounts to the annualised risk to Newcastle and Lake Macquarie. For example, events with impacts at least as severe as the Newcastle 1989 event only contribute about 18% of the total annualised risk. These events have return periods of greater than 1,500 years, and their impacts will be greater than 7.2% of the total value of all the building stock, including contents. Note that these events, with return periods greater than 1,500 years, have a greater than 6% probability of occurring in any 100 year period.

The risk curve allows us to obtain an estimate of the annualised risk posed by earthquakes to the study region. The results of this study suggest that, on average, the Newcastle and Lake Macquarie region will suffer an estimated economic loss of around 0.04% per year. This corresponds to an annualised loss of the order of $11 million per year. If we assume a value of $250,000 for an ‘average’ residential building and its contents, then the annualised loss for this ‘average’ building and contents is around $100 per year. It should be noted that although this is the annualised loss for the entire study region, the annualised loss varies quite significantly from building type to building type. For example, buildings constructed from unreinforced masonry (cavity brick construction) have a higher annualised loss than any other building type in the study region (Figure 1.7).

However, there are many more timber frame buildings in the study area than unreinforced masonry buildings. Consequently, timber frame buildings make a greater contribution to the total risk in the study region than unreinforced masonry buildings.

Figure 1.8 presents the annualised loss by suburb, and clearly demonstrates that the loss varies spatially across the study region. This variation in loss can be partially attributed to differences in the building stock across the study region. However, the underlying regolith also affects the annualised losses, with areas that are built on substantial thicknesses of regolith, such as parts of the Newcastle municipality, having noticeably higher annualised losses than some other areas.

It is also possible to determine the relative contributions to the risk from earthquakes of different magnitudes at varying distances from the buildings within the study region. Over half the earthquake risk in the study region is due to earthquakes with moment magnitudes around 5 at distances of less than 30 km. This result further suggests that that the majority of the risk in the region can be attributed to moderate-impact, relatively infrequent events rather than high-impact, but extremely rare, events.

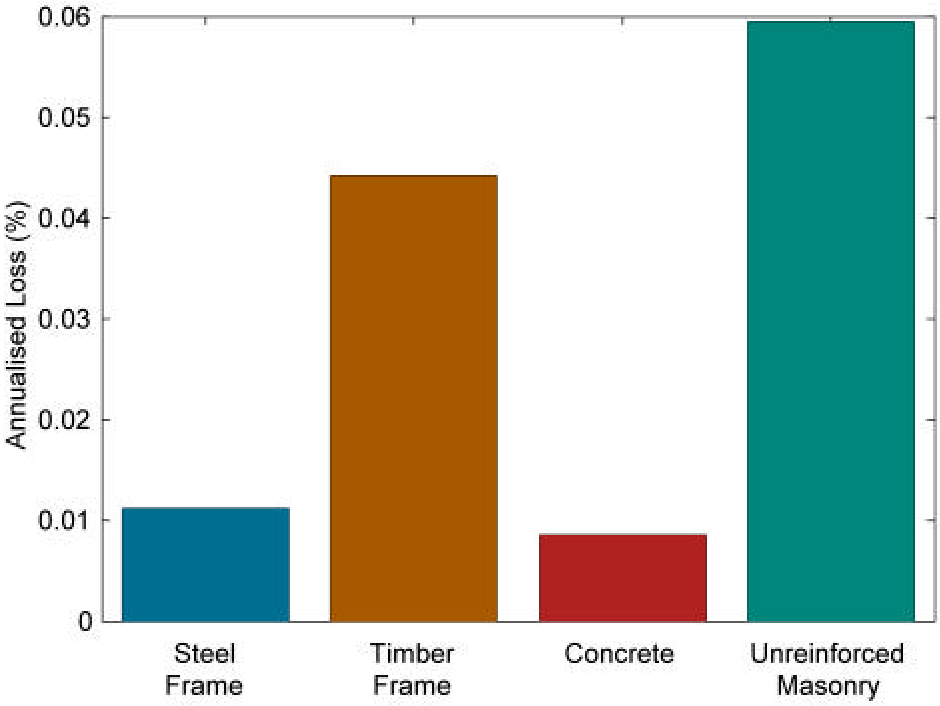

Figure 1.7: Annualised loss for a selection of building types in the study region. The annualised loss for a specific building type is described as a percentage of the total value of that building type and its contents in the study region

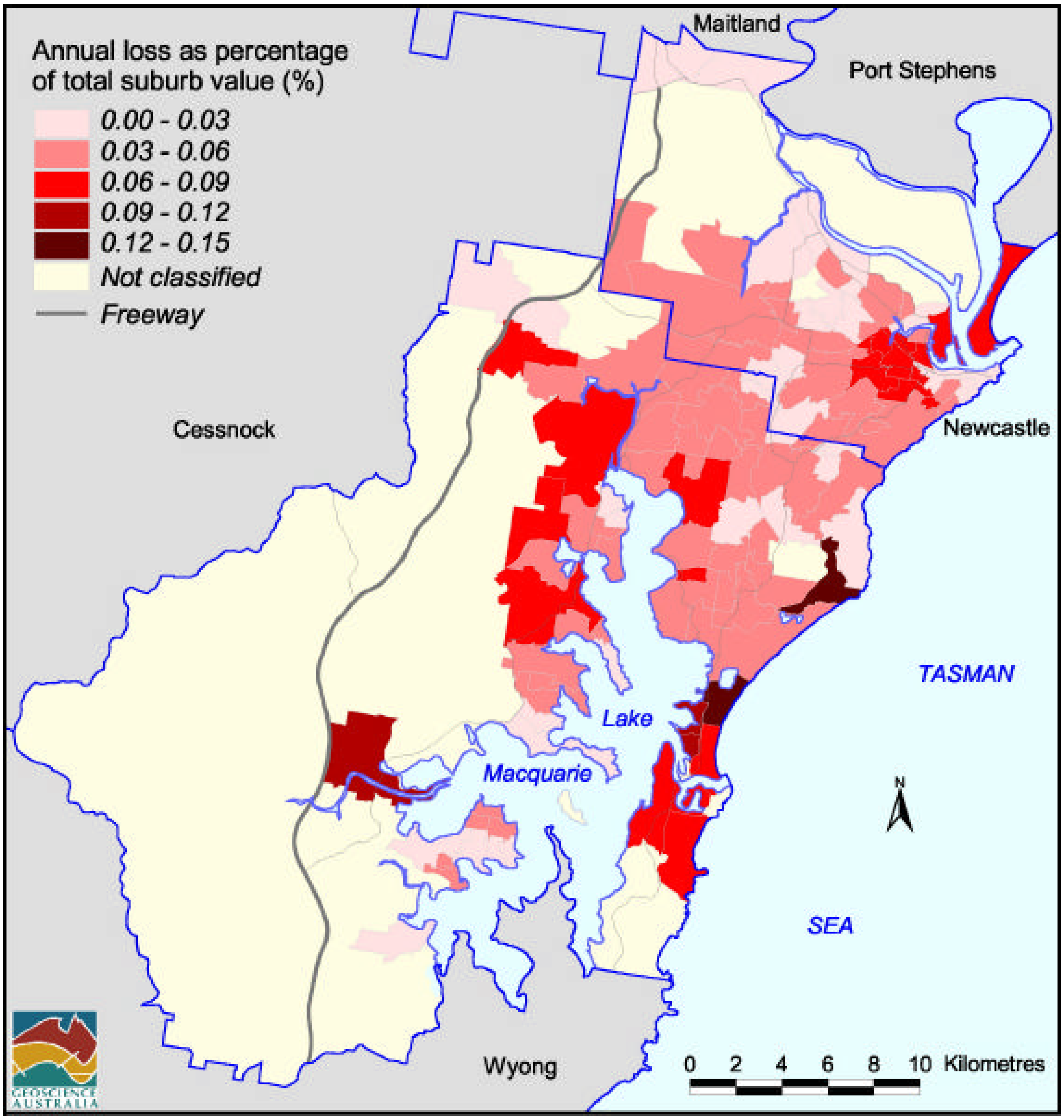

Figure 1.8: Annualised loss by suburb. The annualised loss in each suburb has been calculated as a percentage of the total value of all the buildings and their contents within the suburb. Note that some suburbs have not been classified due to the relatively low number of buildings surveyed

1.5 Summary and Conclusions

The results of our work are dependent upon the accuracy and appropriateness of both the data collected and the models applied in our risk assessment. Further refinement of the models may change some of these results, however, they are a good indicator of the trends and nature of earthquake risk in Newcastle and Lake Macquarie. Our conclusions from this study are:

- The calculated earthquake hazard in the Newcastle and Lake Macquarie region is higher than the hazard suggested by the Australian earthquake loading standard, AS1170.4-1993;
- The regolith in the study region causes a significant increase in the earthquake hazard, and differences in the regolith thickness can cause quite dramatic variations in the hazard and risk across the study region;
- The annualised loss for the study region is of the order of 0.04% or $11 million per year;
- The majority of the annualised earthquake risk in the study region is from events that have annual probabilities of occurrence in the range of 0.02 to 0.001 (return periods of 50 - 1,000 years);

- The risk varies with building construction type, and unreinforced masonry structures have higher average risks per building than other construction types. Brick veneer buildings contribute about half of the total risk. This is partly because they comprise a large proportion of buildings in Newcastle and Lake Macquarie. Timber frame buildings with timber, fibro and other light wall claddings contribute approximately one-quarter of the risk. A further one-sixth of the risk is contributed by unreinforced masonry buildings;

- Damage to residential buildings contributes the vast majority of the risk (approximately 91%). This is largely because residential buildings comprise the vast majority of all buildings in Newcastle and Lake Macquarie;

- The 1989 Newcastle earthquake had an economic impact with a return period of the order of 1,500 years. According to our models, approximately 82% of all annualised risk in Newcastle and Lake Macquarie is due to events with lesser economic impacts than the 1989 earthquake. Thus, events like the 1989 earthquake, or even more catastrophic events, make only a small contribution to the earthquake risk in the region when considered on an annualised basis. However, rare but catastrophic events are very important to emergency managers and the insurance and reinsurance industries;

- Annualised risk varies considerably across Newcastle and Lake Macquarie. It depends on the nature of the underlying regolith, the composition of the building stock and building usage in particular areas. Our results suggest that the suburbs most at risk in Newcastle, determined by a percentage of the total value of buildings and contents in the suburb, are Broadmeadow, Carrington, Hamilton, Hamilton East, Hamilton North, Hamilton South, Islington , Maryville, Stockton, The Junction, Warabrook and Wickham. In Lake Macquarie the suburbs most at risk are Belmont South, Blacksmiths, Caves Beach, Marks Point, Pelican, Swansea and Teralba. Further research into the building parameters for unreinforced masonry construction types may change these conclusions, especially in older suburbs such as Newcastle, Newcastle East, Newcastle West and Cooks Hill. Other Lake Macquarie suburbs such as Cooranbong, Dora Creek, Estelville, Fassifern, Holmesville, Killingworth, Redhead, Toronto and Warners Bay also had high annualised risk in our results, but the results are less reliable because survey rates were low in these suburbs, and the regolith site modelling is inferior to that in Newcastle;

- Over half of the earthquake risk is from moderate-magnitude earthquakes, with moment magnitudes around 5, that occur less than 30 km from the study area. This conclusion has implications for emergency management in the lower Hunter. It may be appropriate to prepare for the possible impacts of such events rather than on catastrophic events that have an extremely small probability of occurring;

- In general, the risk of casualties from earthquakes is low. However, we do not rule out the possibility that casualties in future events could be caused by damage to a single building, or a small number of buildings. It is extremely unlikely that any event capable of causing widespread casualties will occur in the study region;

- The results also have implications for the earthquake risk facing larger Australian cities such as Sydney, Melbourne and Adelaide. This is due to a number of factors, including similarities between the earthquake hazard in Newcastle and Lake Macquarie and other parts of Australia, and similarities between the urban environments, particularly the composition of the building stock;

- The earthquake risk to Newcastle and Lake Macquarie may be reduced gradually over time by improved building construction practices, attrition of vulnerable building stock such as unreinforced masonry, and by reducing vulnerability of existing buildings through renovations constructed to modern code standards;

- Good building practice may be the single, most important, long-term factor in reducing economic losses and casualties from earthquakes in Newcastle and Lake Macquarie.

It should be emphasised that a great deal of variability was included in the models used to generate these results. To some degree this variability was incorporated to account for our lack of knowledge about the various models used in the study. The effect of high levels of variability is to increase the estimates of risk. Future studies on the earthquake risk in the region should focus on improving the models that have been used. This will allow for the variability in the models to be decreased, which will most probably result in a decrease in the estimated risk.

1.6 Suggested Mitigation Options

- Newcastle City Council and Lake Macquarie City Council should consider adopting the site class maps and the associated, period-dependent median amplification factors in their land planning regulations. The amplification factors could replace the site factor S in AS1170.4-1993 in determining earthquake loadings for structures in Newcastle and Lake Macquarie. The amplification factors that refer to a peak ground acceleration on rock of 0.25 g from a magnitude 5.5 earthquake (Table 4-4) are appropriate, for normal structures, for earthquake loadings with a 10% probability of occurrence in 50 years.
- Enforce the compliance of all new structures with current earthquake loading standards. Two important areas where improvements could be made are in ensuring that mortar quality and wall tie placement and specifications comply with code specifications.
- Provide adequate insurance against earthquakes. Householders, small business operators and corporations should ensure that their earthquake insurance is adequate. The cost of repair or replacement of heritage buildings can be significantly higher than the corresponding costs for modern buildings and so there is potential for heritage buildings to be underinsured to a greater extent than other buildings.
- Protect facilities such as police, fire and ambulance stations and hospitals, which provide essential services following any earthquake event. These facilities could be examined by suitably qualified engineers on a site-by-site basis to assess their performance under earthquake loadings. The survey of essential facilities carried out during this study found that many of these facilities were built on regolith site classes that dramatically increased earthquake hazard and/or were of vulnerable construction types.
- Review earthquake loading standards. In this study, certain levels of building damage were estimated as a result of certain levels of ground shaking. The levels of damage may be more or less than what engineers would have expected from the input ground motions. If the damage predicted by the models is higher than would have been expected by expert engineers, then design standards may need to be made more rigorous. The damage models need to be rigorous for this review of design standards to be meaningful.
- Collect future post disaster damage, economic, social and insured loss data in a systematic, pre-planned way with a high degree of detail and accuracy so that risk assessments will be improved and the amount of variability reduced.
- Collect information on building parameters that contribute to vulnerability to earthquakes on a systematic basis and maintain databases containing this information. This need not be a tedious task if it is combined with similar related information gathering as for example through development approval processes. The information may also be useful for other purposes, for example, as estimating the vulnerability of the community to other hazards such as fire and wind, and would be valuable to the insurance industry. This long term strategy would assist risk assessments and risk management in the future.

1.7 Future Directions for Earthquake Risk Assessment

Many improvements and additions can be made to improve the techniques used in this study. Improvement can be made through new scientific, engineering and socio-economic research, by expanding the scope of the risk assessment to capture other sources of risk outside of what has been assessed so far, and by collecting, compiling and assessing new information to assist these initiatives. Chapters 4 and 6 each contain a discussion of the sources of earthquake hazard and risk variability.

Some important measures to improve earthquake risk assessment in Newcastle and Lake Macquarie are suggested below. The list is not comprehensive.

In this study, we have assessed direct economic losses due to building damage. Our study has not addressed the direct losses from business interruption or the indirect losses to other communities resulting from earthquakes in Newcastle and Lake Macquarie. An assessment of these losses would give a more complete estimate of the total risk due to earthquakes in Newcastle and Lake Macquarie.

The importance of the impacts of earthquakes on 'lifelines' such as electric power and water supply needs to be investigated. In Chapter 5, a preliminary analysis was undertaken of the exposure of sewer and water facilities due to their location on the various regolith site classes. Further investigation is required to assess the risk to lifelines in Newcastle and Lake Macquarie. This investigation needs to address the impact that earthquakes could have on lifeline function, as well as the consequent impact on the broader community due to impaired lifeline functioning.

The socio-economic implications of earthquake impacts on Newcastle and Lake Macquarie also need to be assessed. In the first instance, the simplest socio-economic vulnerability models would relate structural damage to the impact on all community activities and the time taken to restore the community to its normal state. Geoscience Australia has assembled some relevant information that could assist such investigations in future, and is working to develop socio-economic loss models for natural hazards.

The methodology used in the modelling approach is a significant improvement over previously published earthquake risk assessment models applied to Australia. However, Geoscience Australia's model will benefit from further validation, which will need to be carried out with the support and cooperation of others.

The engineering vulnerability models need to be checked, modified and produced as necessary to make them appropriate for Australian building stock. This requires a long-term, engineering research effort. Models for some construction types including timber frame buildings were developed by GA and structural engineering experts based on Australian design and construction practice were used in this study. Models for other building types such as some steel frame buildings have been adopted without alteration from US models. The efforts to improve the models should concentrate on the construction types that are the most important contributors to risk, as they have done so far. For Newcastle and Lake Macquarie, these are timber frame structures (especially brick veneer structures) and unreinforced masonry structures. Details such as tile or steel roof, masonry gable ends, parapets and chimneys, number of storeys in low rise buildings, soft storey, are important components of the vulnerability models. Other structural types may be important because, even though they are relatively few in number in the study area, such buildings may be classified as 'important' buildings or house essential services. Concrete frame buildings are one example of such building construction types.

Part of the assessment process for the building vulnerability models is to examine the degrees of structural, non-structural and contents damage, and economic losses, that are predicted by the models for certain levels of input ground shaking. The vulnerability and economic loss models need to be further reviewed by the structural engineering community to improve confidence in the results produced by them. For example, upon further analysis, the results of our modelling may show that significant simulated economic losses are due to acceleration effects rather than lateral displacements. These outcomes should be compared with the expectations of the structural engineering community and the model parameters adjusted if necessary.

The degree of damage and economic loss predicted by the models can be used to assess the appropriateness of earthquake loading standard specifications. For example, is the economic loss predicted by ground shaking with a 10% probability of occurrence in 50 years acceptable to the loading committee, the insurance and construction industries, and to government?

Sensitivity tests should be run by varying parameter values in the models to give alternative estimates of risk. The results may point to areas where efforts should be made to improve the models or collect new data. Reduced variability in the models will lead to more accurate and reliable estimates of risk.

Assessments of future risk based on projections of changes in building stock and demographics would be valuable to the assist decisions on the development of Newcastle and Lake Macquarie. A cost/benefit analysis of the effectiveness of introducing various mitigation measures would also assist the rational development of the cities. Assessments of future risk, and cost/benefit analyses, would be aided by masonry vulnerability models that accounted for building condition.

1.8 Final Remarks

Geoscience Australia is actively developing new techniques and revising its methodologies. Other workers in planning, emergency management, engineering, the insurance industry, the utility corporations, sociology and the finance industry are also putting increasing efforts into risk management for natural hazards including earthquakes. It is our hope that this study will assist these workers, the people of Newcastle and Lake Macquarie, and the broader Australian community, in reducing earthquake risk.

As a final note it should be remembered that, in the aftermath of the 1989 earthquake, there were many studies and recommendations on what should be done to mitigate the effects of future earthquakes. However, thirteen years on, few of the recommendations have been implemented. We urge the relevant authorities to review the recommendations made in this report and previous reports such as that conducted by the Institution of Engineers (Melchers, 1990) and to take appropriate action, so that ultimately we will have safer and more prosperous communities.

ACKNOWLEDGMENTS

We are grateful to Newcastle City Council for its continued support and encouragement over the course of the project that led to this report. The project was conducted over four years. In this time, two Lord Mayors held office, Cr Greg Heys and Cr John Tate, both of whom personally supported this project. Council officers provided many valuable datasets and other information to the project. These included damage datasets and NRMA Insurance records for the 1989 earthquake, datasets on roads, cadastre, drainage, aerial photographs, and many more. We thank Lynn Gray for his close association with the project. Lynn was influential in providing Council office accommodation for Geoscience Australia staff member David Stewart in Newcastle. Lynn was the Council's point of contact with the project. We are grateful for the advice, guidance, provision of data and keen interest in the project provided by Council officers Col Sandeman and Bob Boyce. We thank Newcastle Regional Museum directors Gavin Fry and, before him, Patrick Filmer-Sankey for their support, especially in relation to the 'Earthquake!' exhibition at the museum.

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David Stewart played a key role in the project, as the Newcastle - Lake Macquarie Project Leader, based in Newcastle for two years. David remains an author in some chapters of the report because of his important contributions, even though his role officially was completed in 2001. David was instrumental in gathering the support of the community and many government and private organisations for the project.

John Stehle played a major role in producing results for the Interim Technical Report and convening the group of experts that reviewed the capacity spectrum parameters for the engineering vulnerability models. John also played a primary role in developing some of the original simulation techniques, especially those for the engineering models. John remains an author in some chapters of the report because of his original and still valuable contributions.

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The NSW Department of Mineral Resources hosted a workshop in December 2000 to determine a seismotectonic model for the Hunter region. We would especially like to thank Brad Mullard, Richard Glen and John Brunton for their assistance in making the workshop a success. We also thank other participants in this workshop: Stephen Cox, Ron Boyd, Gary Huftile, Michael Neville, as well as the GA participants.

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The GA Field Data Acquisition Team consisting of Andrew Hislop, Ben Ghol, Nikki Brown, Craig Bagnall, Dave Pownall, John Stehle, and Neil Corby collected comprehensive information on almost 6500 buildings in the study area, creating the backbone dataset for this project.

We also thank the GA Microtremor Data Acquisition Team who collected microtremor data for more than 400 sites in the study area. These data were used to help prepare the site class maps.

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2 INTRODUCTION - URBAN GEOHAZARD RISK ASSESSMENT (D. STEWART AND T. JONES)

2.1 Newcastle & Lake Macquarie Project

This report provides details of investigations and research into the risks that are presented by earthquakes to the Newcastle and Lake Macquarie communities (Figure 2.1). The process of investigating the risk from earthquakes has led the team to recognise the risk to these same communities from a range of natural hazard phenomena. Though they were not investigated, these other natural hazards, which can be acute (ie. potentially fatal or resulting in high economic loss) include floods, landslides, severe storms and bushfires.

This report summarises the technical work carried out by Geoscience Australia on earthquake risk in the Newcastle and Lake Macquarie area. It will be a primary resource for those who have a responsibility or an interest in the management of geohazard risks within the communities of the study area. This includes local and district emergency managers, elected Council officials, and State and Council asset managers, engineers and planners, and managers and operators within the private sector who have a care or concern for life and community well-being. But principally it will be the starting point for Geoscience Australia in its new program of work extending the science supporting risk analysis in the geohazards area.

This Newcastle & Lake Macquarie study is the fifth in a series being undertaken under the Geoscience Australia *National Geohazards Vulnerability of Urban Communities Project*, more commonly referred to as the *Cities Project*. Geoscience Australia and its research partners see this regional study as providing the foundation on which communities of the Lower Hunter region can develop strategies to mitigate those risks and to cope with the impact of hazards when they occur. It builds on *Cities Project* multi-hazard risk assessment work already published on the Queensland centres of Cairns (Granger et al., 1999), Mackay (Middelmann and Granger, 2000) and south-east Queensland (Granger and Hayne, 2001).

Cities Project case studies clearly represent pioneering research. As such the results they present will undoubtedly change as better information, techniques and tools develop. We are confident, none-the-less, that this study is as accurate, scientifically sound, realistic and as practical as can be made at this stage in the evolution of 'risk science'. We encourage readers to view this report as a starting point, rather than an end in itself and we welcome feedback on any aspect covered in our reports.

It must be emphasised at the outset that this report represents a broad 'reconnaissance' of the hazards and the risks that they pose. It is not intended to be used, nor should it be used, to assign measures of risk to individual properties – the scale, resolution and accuracy of the data available to us does not support such precision. The report should therefore be seen as the <u>first</u> step in the process of comprehensive community risk management. The next steps are discussed later in the report and will extend the science of geohazard risk assessment. They will also involve the Newcastle and Lake Macquarie communities and the NSW State government .

2.2 The Cities Project

The *Cities Project* was established in 1996 to undertake research directed towards the mitigation of the risks faced by Australian urban communities that are posed by a range of geohazards. *The ultimate objective is to improve the safety of communities, and consequently make them more sustainable and prosperous.* It formed a significant part of Australia's contribution to the International Decade for Natural Disaster Reduction (IDNDR) which ran through the 1990's and continues to be a focus for Commonwealth community risk research. It can also be seen as a response to the findings of the 1993 Senate Inquiry into Major Disasters and Emergencies (Senate, 1994). In its findings, the Senate Committee encouraged the emergency management community to modify its doctrine from one that had been traditionally dominated by attention to disaster response, to one which gives greater attention and emphasis to risk mitigation and the reduction of community vulnerability.

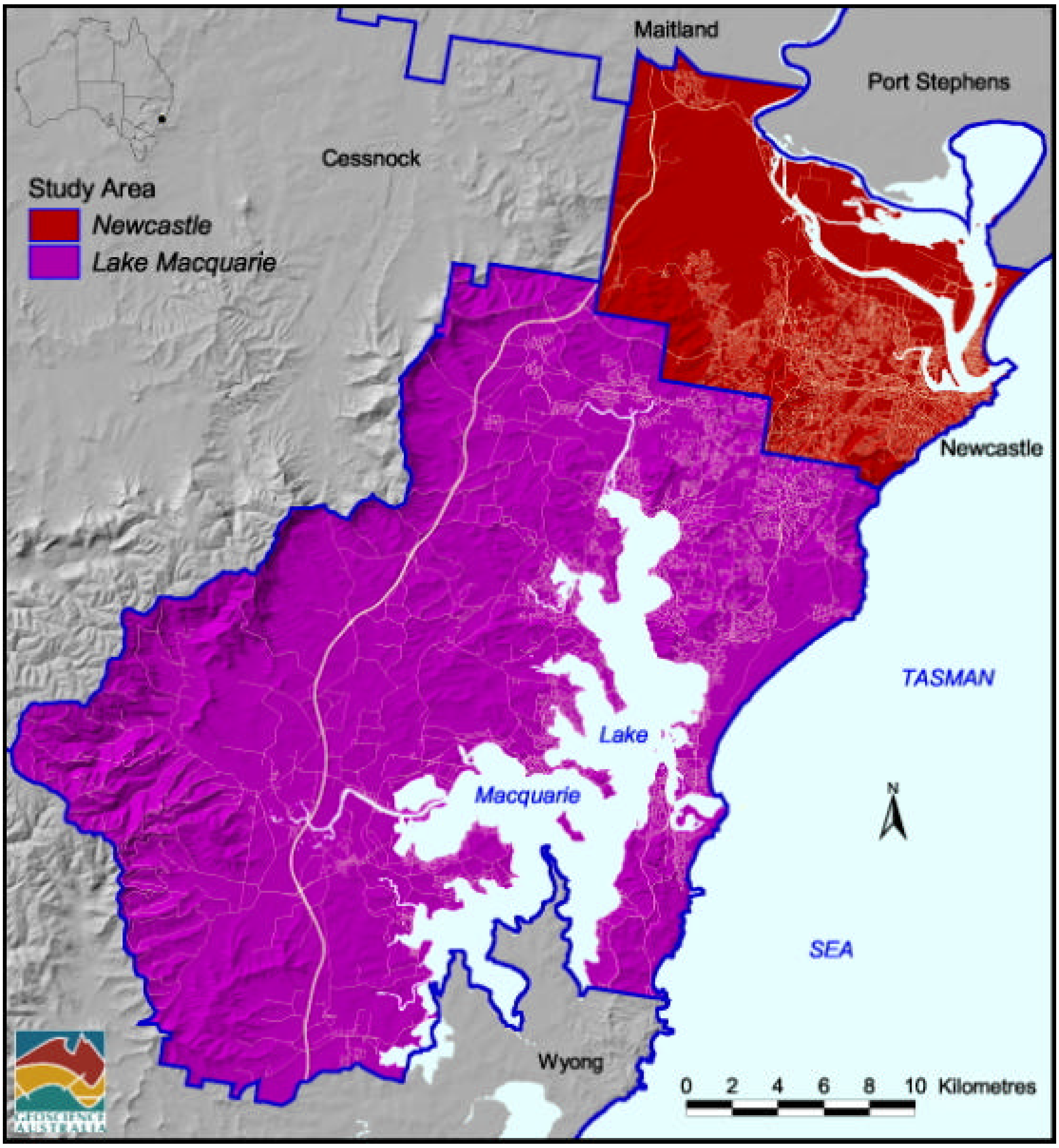

Figure 2.1: The study area of Newcastle and Lake Macquarie

Such a broadly-based program of research obviously requires a multi-disciplinary approach. To enable Geoscience Australia, a research agency traditionally focused on earth science, to achieve the objectives set for the *Cities Project*, a network of operational, research and supporting partners has been developed. We have been most fortunate in attracting the commitment of partners of great quality and enthusiasm. They span a very broad range of scientific disciplines, administrative responsibilities and industry sectors. Of particular value has been the close collaboration with:

Newcastle City Council

Lake Macquarie City Council

The Insurance Council of Australia

AON Reinsurance

Emergency Management Office, Hunter Region

Hunter Water Corporation

The University of Newcastle

2.3 Risk Management

The concept of risk, and the practice of risk management, received a significant boost in Australia with the publication of the Australia and New Zealand Risk Management Standard in 1995 and its subsequent revision as *AS/NZS 4360:1999 Risk Management* (AS/NZS4360, 1999). This generic guide provides the philosophical framework within which the *Cities Project* studies have been developed. That process is outlined in Figure 2.2.

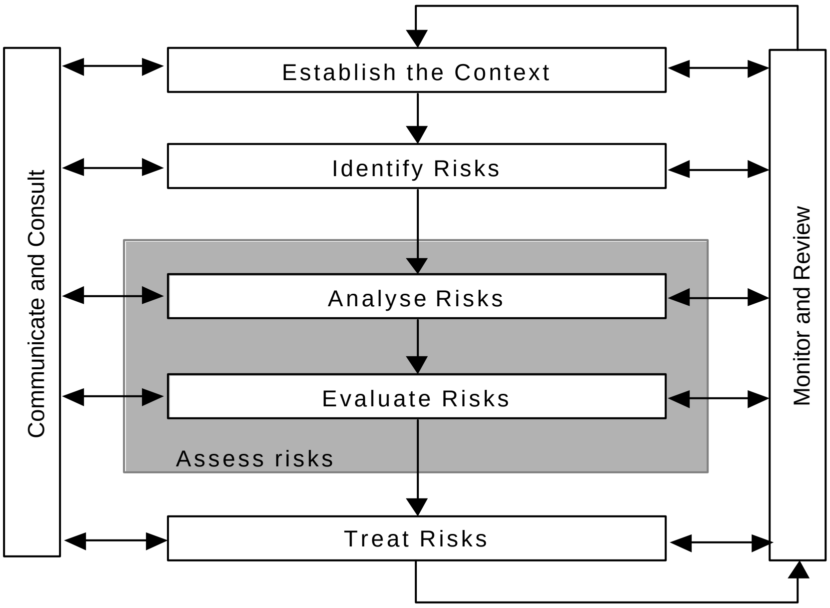

Figure 2.2: Risk management overview (adapted from (AS/NZS4360, 1999))

This study deals largely with the risk identification and risk assessment (ie. the "analyse" and "evaluate") stages of the process. Whilst we provide some opinion on matters relating to risk treatment, these are the responsibility of those, such as the local governments and the New South Wales Government agencies, that have that statutory role.

2.4 What is Risk?

The risk management Standard defines 'risk' as:

"the chance of something happening that will have an impact upon objectives. It is measured in terms of consequences and likelihood"

This definition is really too general for our purposes, consequently we have chosen to follow the conceptual basis and definitions developed under the Office of the United Nations Disaster Relief Coordinator (UNDRO) in 1979 and cited by Fournier d'Albe (Fournier d'Albe, 1979) as follows:

- ***Natural hazard*** *means the probability of occurrence, within a specified period of time in a given area, of a potentially damaging natural phenomenon.*
- ***Vulnerability*** *means the degree of loss to a given element at risk or set of such elements resulting from the occurrence of a natural phenomenon of a given magnitude…*
- ***Elements at risk*** *means the population, buildings and civil engineering works, economic activities, public services, utilities and infrastructure, etc., at risk in a given area.*
- ***Specific risk*** *means the expected degree of loss due to a particular natural phenomenon: it is a function of both natural hazard and vulnerability.*
- ***Risk*** (ie. 'total risk') *means the expected number of lives lost, persons injured, damage to property and disruption of economic activity due to a particular natural phenomenon, and consequently the product of specific risk and elements at risk.*

Total risk can be expressed simply in the following pseudo-mathematical form:

Equation 2-1: Risk framework

RISK

=

HAZARD

*

ELEMENTS AT RISK

*

VULNERABILITY OF THE ELEMENTS AT RISK TO THE HAZARD

Here the * symbol does not mean multiplication, but some unspecified way of combining the various quantities.

This approach is not only elegant, it is also very practical. Given the complexity of urban communities and the degree to which the various elements at risk are interdependent, the 'total risk' approach is considered mandatory. Further, it also lends itself to quantitative, qualitative and composite analytical approaches.

Risk mitigation (ie. moderating the severity of a hazard impact) is the principal objective of risk management. In this context, risk mitigation might be seen as:

> *"the process by which the uncertainties that exist in potentially hazardous situations can be minimised and public (and environmental) safety maximised. The objective is to limit the human, material, economic and environmental costs of an emergency or disaster, and is achieved through a range of strategies ranging from hazard monitoring to the speedy restoration of the affected community after a disaster event"*

after Granger (Granger, 1988; Granger, 1993)

It is clear that uncertainty is a key factor. Indeed, it can be argued that, in many instances, the effectiveness of risk mitigation strategies is inversely proportional to the level of uncertainty that exists. The risk management process, particularly the risk analysis and risk evaluation stages, is clearly aimed at developing the best and most appropriate information with which to reduce that uncertainty. The amount of total risk may be diminished by reducing the size of any one or more of the three variables – the hazard, the elements exposed and their vulnerability.

2.5 Risk Identification

A detailed understanding of what events have occurred in the past (including prehistoric events) and their effects provides the basis for understanding what could or will happen in the future, ie. it is the key step in the risk identification process. To this end, Geoscience Australia has developed catalogues on historic earthquakes and the Insurance Council of Australia, Emergency Management Australia and some local councils (amongst others) maintain some data on the losses associated with such events. Throughout this report we provide details of the known history of earthquake impacts in Eastern Australia in general and Newcastle and Lake Macquarie Cities in particular. This history is not only important in establishing levels of probability for future events but also to illustrate that such threats are very real.

It is worth reflecting that major disasters (excluding drought) cost Australia, as a nation, on average $1.1 billion annually between 1967 and 1999, with earthquakes contributing to approximately 13% of this figure (BTE, 2001). The known fatalities attributed to natural hazards also helps to put them into perspective as shown in Table 2-1.

Table 2-1: Fatalities in Australia caused by natural hazards (based on Coates (Coates, 1996) and Geoscience Australia data)

Natural Hazard	Period Covered	Fatalities
Heatwaves	1803 – 1992	4,287
Tropical cyclones	1827 – 1989	1,863 – 2,312 [2]
Floods	1803 – 1994	2,125
Bushfires	1827 – 1991	678
Lightning strikes	1803 – 1992	650
Landslides	1803 - 1999	83
Earthquakes	1803 - 1999	15

The real number of fatalities is almost certainly greater than listed, given that the statistics in the table were derived largely from reports contained in the Sydney Morning Herald and its predecessor, the Sydney Gazette. Nevertheless, they confirm that we do not live in an especially benign environment.

Monitoring and surveillance: One of the principal sources of historical hazard event information and hazard phenomenon knowledge is the extensive network of monitoring stations and remote sensing resources that have been established. In this regard, Geoscience Australia has access to more than 150 seismographs across Australia.

2.6 Risk Analysis

AS/NZS 4360:1999 (AS/NZS4360, 1999) defines 'risk analysis' as:

> *"a systematic use of available information to determine how often specified events may occur and the magnitude of their likely consequences."*

The focus of hazard science research is on the mechanisms that cause, create, generate or drive the hazard phenomena, eg. what causes earthquakes and what influences the transmission of their energy through various geological strata. This is underpinned by information relating to the background geological aspects of the site that are relevant to hazard studies, eg. the depth and nature of the sediments and their likely behaviour under earthquake shaking. Whilst there is little that can be done to eliminate or reduce the severity or frequency of these phenomena, a good understanding of what drives them enhances our ability to forecast or predict their behaviour. It is also fundamental to establishing an understanding of event probabilities.

Elements at risk and their vulnerability is a relatively new area of study and is focused on developing an understanding of the vulnerability of the wide range of elements that are at risk within the community eg. the people and their physical and social infrastructures. It involves disciplines as diverse as geography, demography, psychology, economics and engineering. A significant effort has been made to develop very detailed data on the principal elements at risk in the built environment of Newcastle and Lake Macquarie. Also, the development of vulnerability models, which predict the impact of earthquakes with sufficient accuracy, is a key component of the research undertaken.

In an effort to address the diverse range of applications to which the output from risk scenarios may be put, we have adopted the practice of running a range of earthquake scenarios. These typically extend from the relatively small and more frequently occurring events, to those in the so-called 'maximum probable' or 'maximum credible' range. Each earthquake scenario is associated with a probability of occurrence, and hence probabilistic loss curves and annualised loss estimates can be generated.

[2] *minimum and maximum estimates which also include approximately 170 flood fatalities*

2.7 Risk Evaluation

AS/NZS 4360:1999 (AS/NZS4360, 1999) defines 'risk evaluation' as:

> *"the process used to determine risk management priorities by evaluating and comparing the level of risk against predetermined standards, target risk levels or other criteria."*

Before risks can be evaluated, a basic understanding of probability is required.

A common description of event probability is the so-called 'return period' of a particular phenomenon, typically given in a form such as a '1-in-1,000 year earthquake'. Not only are such figures typically based on less than 1,000 years of record, it has been widely reported that such an expression of probability is prone to be misinterpreted and misused. Description of an event as a '1 in 1,000 year event' is frequently taken (wrongly) to indicate that there will not be another such event for another 1,000 years.

Another term used for 'return period' is the 'average recurrence interval' (ARI). This latter term describes more accurately what is meant by 'return period'. A correct interpretation of the term 'return period', would be that an earthquake of magnitude 'X' or greater occurs, on average, once every 1,000 years, for example. On an annual basis, this is approximately equivalent to an annual probability of exceedence (AEP) of 0.1% (1/1000).

Within a given period of n years, the probability of exceedance of an event with a given ARI is given in Table 2-2. It should be noted that, within n years, the probability of more than one event is implicitly considered. For n=1, the probability calculated is precisely the AEP.

It is easy to see that the short term risk of a developer, or an elected official, whose exposure is typically from three to five years, will be considerably less than that of a householder or company (say 25 to 50 year exposure), or individual (perhaps a 100 year exposure).

In the approach to risk assessment set out in AS/NZS4360 (AS/NZS4360, 1999), it is the practice to compare the level of risk found during the assessment process with previously established risk criteria. This practice enables the judgement of whether the risk is 'acceptable' (or at least tolerable) or not. Levels of acceptability, or risk aversion, are built into such things as urban planning design constraints and the Australian Building Code, where criteria are based on 'design levels'. For example, under the earthquake loading code, AS1170.4-1993 Minimum design loads on structures Part 4: Earthquake loads (AS1170.4, 1993), the 'design level of earthquake shaking' is one in which there is an estimated 10% probability of the ground motions being exceeded in a 50 year period, ie. the acceptability criterion is set at a 10% chance of exceedance over the nominal lifetime of a typical building.

Not all acceptability criteria can be expressed as categorically as those outlined in the Building Code because they deal with human nature and the political outrage dimension of risk management. There is a considerably lower aversion to risks that are 'voluntary', ie. those willingly undertaken by individuals, such as air travel or smoking, than there is to those that are seen as being 'involuntary', many of which carry a significantly lower risk. For example, in NSW, the chances of a fatality occurring from smoking 20 cigarettes a day has been calculated as being 5,000 per million people per year and for travel by motor vehicle as 145 chances per million people per year. By contrast, the chances of fatality from 'cataclysmic storms and storm floods' is calculated as 0.2 chances per million per year and lightning strike as 0.1 per million people per year (Higson,). Such expressions of risk, in terms of annual probability, are very useful since they incorporate the effects of rarer and more common events.

Similar information is shown graphically in Figure 2.3.

The acceptability criteria for economic risk are an important issue. Different people will have different levels of risk averseness to earthquake induced economic losses. For example, many do not consider earthquakes to be a threat at all. For those who do consider the risk, the level of risk acceptability will be often influenced by the cost of reducing risk through mitigation.

The level of risk acceptance also varies considerably over time. The threshold of acceptance is typically much lower immediately after a hazard impact, for example, than it was immediately before the impact. The existence of changing and conflicting frames of reference reinforces the need for a strong feedback mechanism between establishing acceptability and formulating risk mitigation and response strategies. In developing risk management options and strategies, the competing value systems and expectations of these various frames of reference need to be taken into account.

The acceptability factor is central to the process of risk prioritisation. This is the first step in the allocation of resources to risk mitigation, especially if considered in a multi-hazard context.

Table 2-2: Probability of exceedance in n years

Probability of exceedence		Return period (years)						
		100	200	475	1,000	2,000	5,000	10,000
n years considered	1	1.00%	0.50%	0.21%	0.10%	0.05%	0.02%	0.01%
	2	1.99%	1.00%	0.42%	0.20%	0.10%	0.04%	0.02%
	5	4.90%	2.48%	1.05%	0.50%	0.25%	0.10%	0.05%
	10	9.56%	4.89%	2.09%	1.00%	0.50%	0.20%	0.10%
	20	18.21%	9.54%	4.13%	1.98%	1.00%	0.40%	0.20%
	50	39.50%	22.17%	10.00%	4.88%	2.47%	1.00%	0.50%
	100	63.40%	39.42%	19.00%	9.52%	4.88%	1.98%	1.00%
	200	86.60%	63.30%	34.39%	18.14%	9.52%	3.92%	1.98%
	500	99.34%	91.84%	65.14%	39.36%	22.12%	9.52%	4.88%
	1,000	100%	99.33%	87.85%	63.23%	39.35%	18.13%	9.52%
	2,000	100%	100%	98.52%	86.48%	63.22%	32.97%	18.13%
	5,000	100%	100%	100%	99.33%	91.80%	63.22%	39.35%
	10,000	100%	100%	100%	100%	99.33%	86.47%	63.21%

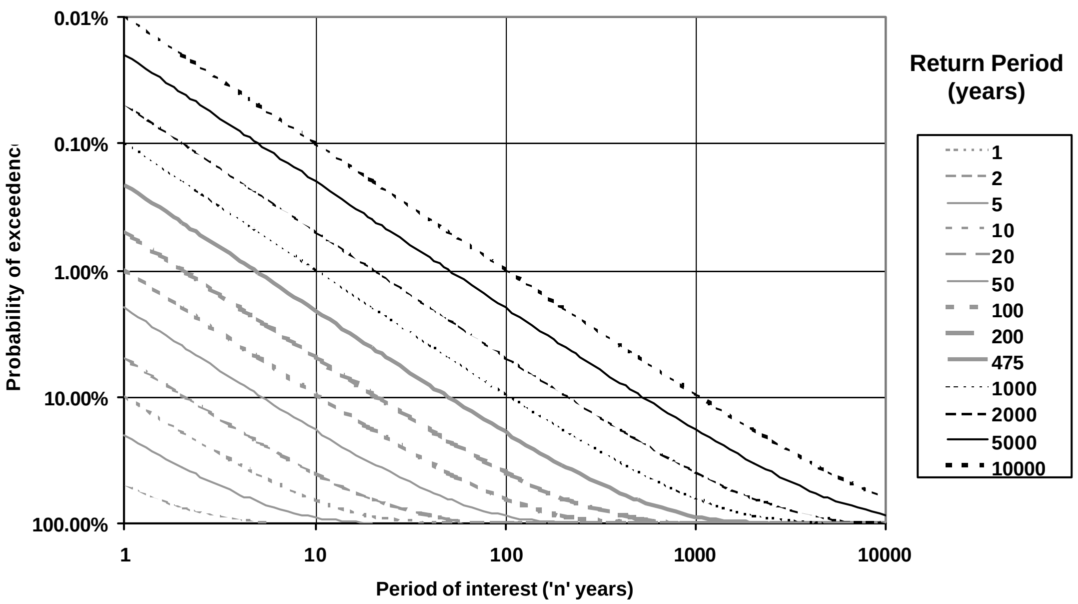

Figure 2.3: Probability of exceedance for a given return period event occurring in n years

2.8 Risk Mitigation Strategies

While the role of Geoscience Australia and the Cities Project is concerned primarily with risk identification and assessment, the following processes provide some insight into the risk mitigation process.

An effective forecasting system, combined with a high level of community awareness and risk appreciation, is clearly one of the most potent mechanisms by which to achieve risk reduction. This embraces the longer-term estimates of the 'hazardousness' of areas such as those contained in the earthquake hazard (acceleration coefficient) maps that accompany AS1170.4 (AS1170.4, 1993), or by hazard and risk maps specifically prepared as has been performed in this study.

Risk assessments are made so that strategies may be developed that will ultimately lead to the elimination, reduction, transfer or acceptance of the risks, and to ensure that the community is prepared to cope with a hazard impact. While the development and implementation of these strategies lie essentially outside the scope of the Cities Project, our experience in working with emergency managers and others to date suggests that some of the most effective strategies are:

- a strong risk management culture;
- well maintained and appropriate information about risk, linked to comprehensive monitoring systems;
- wide-spread and ongoing community awareness programs based on risk history, scenario analysis and an effective risk communication capability;
- emergency management plans, resources, training and decision support tools based on risk assessments;
- risk-based planning of settlement, development and the siting of key facilities (such as hospitals);
- protection plans for key facilities and lifelines;
- appropriate and enforced building and planning codes; and
- cost-effective engineered defences such as retrofit programs.

2.9 Confidence, Uncertainty and Probability

The analysis of issues as complex as community risk is highly dependent on the accuracy, currency and appropriateness of the data and models that it employs. Every effort has been made to ensure that the best available data and models have been used in the various analyses included in this study. For the most part, the results of modelling and other forms of analysis have been subjectively examined for 'reality' against recordings of the 1989 Newcastle earthquake and the experience of the authors and a good number of reviewers with appropriate local knowledge and experience.

2.10 Earthquake Risk Assessment Methodology Adopted for this Study

The overall risk assessment methodology used in this study can be summarised by the flowchart in Figure 2.4. Chapters 3 and 4 of this report cover the hazard components of the risk process. The elements at risk and their vulnerability are considered in Chapter 5. The verification of the impact modelling process using records of the 1989 Newcastle earthquake as well as the final risk assessment results are presented in Chapter 6.

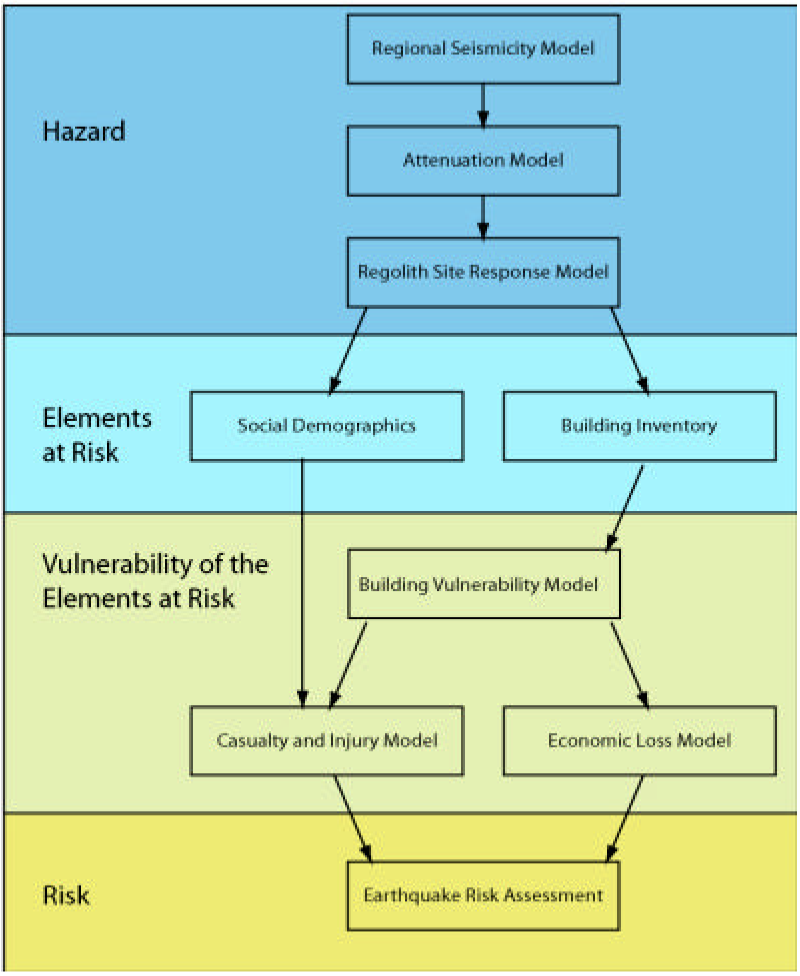

Figure 2.4 : Flowchart of the risk assessment methodology

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.

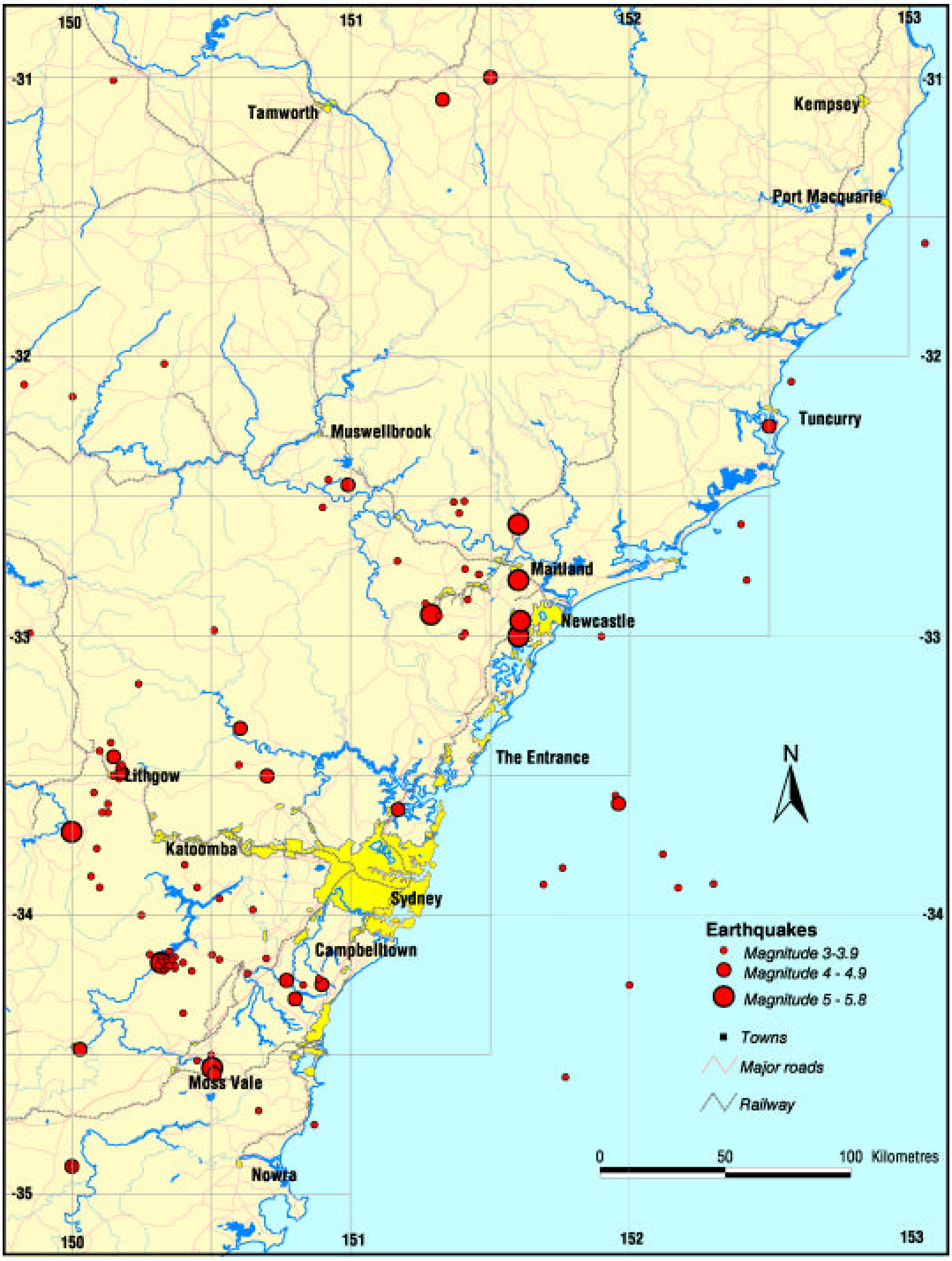

Figure 3.1: Earthquake epicentres within about 200 km of the study region

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*

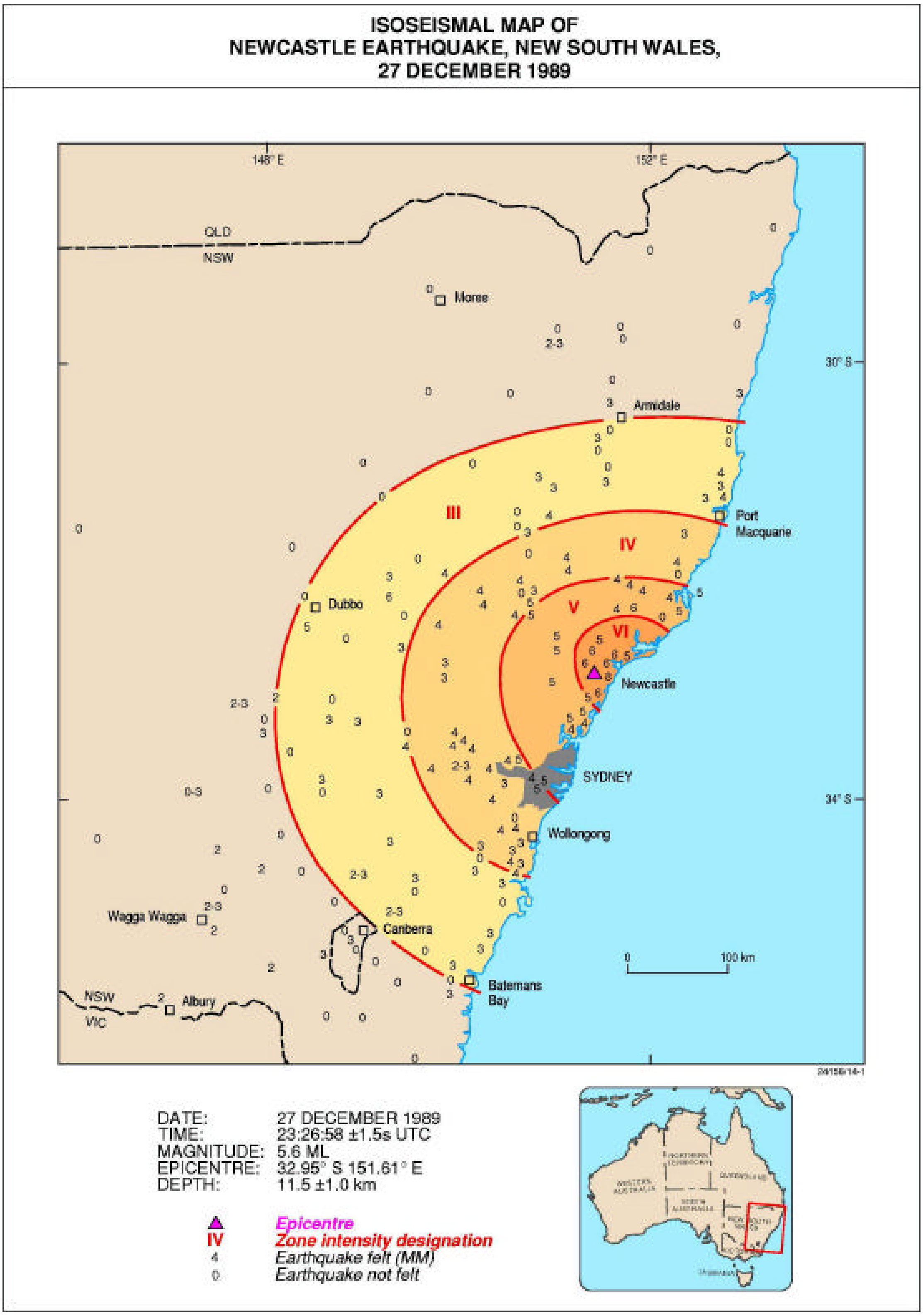

Figure 3.2: Isoseismal map of the Newcastle earthquake, New South Wales, 27 December, 1989 (UTC). Note that this event occurred on the 28 December local time

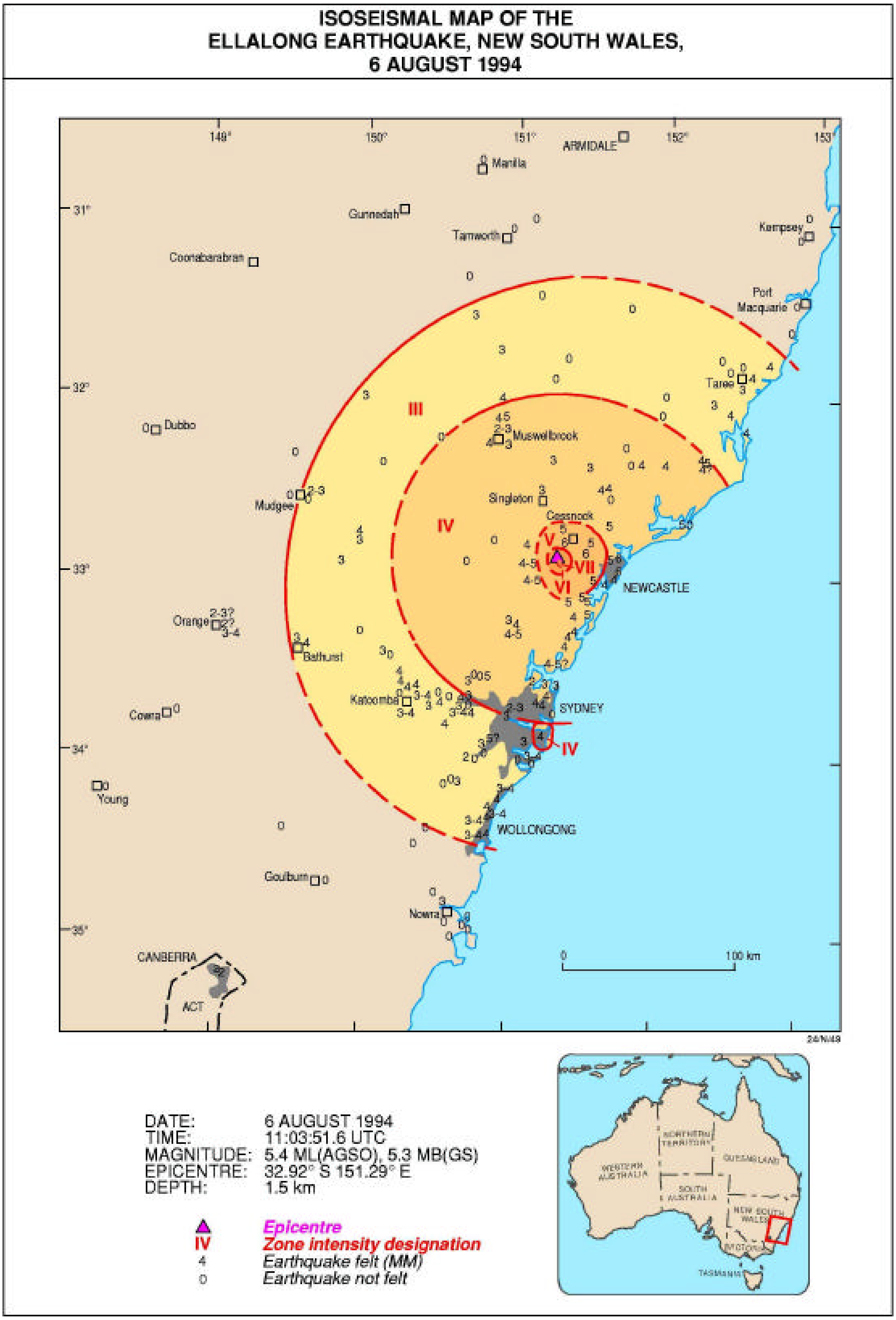

Figure 3.3: Isoseismal map of the Ellalong earthquake, New South Wales, 6 August 1994

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).

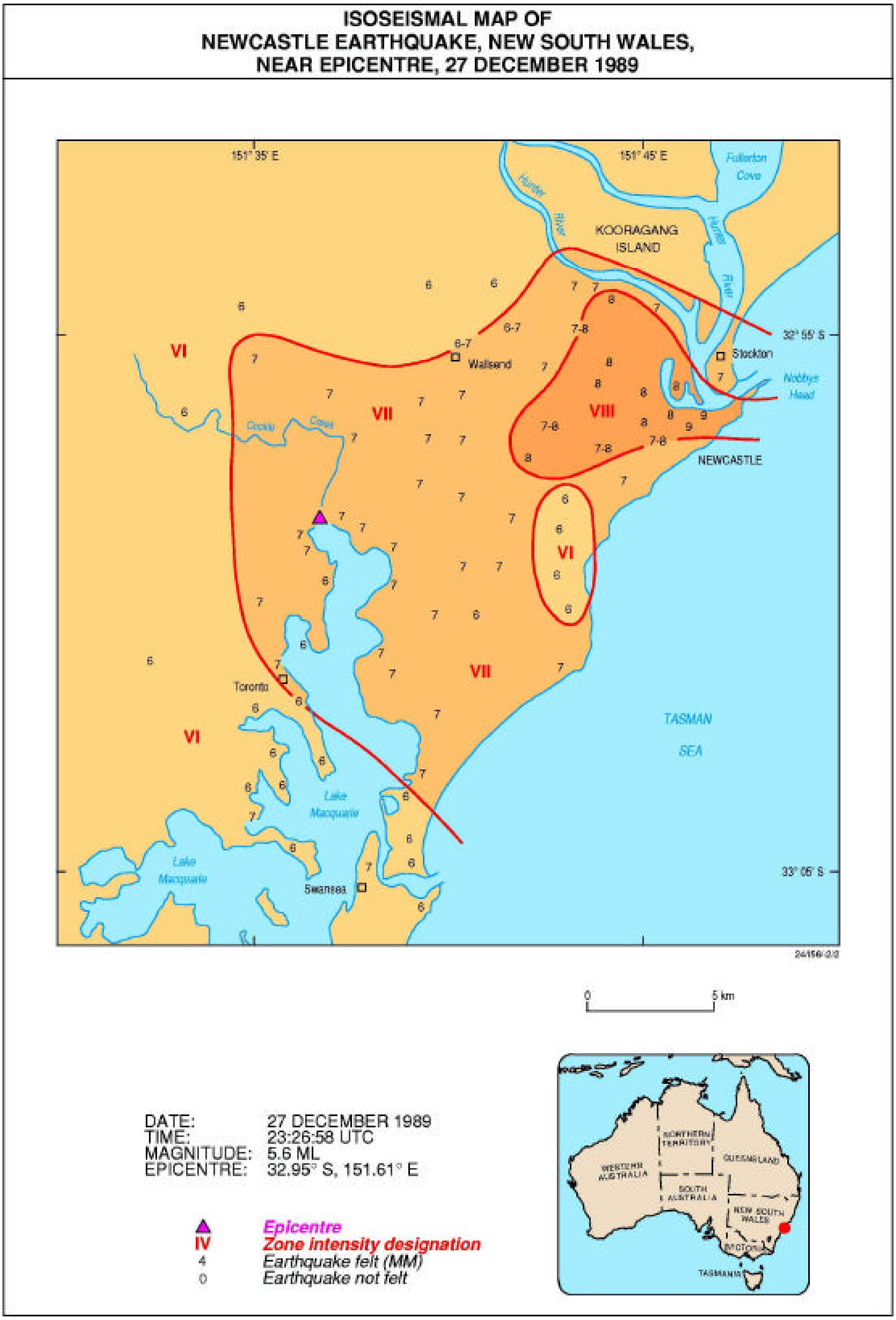

Figure 3.4: Intensity map for the Newcastle and Lake Macquarie area of the 27 December (UTC) 1989 earthquake (after Rynn et al., 1992)

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).

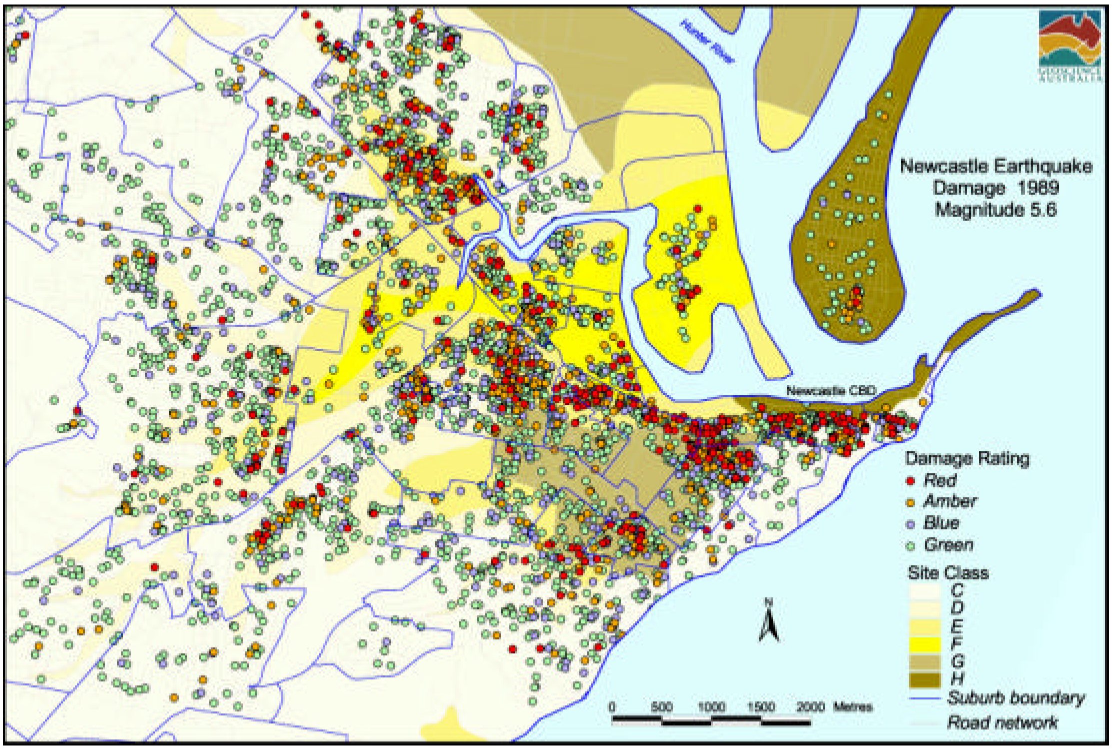

Figure 3.5: Recorded damage distribution in the Newcastle area, according to Newcastle City Council colour coded damage ratings for the 1989 earthquake

4 Earthquake Hazard (T. Dhu, D. Robinson, C. Sinadinovski, T. Jones, N. Corby, A. Jones and J. Schneider)

4.1 Introduction

Earthquake hazard can be measured by considering *the level of ground shaking that has a certain probability of being exceeded in a period of time*. For example, a common way to describe hazard is with maps of peak ground accelerations (PGAs) that have a 10% chance of being exceeded in 50 years. In order to calculate earthquake hazard, Geoscience Australia (GA) has adopted a probabilistic approach which:

- simulates numerous earthquakes using an *earthquake source model;*
- estimates how ground shaking decreases with increasing distance from the source using an *attenuation model*; and
- accounts for the local regolith and its effect on ground shaking by incorporating a *site response model*.

This Chapter describes the source, attenuation and site response models and how they are amalgamated to estimate the earthquake hazard in Newcastle and Lake Macquarie. It concludes with a series of maps detailing the hazard in the region. Further technical details are available from the authors at Geoscience Australia. *Readers who are not concerned with the technical detail of this study may progress directly to Section 4.6*.

4.2 Earthquake Source Model

4.2.1 Introduction

The earthquake source model details the probability of occurrence, location and magnitude of earthquakes that could affect the study area. The earthquake source model can be separated into two components: the *source zones* and the *simulation of earthquakes*.

An earthquake source zone is a region of the Earth identified as having a consistent level of seismicity throughout the region. The selection of the *earthquake source zones* used in this study was guided by a panel of expert geologists and seismologists who met at a workshop convened by Geoscience Australia in December 2000 at the New South Wales Department of Mineral Resources. A report on the outcomes of this workshop is included as Appendix C.

The *simulation of earthquakes* involves the creation of a database of representative earthquakes that are likely to contribute to the hazard in the study region. The simulation incorporated assumptions that reflect our current understanding of earthquakes in the region. The main assumptions we used are as follows.

1. Each independent earthquake has no memory of previous earthquakes.
2. The earthquake magnitude follows a truncated Gutenberg-Richter distribution.
3. Each earthquake is a rectangular rupture, with width and length assumed to be deterministic functions of the magnitude.

The source zones used in this study and the methodology adopted to simulate earthquakes are described in the following two Sections.

4.2.2 Earthquake Source Zones

As mentioned previously, earthquake source zones are defined as regions of the Earth that have consistent seismicity. That is, earthquakes of a given magnitude are assumed to have an equal probability of occurrence anywhere within the source zone. The earthquake source zones developed for this study are the Tasman Sea Margin Zone (TSMZ), the Newcastle Triangle Zone (NTZ) and the Newcastle Fault Zone (NFZ). A description of each of these zones is outlined below.

Tasman Sea Margin Zone (TSMZ)

The TSMZ extends from northern Bass Strait to the southern extremity of the Great Barrier Reef, Queensland (Figure 4.1). Its area is 870,230 km^2. The western margin of the TSMZ corresponds approximately with the contour 150 m above sea level to the west of the Great Dividing Range. Its eastern margin is located along the 200 m isobath at the eastern Australian continental shelf margin.

The TSMZ was proposed by the panel of geological and seismological experts in December 2000 (see report in Appendix C) and its boundaries and seismicity parameters were developed by GA. The TSMZ is thought to be associated with the opening of the Tasman Sea and the separation of the New Zealand and Australian land masses. The region is believed capable of producing events with moment magnitudes up to and including 6.5.

Newcastle Triangle Zone (NTZ)

The NTZ is a triangular zone with area of 5,054 km^2. It is defined by geological structures of the Lower Hunter region that bound a region of anomalously high seismicity for events with moment magnitudes up to and including 5.4. The region is bounded by a north-west – south-east line through Port Stephens, a north-west – south-east line through Wyong and Singleton and the coastline (Figure 4.2). The vertices of the NTZ are near Anna Bay, Terrigal, and Singleton.

Newcastle Fault Zone (NFZ)

The NFZ incorporates the proposed earthquake-generating fault structures in the Lower Hunter region. The faults considered to be potentially active are the *Newcastle Fault* and the *Hunter River Cross Fault*. Together these faults are known as the *Newcastle/Hunter River Cross Fault Zone (or the NFZ in this study)*. Details of the two faults are given below:

The Newcastle Fault lies south-east of Newcastle (Lawson, 1908; Huftile et al., 1999) and is known to exist approximately 20 to 50 km offshore. The fault is considered to be a reverse fault dipping to the south-west.

The Hunter River Cross Fault is an onshore feature proposed by the workshop delegates to link the eastern end of the Hunter Mooki Thrust near Maitland with the Newcastle Fault lying offshore. Its location is uncertain. It has been hypothesised that the 1989 earthquake could have occurred on the on-shore component of the Newcastle Fault (Chaytor and Huftile, 2000), i.e., the Hunter River Cross Fault.

The NFZ is shown in Figure 4.2. The rectangular-shaped zone has an area of approximately 3,046 km^2. It is aligned north-west – south-east and is centred on a line approximately through Nobbys Head. The dimensions of the NFZ attempt to capture the uncertainties in the position and orientation of the Newcastle Fault and the Hunter River Cross Fault.

Note that a major fault system, the Hunter Mooki Thrust, was not considered by the panel of experts to be an active fault structure.

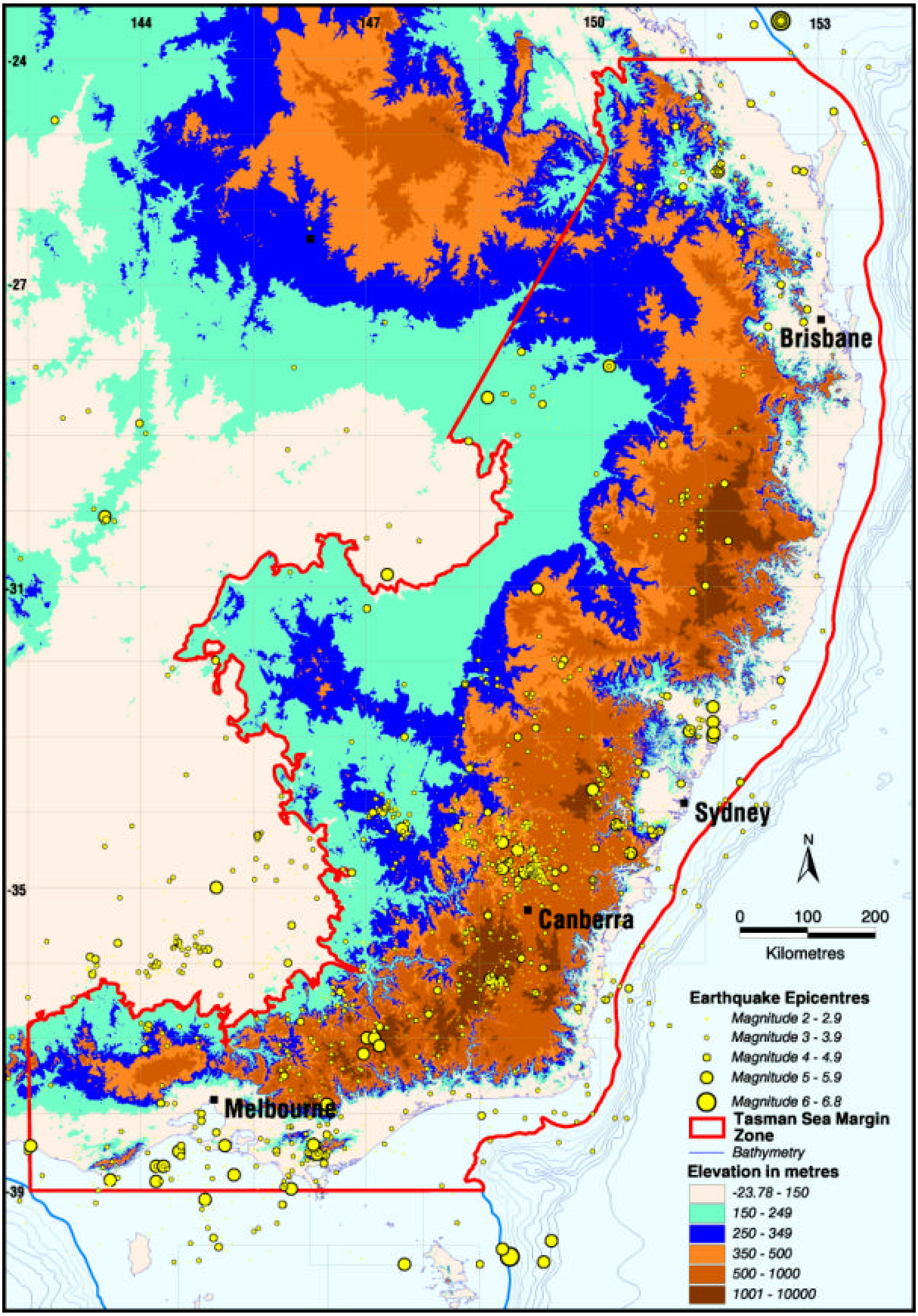

Figure 4.1: Tasman Sea Margin earthquake source Zone (TSMZ)

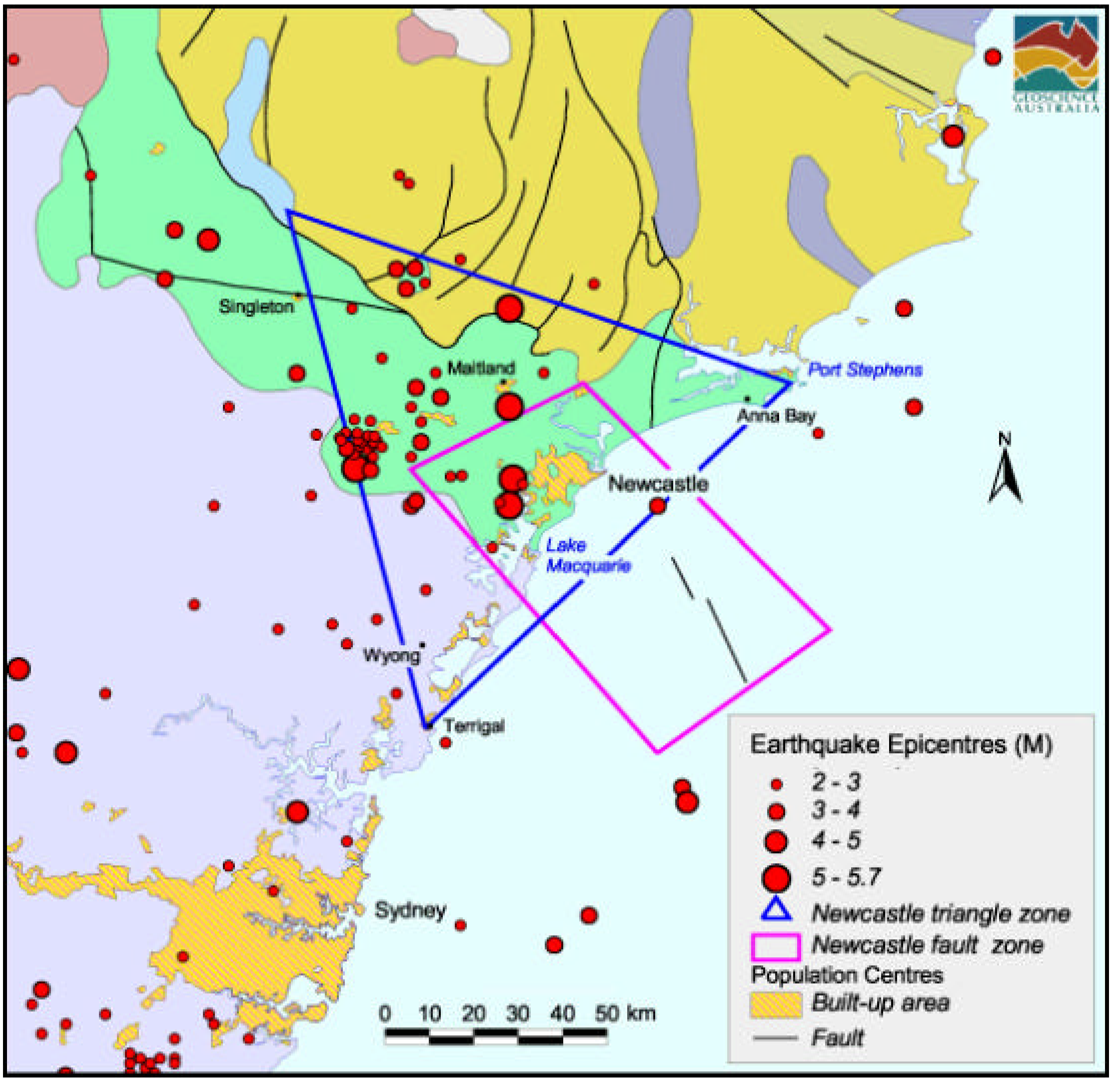

Figure 4.2: Earthquake source zones in the study area

Two different configurations of the three earthquake source zones were used to simulate earthquakes in this study (Figure 4.3). The first configuration was used to generate earthquakes with moment magnitudes between 3.3 and 5.4. It consists of the NTZ and two portions of the TSMZ (re-labelled as TSMZ1 and TSMZ2). The second configuration was used to generate earthquakes with moment magnitudes between 5.41 and 6.5. This configuration consists of the NFZ and two different portions of the TSMZ (re-labelled as TSMZ3 and TSMZ4). The separation of the region into the two configurations accounts for the fact that the different geological structures are believed to give rise to different magnitude earthquakes (see Appendix C). The division of the TSMZ into four sub-regions was done to simplify the simulation of earthquakes. *This division does not reflect variations in the seismicity across the TSMZ.* Regions of the TSMZ that are sufficiently far from the Newcastle and Lake Macquarie region, and hence do not contribute to the hazard, were not considered in this study.

The cumulative version of the *Gutenberg-Richter Recurrence (GR) Relationship* (Gutenburg and Richter, 1942) was used to characterise the seismicity in each of the source zones. The cumulative GR relationship is described by Equation 4-1.

Equation 4-1: The cumulative Gutenberg-Richter Recurrence Relationship

$$\log_{10}(\lambda_m) = a - bM$$

where M is the earthquake magnitude, λ_m the mean annual rate of exceedance and the parameters a and b are constants. The mean annual rate of exceedance (λ_m) is the number of earthquakes with magnitude greater than or equal to M per year. The constant, a, describes the level of earthquake activity in the zone (it's the logarithm of the number earthquakes in one year). The constant, b, describes how the number of earthquakes in the zone varies for different magnitudes (it is the negative of the slope of the GR relationship).

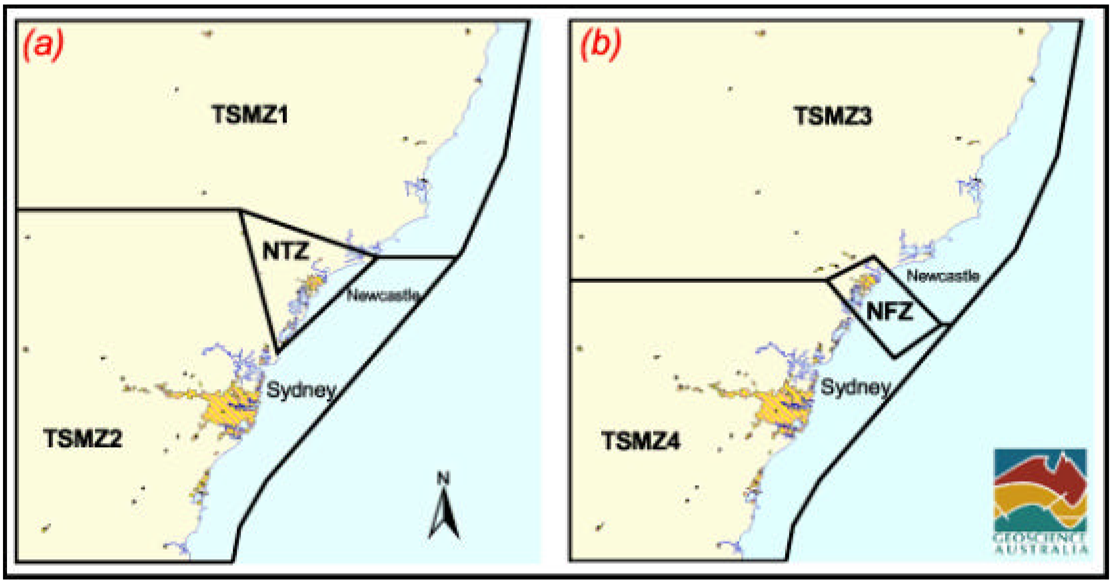

Figure 4.3 Two configurations of Earthquake Source Zones. The two configurations are believed to generate events with moment magnitude: (a) less than 5.4, and (b) between 5.41 and 6.5

The GR relationships were defined using moment magnitudes rather than local magnitudes, as moment magnitude provides a magnitude measure that is based on a physical model of the causative rupture. Most of the magnitude measures in Australia are local magnitudes, and hence it was necessary to convert these to moment magnitudes prior to the characterisation of the seismicity in each zone. Previous work has defined relationships between local magnitude and moment magnitude for stable continental regions around the world (pers. comm. Johnston, 2000). The relationship defined by Johnston is shown in Equation 4-2, and the conversion from local magnitude to moment magnitude is presented in Figure 4.4 for the range of magnitudes considered in this work.

Equation 4-2: Johnston relationship to convert from local magnitude (MLg[10]) to moment magnitude (Mw)

$$Mw = 3.45 - 0.473MLg + 0.145MLg^2$$

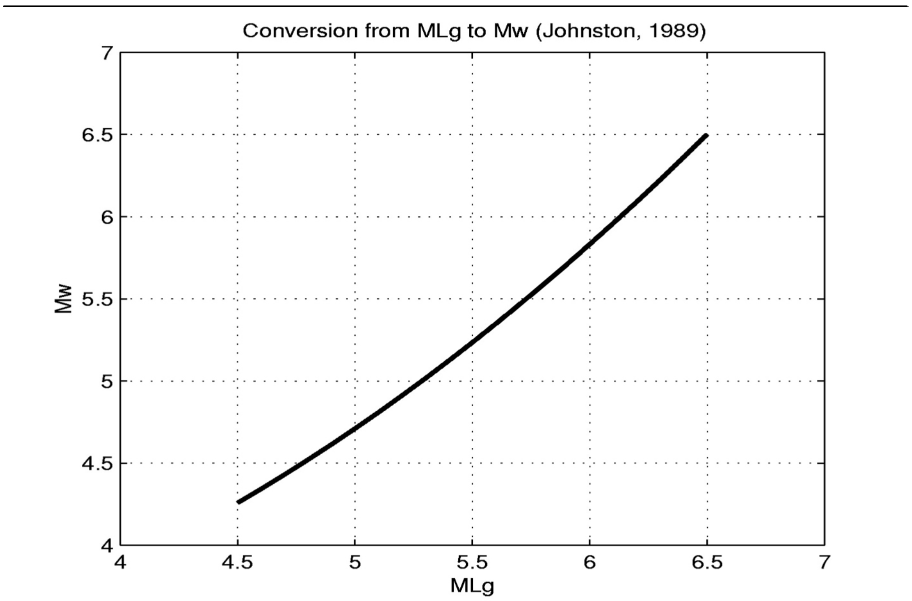

Figure 4.4: Relationship between moment and local magnitude

[10] *Although magnitudes measured in Australia are typically local magnitudes,* ML, *rather than* MLg *they are assumed to be equivalent for the purpose of this study.*

The techniques used to calculate the *a* and *b* parameters varied between the different zones. The details for each of the source zones are as follows:

TSMZ1 and TSMZ2

The earthquakes that were located in either the TSMZ1 or TSMZ2 were extracted from a historical database and a maximum likelihood method (Weichert, 1980) was used to determine the *a* and *b* parameters that best described the extracted data. The *a* value for the combined TSMZ1 and TSMZ2 data was then re-scaled for both the TSMZ1 and TSMZ2 zones separately. This is necessary since the combined area of TSMZ1 and TSMZ2 has experienced many more earthquakes then either the TSMZ1 or TSMZ2 individually. There was no need to re-scale the *b* values since these do not depend upon the size of the zone.

TSMZ3 and TSMZ4

The approach used to determine the best *a* and *b* parameters for TSMZ3 and TSMZ4 was exactly the same as that adopted for TSMZ1 and TSMZ2 except that the original data extracted from the historical database consisted of those earthquakes that lay in either TSMZ3 or TSMZ4.

NTZ

The maximum likelihood method was used to determine the best *a* parameter by extracting earthquakes located within the NTZ from the historical database. The *b* parameter determined in this manner had an unsatisfactorily high level of uncertainty and was therefore not used in the study. Instead, a *b* value of 1.0 was adopted for the NTZ based on observations of global seismicity (Utsu T., 1999). This value is consistent with the data. In this case the excessive uncertainty in the computed *b* parameter can be attributed to the relatively small area covered by the NTZ. A more general discussion on uncertainty is given in Section 4.7

NFZ

An estimate of the *a* parameter for the NFZ was determined using an approach based on the observed seafloor deformation associated with the offshore Newcastle Fault. The maximum observed vertical deformation is about 30 m at the edge of the continental slope (Huftile et al., 1999). Whilst the estimated age of fault slippage is uncertain, the best estimate is that fault slippage commenced around 3.5 Ma ago (Ron Boyd, pers. comm., 2001; Gary Huftile, pers. comm., 2001). A resultant slip rate of approximately 0.01 mm per year was calculated by considering estimates of the total displacement, the age of slippage and the dip of the Newcastle Fault. It was assumed that the slip rate of the Hunter Valley Cross Fault was the same as the Newcastle Fault. Empirical regression relationships between fault dimensions and earthquake magnitudes were used with the slip rate to estimate the *a* parameter (Wells and Coppersmith, 1994). As with the NTZ, the *b* value for the NFZ was assumed to be 1.0 to reflect global seismicity.

Each of the earthquake source zones was thought to be capable of producing earthquakes within a certain range of magnitudes. Estimates of maximum magnitude could not be calculated from the data for any of the zones due to the short period of time recorded in the earthquake catalogues. Consequently, the estimates of maximum magnitude used in this study have come from expert opinion based on earthquake history, tectonic considerations such as thickness of the seismogenic zones, and estimates of fault dimensions (Appendix C).

In order to account for the magnitude bound mentioned above the calculated *a* and *b* parameters, determined above were actually used with a modified version of the GR Relationship when simulating earthquakes (Section 4.3). This modification accounts for the maximum (M_{max}) and minimum (M_{min}) moment magnitudes of events that are likely to occur within each zone. The modified GR Relationship is often called *the Bounded Gutenberg-Richter Recurrence (BGR)* Relationship and is given by Equation 4-3.

Equation 4-3 The Bounded Gutenberg-Richter Recurrence Relationship

$$l_m = e^{\alpha - \beta M_{\min}} \frac{e^{-\beta (M - M_{\min})} - e^{-\beta (M_{\max} - M_{\min})}}{1 - e^{-\beta (M_{\max} - M_{\min})}}$$

where $\alpha = a \ln(10)$ and $\beta = b \ln(10)$ (Kramer, 1996).

The important parameters for each of the zones are given in Table 4-1 and the GR relationships for the TSMZ1, NTZ, TSMZ3 and NFZ are illustrated in Figure 4.5. Note that in the figure the *a* parameters of the TSMZ1, NTZ, TSMZ3 and NFZ are re-scaled to account for the differences in area between the three zones. Each *a* value is re-scaled to an area of 100,000 km^2.

Table 4-1: Important parameters for the earthquake source zones. Note that the 'a' parameter values have been normalised to 100,000 km^2 for ease of comparison. Contrastingly, the a_{min} values have not been normalised and are the actual values used in the simulation of earthquakes

Zone	Area (km^2)	b	a	a_{min}[11]	M_{min}	M_{max}
TSMZ1	57,731	1.14	4.40	2.53	3.3	5.4
TSMZ2	56,703	1.14	4.40	2.48	3.3	5.4
NTZ	5,054	1.0	4.35	0.568	3.3	5.4
TSMZ3	72,205	1.118	4.33	0.014	5.41	6.5
TSMZ4	44,149	1.118	4.33	0.0086	5.41	6.5
NFZ	3,047	1.0	4.13	0.0016	5.41	6.5

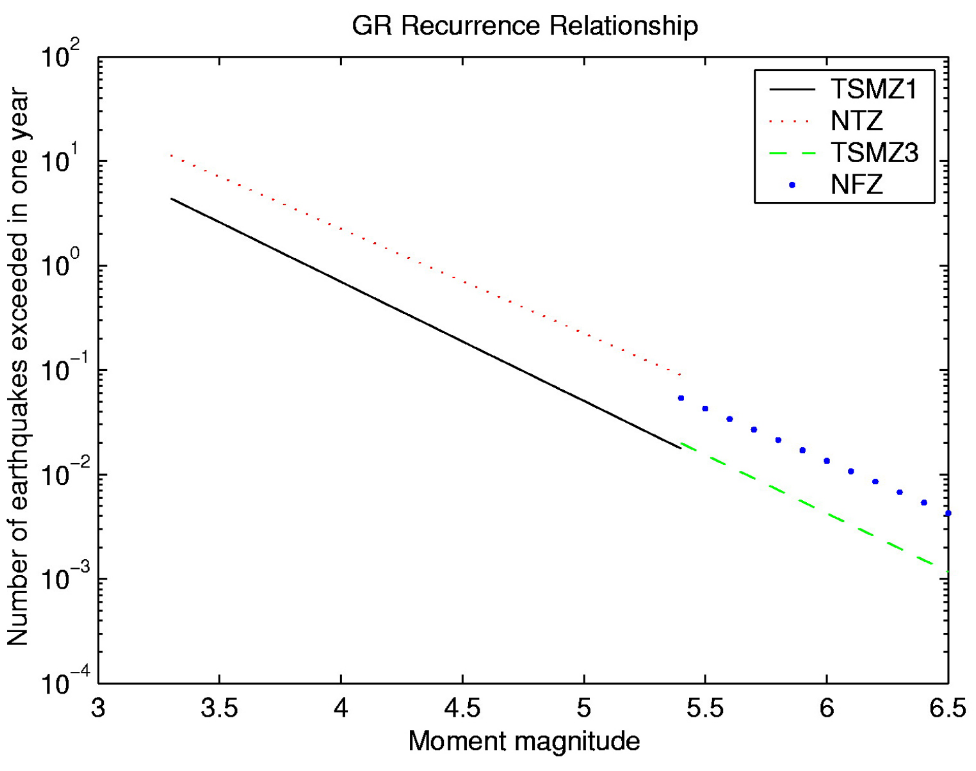

Figure 4.5: The cumulative Gutenberg-Richter recurrence relationship for the TSMZ1, NTZ, TSMZ3 and NFZ. Note that the 'a' parameters are normalised to represent an area of 100,000 km^2

[11] a_{min} *is the number of earthquakes occurring within the appropriate zone that have magnitude greater than or equal to* M_{min} *per year.*

4.3 Simulation of Earthquakes

The computation of hazard relies on the simulation (or creation) of earthquake events within each of the source zones. The earthquakes are modelled to occur on ‘virtual’ rupture planes within the Earth. A brief outline of the process used to simulate the events is given below.

1. *Define the number of desired events in each zone.* The number of desired events within a zone depends on the influence of that zone on the overall hazard in the study region. The desired number of events for each of the zones was defined to be the minimum value which, when increased, does not significantly change the hazard. These values were determined through a sensitivity analysis and are shown in Table 4-2, along with the number of events actually simulated. Note that the actual number of simulated events may vary from the desired number. Typically the actual number of events is within ± 10% of the desired number.

Table 4-2 Desired number of simulated events in each of the source zones

Zone	Number of Events Desired	Number of Events Simulated
NTZ	5,000	5,306
TSMZ1	1,000	1,076
TSMZ2	1,000	1,052
NFZ	3,000	3,092
TSMZ3	1,000	1,037
TSMZ4	1,000	1,063

2. *Define a characteristic dip angle for the seismic zone*. A characteristic dip angle of 35 degrees was used for each of the source zones in the Newcastle region. This value is based on seismic evidence in the region and is used as the dip for all of the simulated events.

3. *Randomly assign a rupture location for each of the desired events*. The location represents a latitude and longitude for the start of the rupture trace (see Figure 4.6).

4. *Assign a moment magnitude for each event*. The software adopts an approach that forces uniform sampling across the range of magnitudes. In other words, the number of simulated magnitude 5.2 earthquakes in each zone is roughly similar to the number of simulated magnitude 4.6 earthquakes. This ensures that earthquake events with a range of moment magnitudes contribute to the estimated hazard without requiring excessive computation of small events.

5. *Compute a likelihood (or probability) of occurrence for the magnitude of each simulated event*. The likelihood of occurrence accounts for the uniform sampling mentioned above, i.e., the number of actual magnitude 5.2 events in each zone is not the same as the number of magnitude 4.6 events. The probabilities are computed using the *Bounded Gutenberg-Richter Probability Density Function (BGR-PDF)* defined by the Gutenberg-Richter parameters in each zone (Kramer, 1996). Note that the BGR-PDF is closely related to the BGR Relationship (Equation 4-3).

6. *Randomly assign an azimuth for each of the events.* These are selected uniformly in the range from 0 to 360 degrees from True North.

7. *Compute the geometry (or dimensions) and location (including depth) of each event*. The motion experienced at a point on the Earth’s surface depends on the distance to the rupture plane, not the distance to the plane’s centre (hypocentre). Therefore it was important that we modelled the position of the rupture plane as best we could. The important rupture parameters are its dimensions (i.e. area, length and width) and the location of the hypocentre. These are computed using empirical relationships based on magnitude.

8. *Compute the end point of each rupture trace.* The end point is computed using the start of the rupture trace, the azimuth and the rupture dimensions. This information is useful for diagnostics such as Figure 4.7 which gives an overview of the geographical distribution of the simulated events. The location of the rupture trace is also required for Step 9.

9. *Adjust the azimuth of each event* to force, where possible, the rupture trace to lie within the source zone.

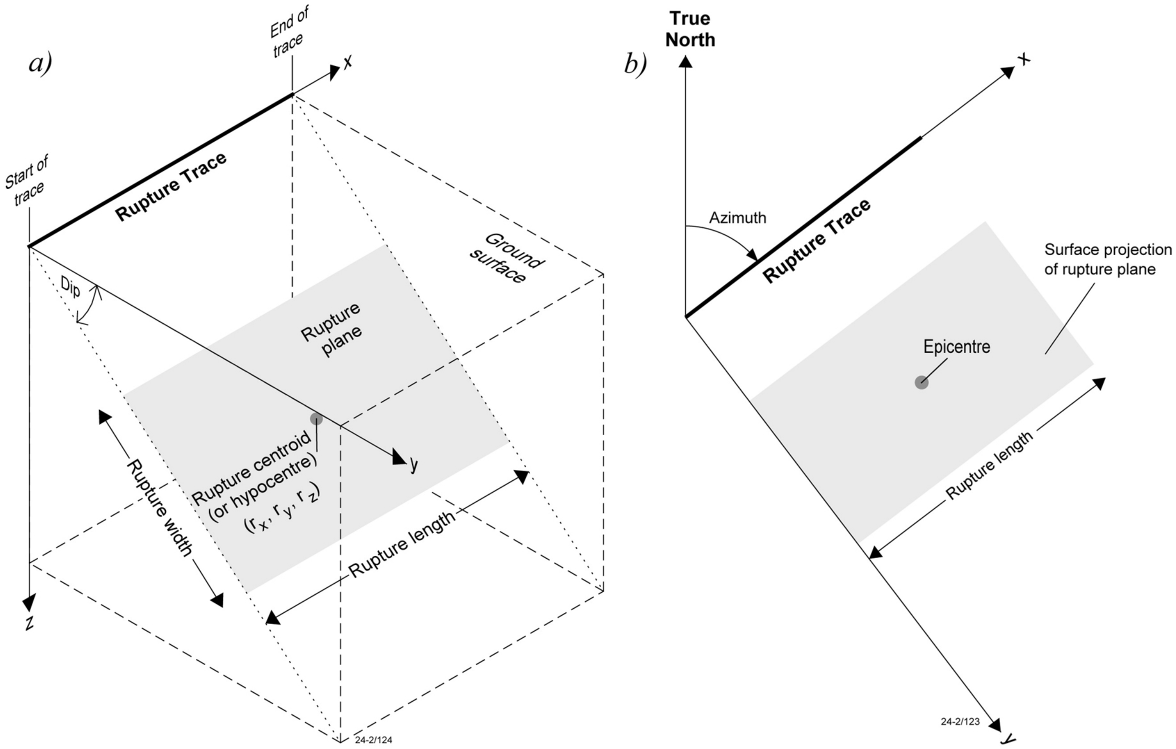

Figure 4.6 The orientation and dimensions of the rupture plane in: (a) 3D space, and (b) Plan View

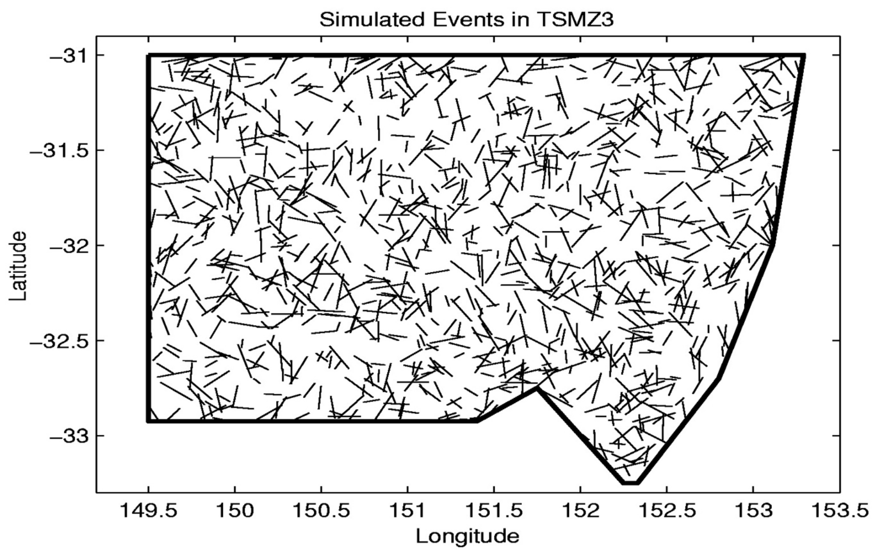

Figure 4.7 The fault traces of simulated events in the source zone TSMZ3

4.4 Attenuation Model

Attenuation models describe how the intensity of ground shaking decreases with increasing distance from an earthquake. The nature of earthquake attenuation in the study region is poorly understood due to a lack of strong ground motion data. When few data exist, as for the Newcastle region, attenuation relations for Modified Mercalli Intensity can be developed and then converted by empirical formulae to equivalent peak ground accelerations. This approach was employed in the development of the Australian earthquake hazard maps (Gaull et al., 1990), which were largely adopted in the Australian earthquake loading standard (AS1170.4, 1993).

This study adopted an attenuation model developed for central and eastern North America (Toro et al., 1997). The Toro et al. (1997) model was selected because:

- the 'intraplate' tectonic environment in central and eastern North America is thought to be generally similar to the environment in south-east Australia;
- it describes the attenuation of response spectral acceleration[12] (RSA) as well as PGA, and;
- it includes both a median attenuation model and a measure of the model variability[13] due to the randomness inherent in natural processes.

However, it should be emphasised that this study has *not conducted any detailed analysis of the applicability of the Toro et al. (1997) model to Australia*.

A comparison of the Toro et al. (1997) and the Gaull et al. (1990) attenuation models for PGA is presented in Figure 4.8. Typically, the Toro et al. (1997) model attenuates less, and consequently has higher PGA values, than the Gaull et al. (1990) model. It should be emphasised that the Gaull et al (1990) model used source depths of 10 km and is based on local magnitudes. For the comparison in Figure 4.8 the local magnitudes were calculated from moment magnitudes using the previously described Johnston relationship (Equation 4-2).

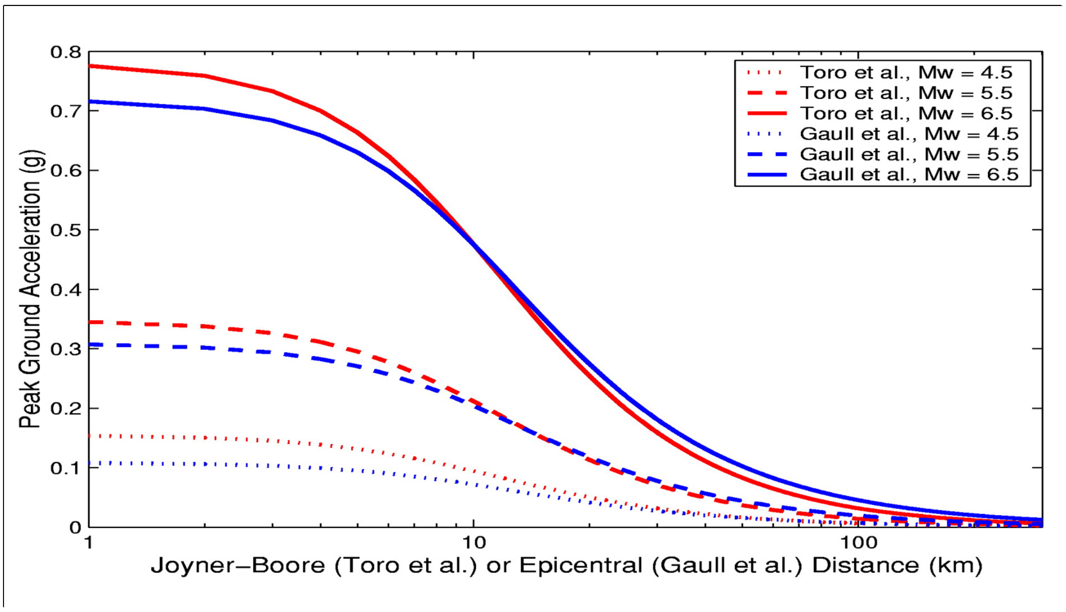

Figure 4.8: Comparison of attenuation models

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[12] *The RSA describes the maximum acceleration experienced by a single degree of freedom (SDOF) system due to a particular ground motion. The RSA is a function of the natural period and damping ratio of the SDOF system. It should be noted that in this study we model building damage by assuming that buildings behave as SDOF systems.*

[13] *The RSA of a given SDOF system is assumed to be lognormally distributed. The variability parameter is defined as the standard deviation of the natural logarithm of the RSA distribution. Note that the median RSA model is equivalent to the mean of the natural logarithm of the RSA distribution.*

4.5 Site Response Model

4.5.1 Introduction

The presence of regolith (soils, geological sediments and weathered rock) can affect earthquake ground shaking, and hence influence the local earthquake hazard in a region. The regolith in the Newcastle and Lake Macquarie region consists of regions of sediment (deposited over the last 20 thousand years) overlying weathered and unweathered rock (laid down over 200 million years ago). The rock consists of sedimentary rocks of the Sydney Basin, and includes the coal horizons of the Newcastle Coal Measures. The Quaternary sediments were laid down in a marine influenced environment, with estuarine muds and tidal delta sands comprising the most dominant depositional systems. A detailed description of the region's geology is in Appendix D.

In order to identify localised changes in earthquake hazard due to variations in the regolith, the Newcastle and Lake Macquarie region was divided into a series of six regolith site classes. These classes represent regions that are considered to have a similar response to earthquake ground shaking. Amplification factors, which are a measure of how much the regolith will amplify ground shaking, were then calculated for each site class.

4.5.2 Geotechnical Site Class Models

The study area was classified into six distinct regolith site classes (Figure 4.9), specifically:

Class C. Weathered rock (maximum thickness 15 m).

Class D. Silt and clay (maximum thickness 16.5 m).

Class E. Sand overlying silt and clay (maximum thickness 30 m).

Class F. Sand with interbedded silt and clay (maximum thickness 39 m).

Class G. Silt and clay with interbedded sand (maximum thickness 30 m).

Class H. Barrier sand (maximum thickness 30 m).

The site classes containing sands, silts and/or clays overly up to 15 m of weathered rock.

The development of these site classes is described in detail in Appendix D. However, it is important to note that all of the site classes containing sands, silts and/or clays were developed from cone penetrometer tests (CPTs) undertaken primarily in the Newcastle municipality and the barrier sands to the east of Lake Macquarie (Figure 4.9). These site classes were then extrapolated to the remainder of the study region based on limited CPT data, microtremor data (Appendix E) and inferences regarding the depositional processes in the region.

Once the regolith in Newcastle and Lake Macquarie had been classified, representative geotechnical models were developed for each site class. These models incorporated the regolith's thickness, density, shear wave velocity and strain dependent material properties[14]. Idealised cross sections for each of these site classes are presented in Figure 4.10, and the detail behind them is presented in Appendix F.

In addition to the geotechnical information presented in Figure 4.10 the other important feature of the regolith models is the choice of shear modulus and damping curves used to describe the strain dependant properties of the regolith. The curves used in this work are summarised in Table 4-3.

Table 4-3 Strain dependent curves used in amplification modelling

Material	Curve
Sand	EPRI Depth Dependant Sand Curves (Electric Power Research Institute, 1993)
Silt and Clay	Vucetic and Dobry Clay Curve for a plasticity index of 30 (Vucetic and Dobry, 1991)
Weathered and Unweathered Rock	Constant Linear

[14] Strain dependent material properties describe how the regolith performs during earthquake ground shaking. Specifically, the shear modulus and damping curves describe how the shear modulus and damping vary with strain.

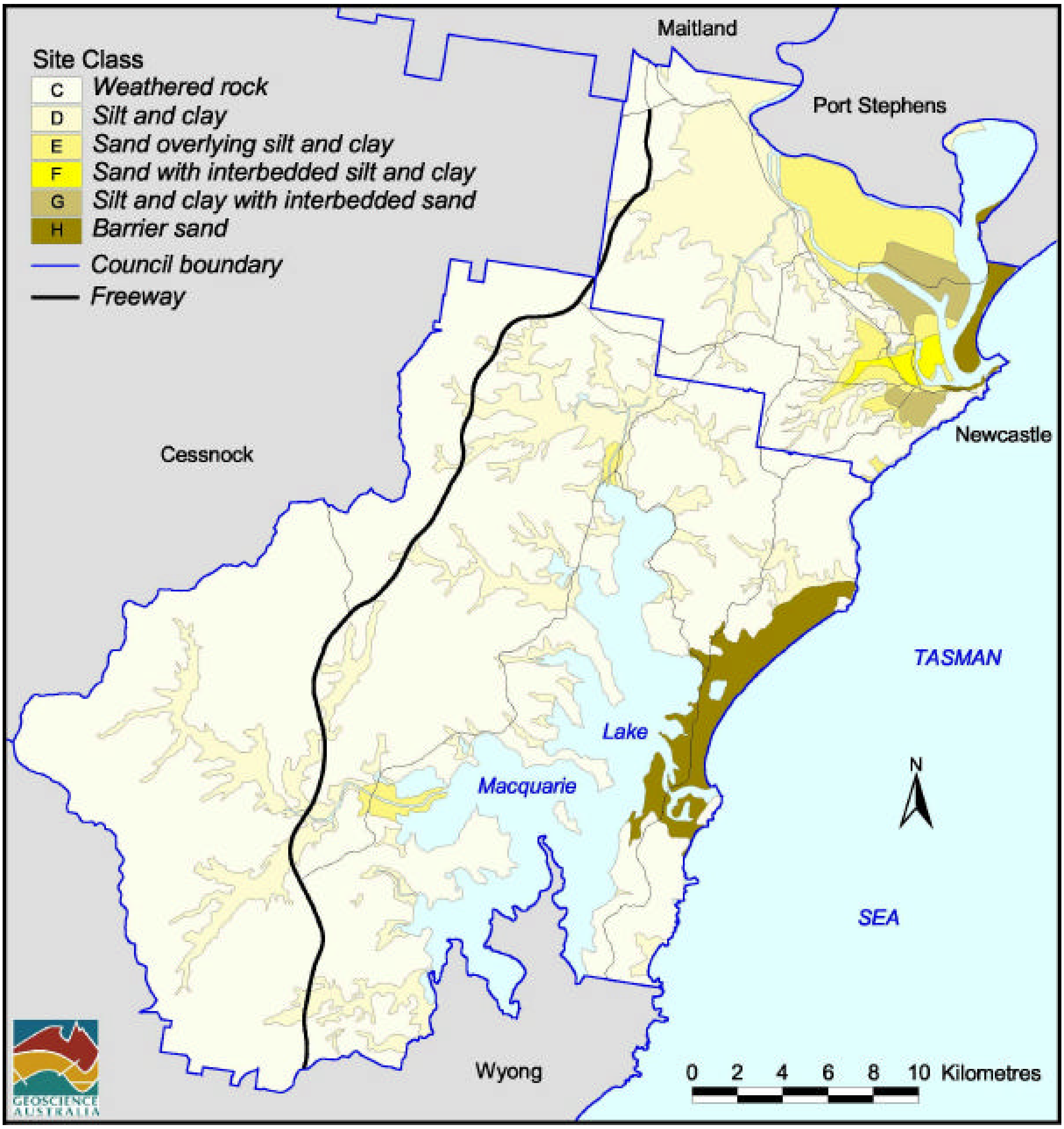

Figure 4.9: Classification of the regolith in the Newcastle and Lake Macquarie region

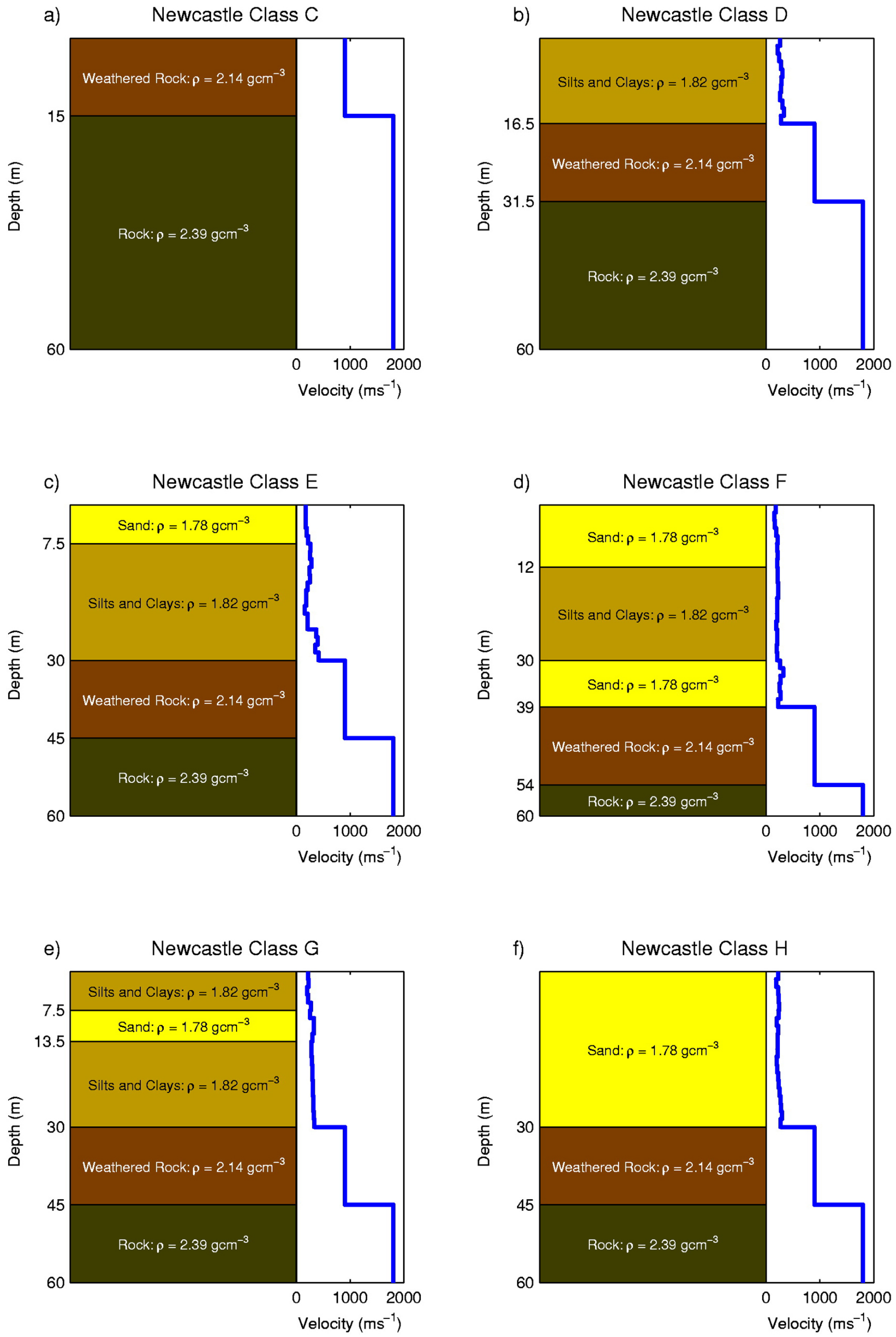

Figure 4.10: Idealised cross sections of the site classes used to classify the regolith in Newcastle and Lake Macquarie

4.5.3 Amplification Factors

Amplification factors were calculated using RASCALS software provided by Dr. Walt Silva of Pacific Engineering and Analysis (California, U.S.A.). This software uses an equivalent-linear methodology to determine the response of a regolith model to an input rock motion by calculating the RSA at the surface of the regolith model. The amplification factor for this model is then calculated as the ratio of the soil RSA to the rock RSA. Note that the amplification factor is a function of period. For more technical details on the calculation of amplification factors, please contact the authors at Geoscience Australia.

The response of regolith to earthquake ground shaking is influenced by the intensity of the ground motion experienced, as well as the magnitude of the causative earthquake. Consequently, amplification factors were calculated for a series of input rock motions with:

- moment magnitudes of 4.5, 5.5 and 6.5, and;
- peak ground accelerations of 0.05, 0.1, 0.25 and 0.5 g.

Natural processes are inherently variable, and consequently it is not realistic to assume that a single geotechnical model will accurately represent the entire region classified as a single site class. Therefore, calculating the site response of a single representative velocity profile will not adequately capture the response of an entire site class. Consequently, a series of 50 velocity profiles was statistically generated for each site class. The velocity profiles presented in Figure 4.10 were used as median profiles for each class and 50 velocity-depth profiles were then generated from lognormal distributions based on variability observed in North America. Examples of the randomised velocity profiles are displayed in Figure 4.11. The total regolith thickness and strain dependent material properties were also randomised for each of the velocity profiles.

For each input rock motion, amplification factors were calculated for all 50 of the randomised profiles within each site class. As with the RSA (Section 4.4) and the velocity profiles described above, the amplification factors are assumed to be lognormally distributed. Median amplification factors and variability parameters were calculated for each regolith site class. The amplification factors derived using a rock motion from an earthquake with moment magnitude 5.5 and a rock PGA of 0.25 g are displayed in Figure 4.12. This figure demonstrates that all of the site classes in the region have the potential for significant amplification of RSA. Note that the classes containing silts, clays and/or sands all have peak amplification factors greater than 2.3. Whilst the weathered rock class has smaller amplification factors than the other site classes, it nonetheless has a peak amplification factor of 1.50. Figure 4.12 also shows the 16th and 84th percentiles calculated from the 50 different velocity profiles. These give an indication of how variable the amplification factors are due to variations in the regolith across each site class.

A summary of the peak median amplification factors for each class across the range of rock motions used is presented in Table 4-4. This table demonstrates that an increase in the PGA of the rock motion is generally associated with a decrease in the maximum amplification factor. In addition to this, an increase in the PGA causes the maximum amplification factor to occur at higher periods.

Table 4-4: Peak median amplification factors for the regolith site classes in Newcastle and Lake Macquarie

Rock Motion		Class C		Class D		Class E		Class F		Class G		Class H	
Mw	PGA (g)	T (s)	Max Amp	T (s)	Max Amp	T (s)	Max Amp	T (s)	Max Amp	T (s)	Max Amp	T (s)	Max Amp
4.5	0.05	0.06	1.50	0.25	2.95	0.67	3.17	0.91	3.32	0.40	3.17	0.67	3.60
4.5	0.10	0.06	1.50	0.26	2.81	0.67	3.02	0.91	3.20	0.40	3.06	0.71	3.38
5.5	0.05	0.06	1.50	0.25	2.61	0.71	2.87	0.91	3.03	0.40	2.81	0.71	3.23
5.5	0.10	0.06	1.50	0.26	2.49	0.71	2.74	1.00	2.90	0.42	2.69	0.77	3.00
5.5	0.25	0.06	1.50	0.28	2.30	0.83	2.58	1.11	2.67	0.45	2.51	0.91	2.70
6.5	0.05	0.06	1.49	0.25	2.59	0.67	2.52	0.83	2.59	0.40	2.74	0.71	2.72
6.5	0.10	0.06	1.50	0.26	2.47	0.71	2.40	1.00	2.41	0.42	2.62	0.77	2.48
6.5	0.25	0.06	1.50	0.28	2.29	0.83	2.17	1.25	2.12	0.45	2.39	1.00	2.15
6.5	0.50	0.06	1.50	0.30	2.09	1.00	1.95	1.67	1.90	0.53	2.13	1.25	1.85

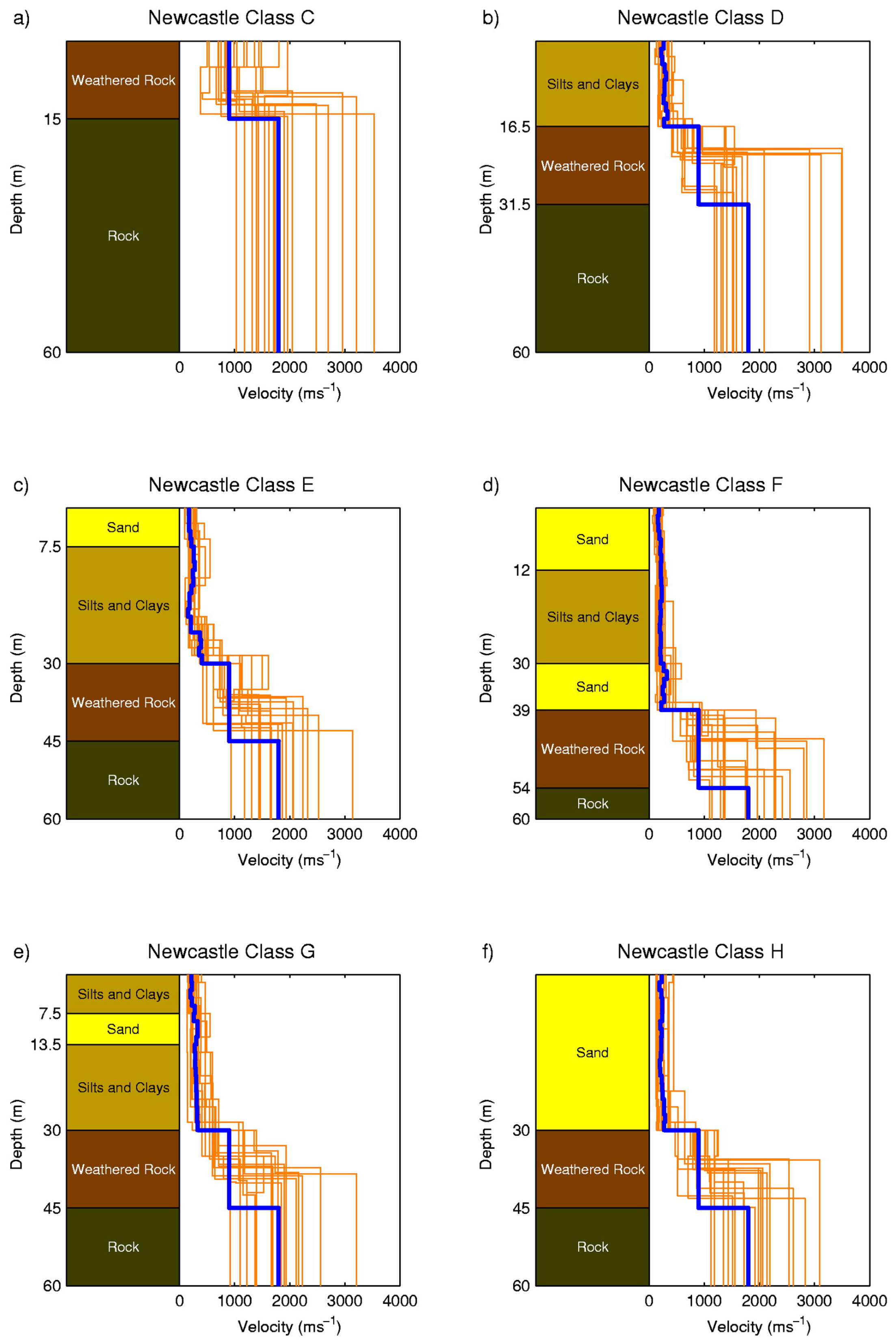

Figure 4.11: Examples of randomised velocity profiles generated for the Newcastle and Lake Macquarie site classes

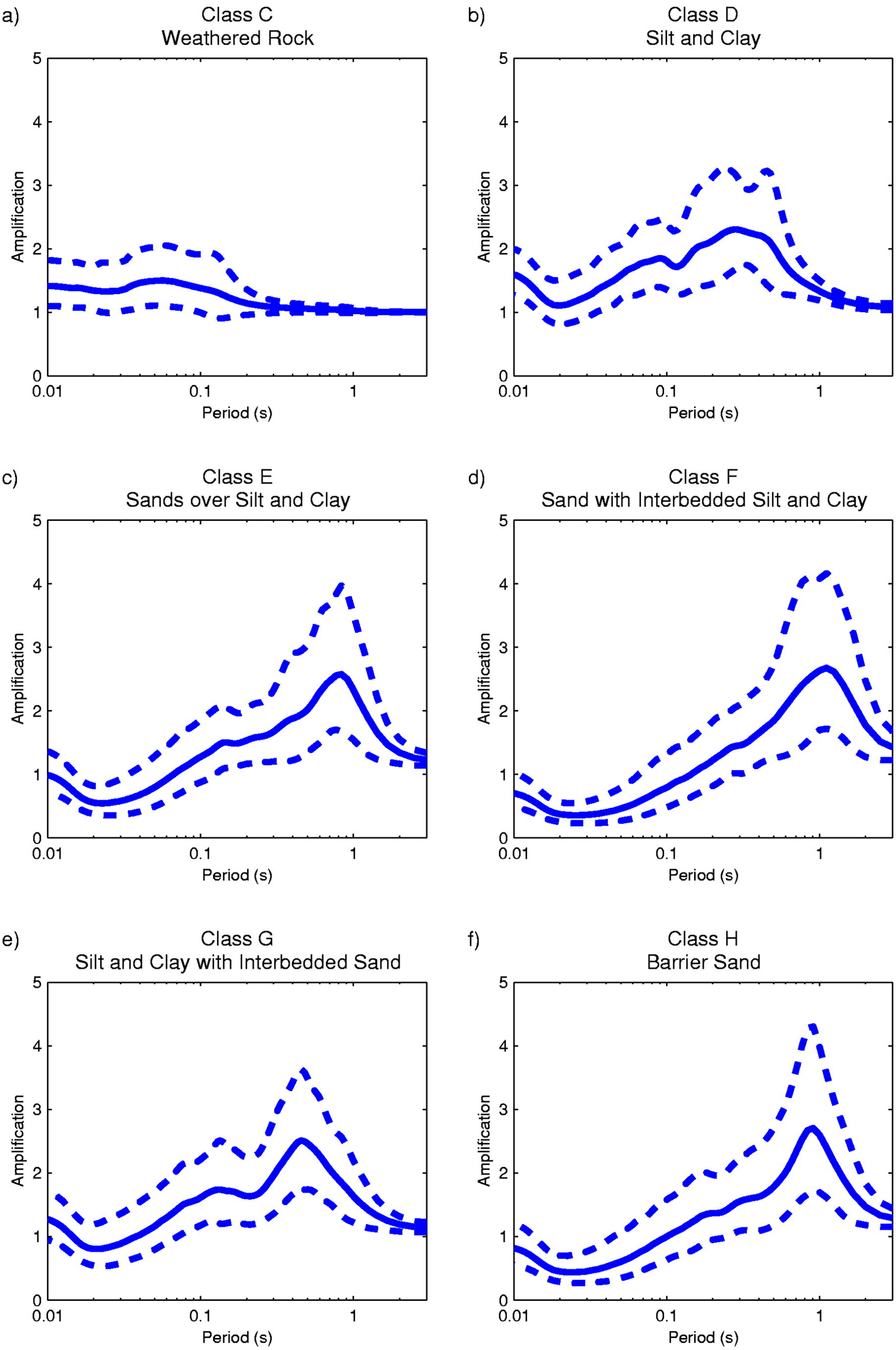

Figure 4.12: Amplification factors for Newcastle site classes, based on an input rock motion from a moment magnitude 5.5 event with PGA of 0.25g. The solid line is the median amplification factor calculated from 50 randomly generated soil models, and the dashed lines represent the 16th and 84th percentiles (ie ± the variability parameter in log space)

A comparison of the amplification factors for an earthquake of moment magnitude 5.5 and a PGA of 0.25 g with those suggested by the Australian Standard for earthquake loading (AS1170.4, 1993) highlights the significance of the new amplification factors (Figure 4.13). Figure 4.13 (a) compares site class C with the weak rock class from the standard. Generally these two sets of amplification factors are very similar. However, the amplification factors for site class C are greater than those for weak rock at periods less than 0.3 s.

Figure 4.13 (b) compares the amplification factors for site classes D, E, F and G with the factors from the Australian earthquake loading standard for soils containing 6-12 m of silt. The amplification factors from the loading standard do not accurately match the calculated amplification factors for any of the site classes displayed here. For periods less than 0.6 s, the factors from the standard are smaller than the amplification factors calculated for any of the Newcastle and Lake Macquarie site classes.

Figure 4.13 (c) compares site class H with the soil class from the Australian earthquake loading standard containing greater than 12 m of silt. The factors from the standard are generally less than those calculated for site class H. This difference is greatest near a period 0.9 s which is where site class H has its maximum amplification.

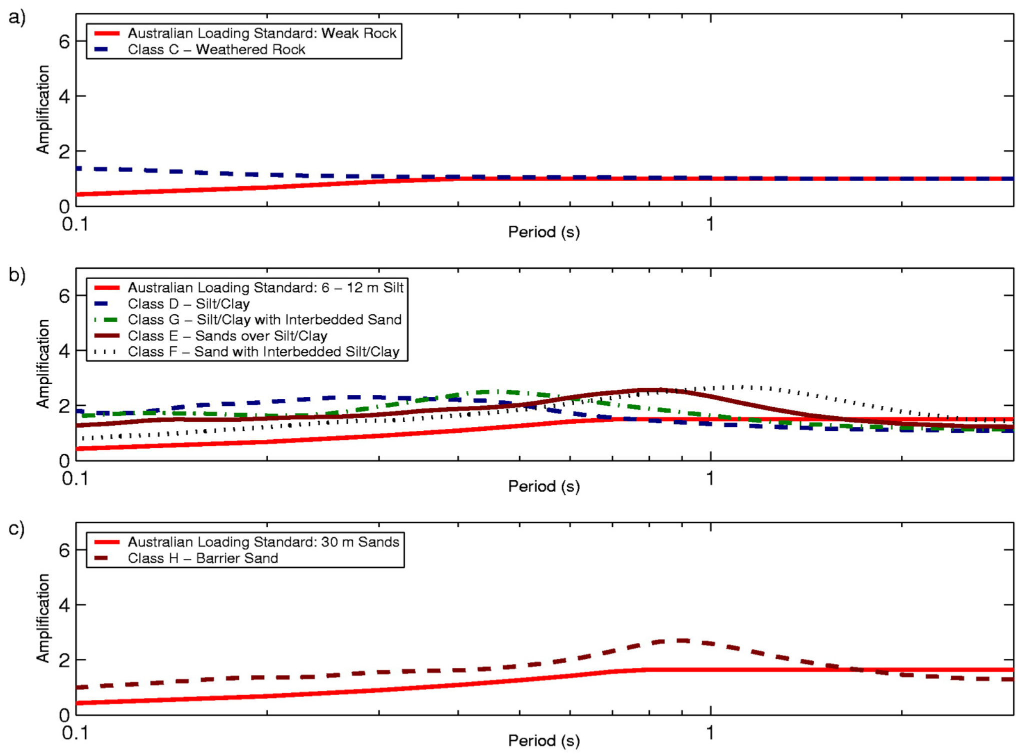

Figure 4.13: Comparison of amplification factors calculated for the Newcastle and Lake Macquarie site classes with the amplification factors suggested by the Australian standard for earthquake loading (AS1170.4, 1993)[15].

[15] *The Australian earthquake loading standard presents a single number, known as the site factor (S), for each soil class. In practice, this number is limited to be the minimum of S or $2T^{2/3}$, where T is period in seconds, to create the period dependent amplification factors presented in Figure 4.13.*

4.6 Earthquake Hazard

4.6.1 Introduction

As mentioned at the start of this Chapter, earthquake hazard is typically measured in terms of the level of ground shaking that has a certain chance of being exceeded in a given time period. This Section presents two levels of earthquake hazard for the study region, specifically the hazard that has a 10% chance of being exceeded in 50 years and the hazard that has a 2% chance of being exceeded in 50 years. These levels of hazard correspond to impacts with return periods of approximately 500 years and 2,500 years respectively. We have used PGA and spectral acceleration as our indicators of earthquake hazard. The reader should note that other parameters such as spectral displacement and spectral velocity are also important, especially for medium-rise and high-rise buildings and other large structures.

4.6.2 Calculation of Earthquake Hazard

The previous four Sections described the source, attenuation and site response models that have been developed for the Newcastle and Lake Macquarie region. In order to calculate the earthquake hazard in the region, it is necessary to amalgamate these models. The approach taken in this study is outlined below:

1. A spacing of 250 m was used to create a uniformly spaced grid of sample points at which the hazard was calculated.
2. Earthquakes were simulated using the method described in Section 4.3.
3. For each earthquake - sample point combination the following procedure was carried out:
    - An attenuation function was selected by choosing a random variation from the median attenuation model[16];
    - The attenuation function was used to determine the rock RSA at the sample point;
    - The appropriate median amplification factor was selected based on the sample point's site classification, the magnitude of the earthquake and the level of the rock RSA, and;
    - A random variation of the amplification factor was selected[16] and used to amplify the rock RSA to produce a regolith RSA.
4. Each regolith RSA had a likelihood of occurrence the same as its causative earthquake (Section 4.3).
5. For a given level of hazard identify the maximum regolith RSA that has at least that chance of being exceeded in the given time frame. For example, given a hazard level of 10% probability of exceedance in 50 years, the hazard at a sample point is defined as the maximum RSA that has at least a 10% chance of being exceeded in 50 years.

4.6.3 10% Chance of Exceedance in 50 Years (approx. 500 year return period)

The Australian earthquake loading standard, AS1170.4-1993, presents earthquake hazard in terms of an 'acceleration coefficient' that has a 10% chance of being exceeded in 50 years. This acceleration coefficient is considered equivalent to peak ground acceleration (PGA). Figure 4.14 and Figure 4.15 allow a comparison of the earthquake hazard from AS1170.4-1993 with the equivalent hazard calculated in this study. Both maps have the same trend of increasing hazard towards the north-east of the study region. However, the hazard calculated within this study is typically greater than the hazard suggested by the Australian earthquake loading standard.

The hazard maps presented in Figure 4.14 and Figure 4.15 were calculated using the *peak ground acceleration* or acceleration coefficient that would be experienced on a rock outcrop. However, the buildings in Newcastle and Lake Macquarie are not built on rock, but on varying thicknesses of regolith (Section 4.5.2). Figure 4.16 presents the earthquake hazard on regolith in the study region. This figure demonstrates that the

[16] Random variations for both the attenuation function and the amplification factors were selected by randomly choosing a scaling variable from a normal distribution with a zero mean and a standard deviation of one. This scaling variable was multiplied against the appropriate variability parameter and then added to either the attenuation function of the amplification factors.

presence of regolith increases the earthquake hazard in the study region compared to hard rock. All of the regolith site classes have a similar, amplifying effect on PGA values.

The damage that is experienced by buildings is often influenced not only by the peak ground acceleration, but also the level of ground shaking at a specific period of vibration. For example, low- to medium-rise structures are typically more vulnerable to ground shaking that has a *period of vibration of approximately 0.3 s* than they are to PGA. Figure 4.17 and Figure 4.18 present maps of earthquake hazard for both outcropping rock and regolith, based on the response of idealised low- to medium-rise structures. The hazard at 0.3 s on rock is very similar to the PGA hazard on rock presented in Figure 4.15. Both figures indicate a similar level of hazard, as well as a trend of increasing hazard to the north-east. A comparison of Figure 4.17 and Figure 4.18 demonstrates that the regolith causes an increase in the earthquake hazard. Moreover, unlike the PGA hazard presented in Figure 4.16, variations in the regolith material cause significant variations in the hazard across the study region, with areas of deeper regolith generally corresponding to regions of higher hazard. The regions of highest hazard are generally located on the silts and clays of site class D.

Medium- to high-rise structures are typically more vulnerable to ground shaking that has a *period of vibration of approximately 1 s*. Figure 4.19 and Figure 4.20 present maps of earthquake hazard for both outcropping rock and regolith, based on the response of idealised medium- to high-rise structures. The spectral acceleration at 1 s on rock is less than either the PGA on rock or the spectral acceleration at 0.3 s on rock. Similarly, the spectral acceleration at 1 s on regolith is less than either the PGA on regolith or the spectral acceleration at 0.3 s on regolith.

A comparison of Figure 4.19 and Figure 4.20 demonstrates that the regolith causes an increase in the earthquake hazard as compared to the hazard on rock. As with the hazard at 0.3 s on regolith, variations in the regolith material cause significant variations in the hazard across the study region. However, unlike the hazard at 0.3 s on regolith, the silts and clays of site class D do not vary the hazard at 1 s from the hazard experienced on the weathered rock of site class C.

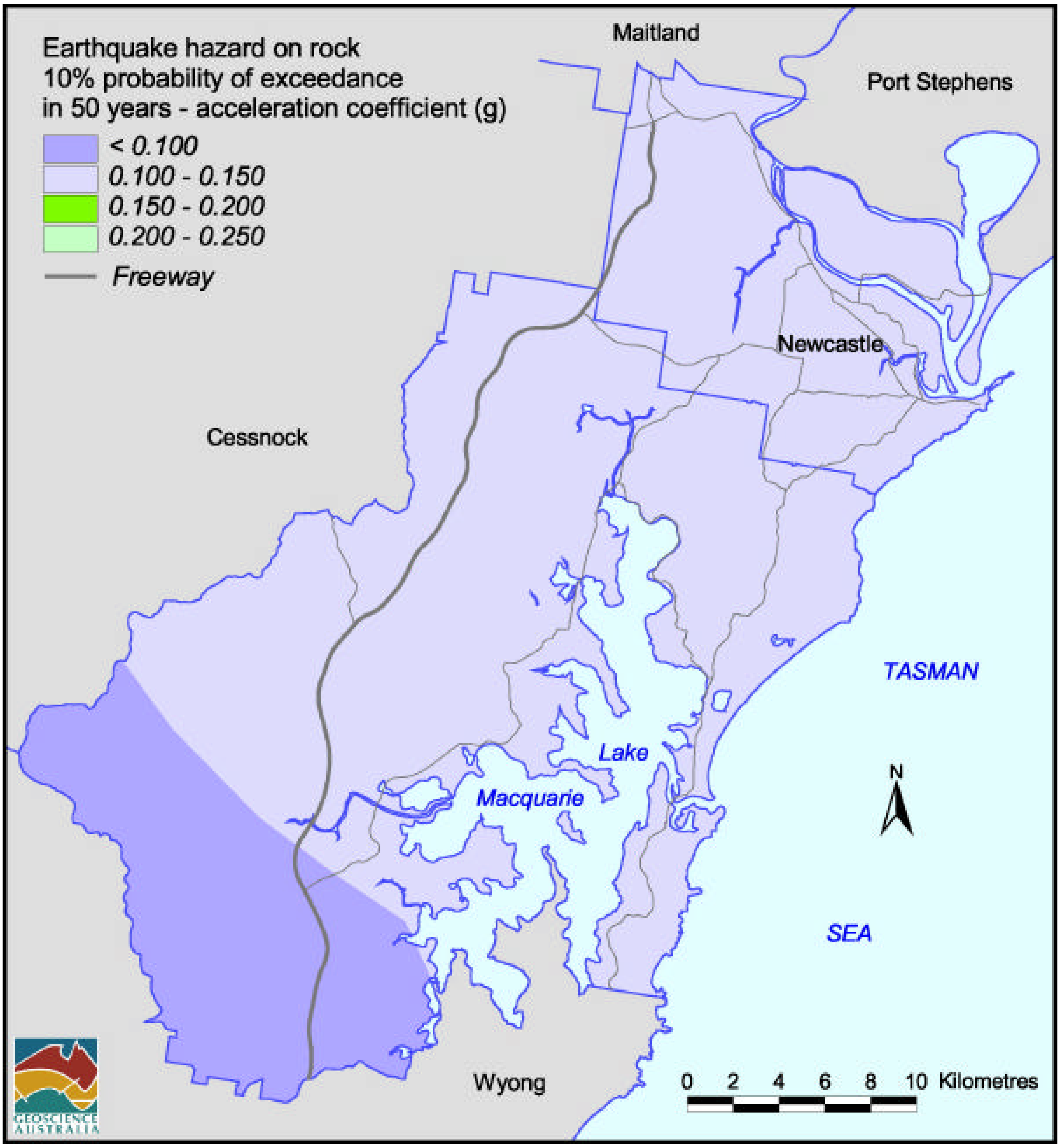

Figure 4.14: Earthquake hazard on rock in Newcastle and Lake Macquarie as suggested by the Australian earthquake loading standard, AS1170.4-1993. Earthquake hazard is defined as the acceleration coefficient (considered equivalent to peak ground acceleration) that has a 10% chance of being exceeded in 50 years

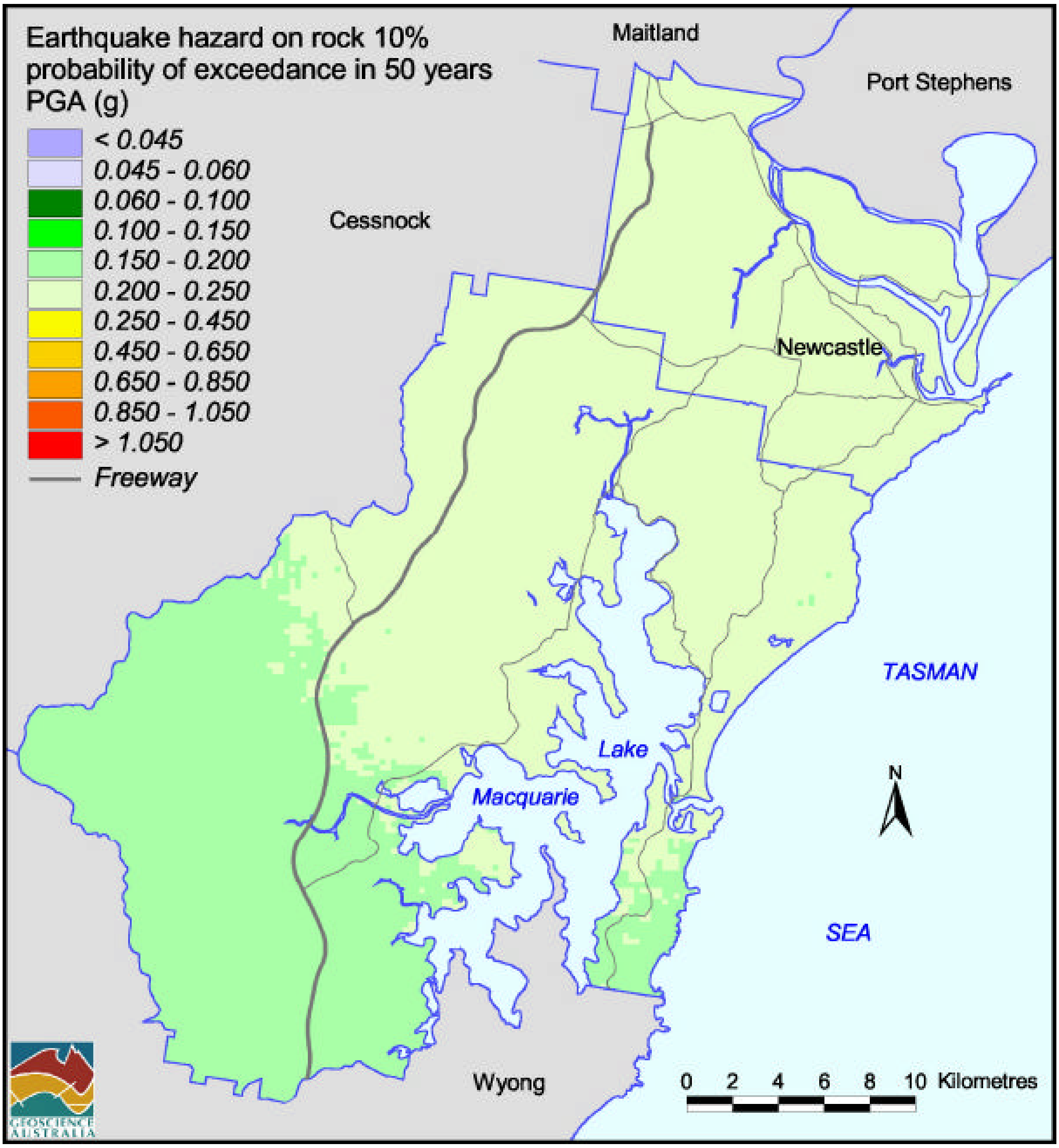

Figure 4.15: Earthquake hazard on rock in Newcastle and Lake Macquarie as suggested by the hazard assessment conducted for this study. Earthquake hazard is defined as the peak ground acceleration that has a 10% chance of being exceeded in 50 years

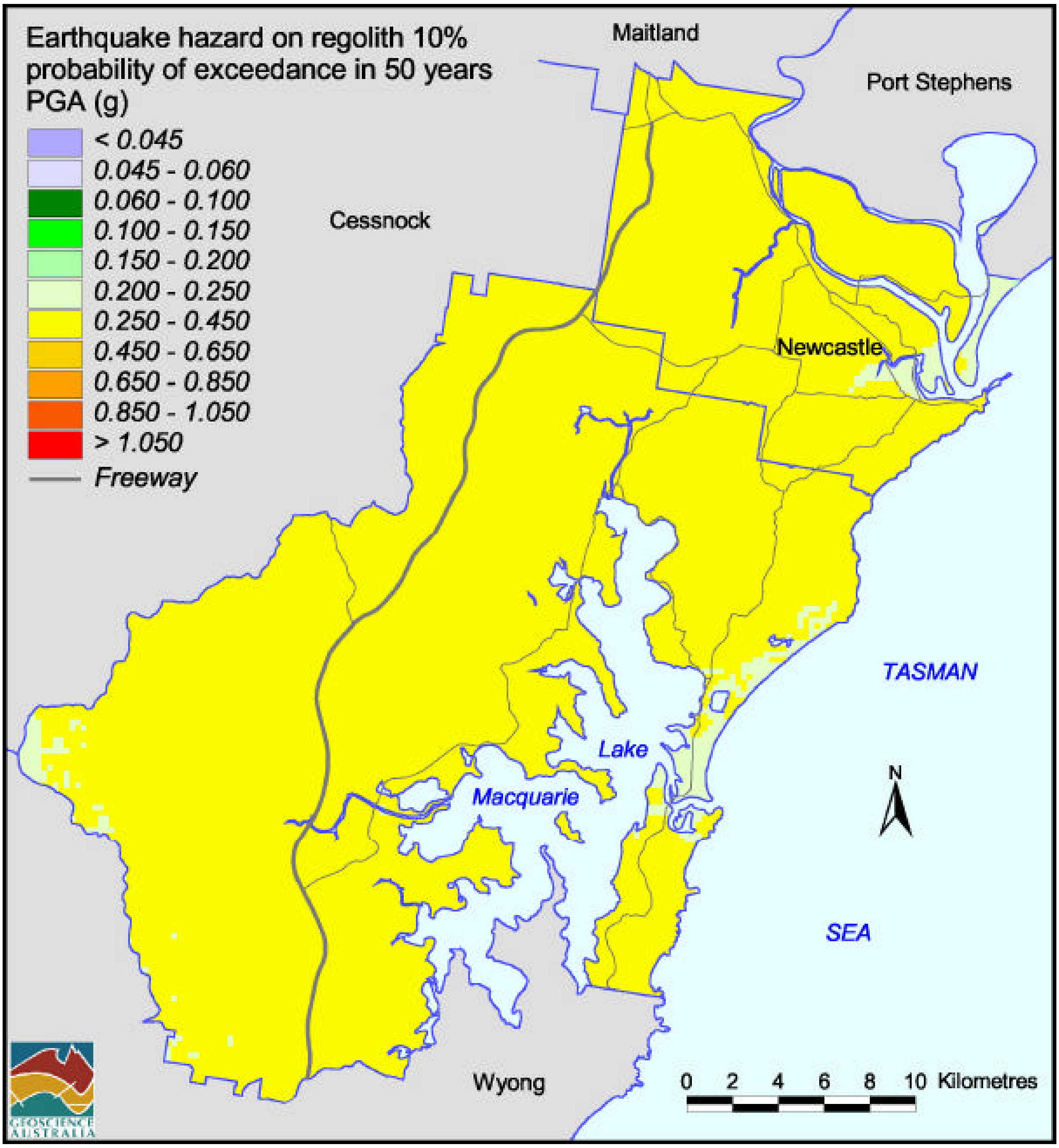

Figure 4.16: Earthquake hazard on regolith in Newcastle and Lake Macquarie as suggested by the hazard assessment conducted for this study. Earthquake hazard is defined as the peak ground acceleration that has a 10% chance of being exceeded in 50 years

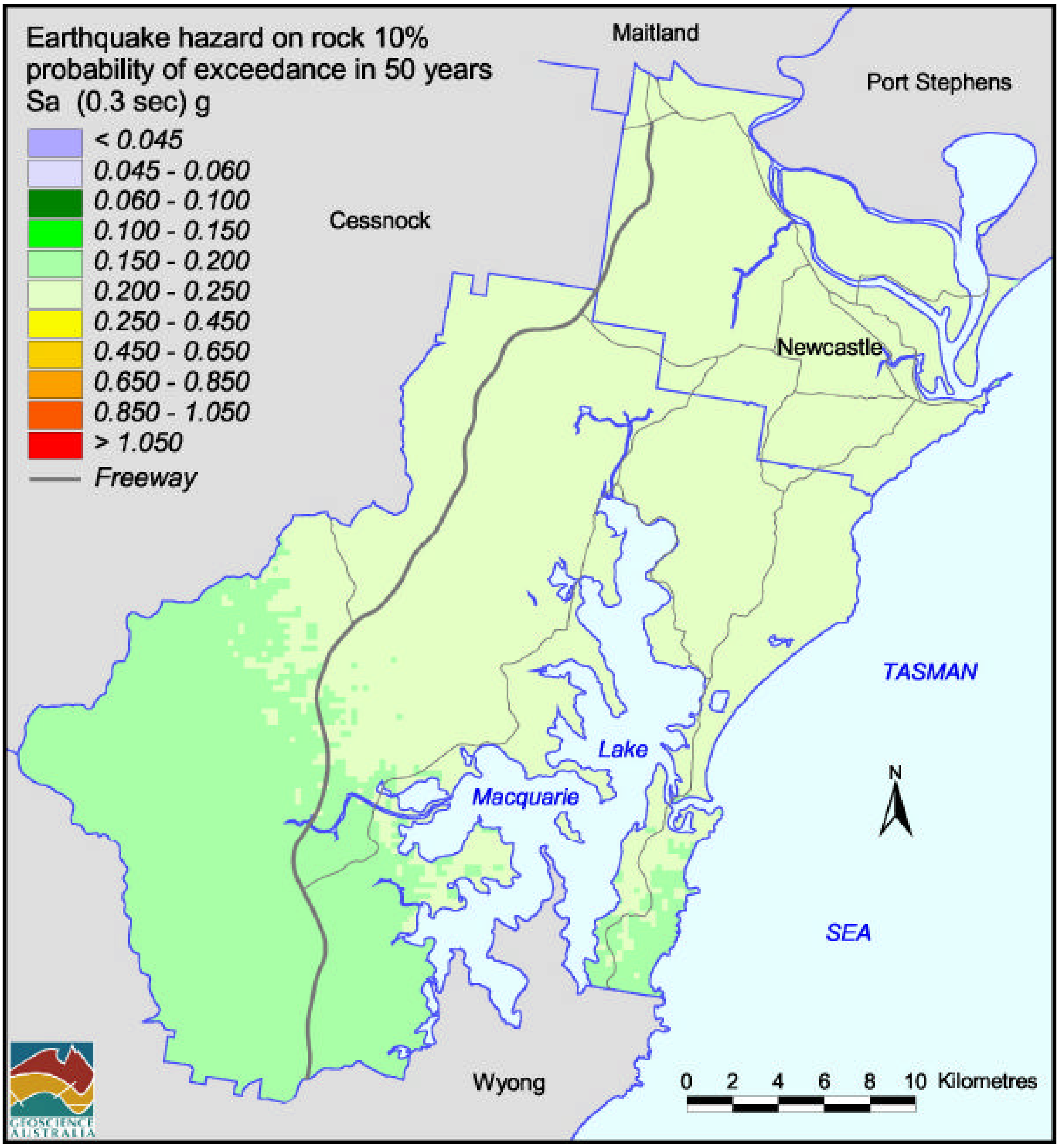

Figure 4.17: Earthquake hazard map on rock with a 10% chance of being exceeded in 50 years. Hazard is defined by the response of idealised low- to medium-rise buildings with a natural period of 0.3 s

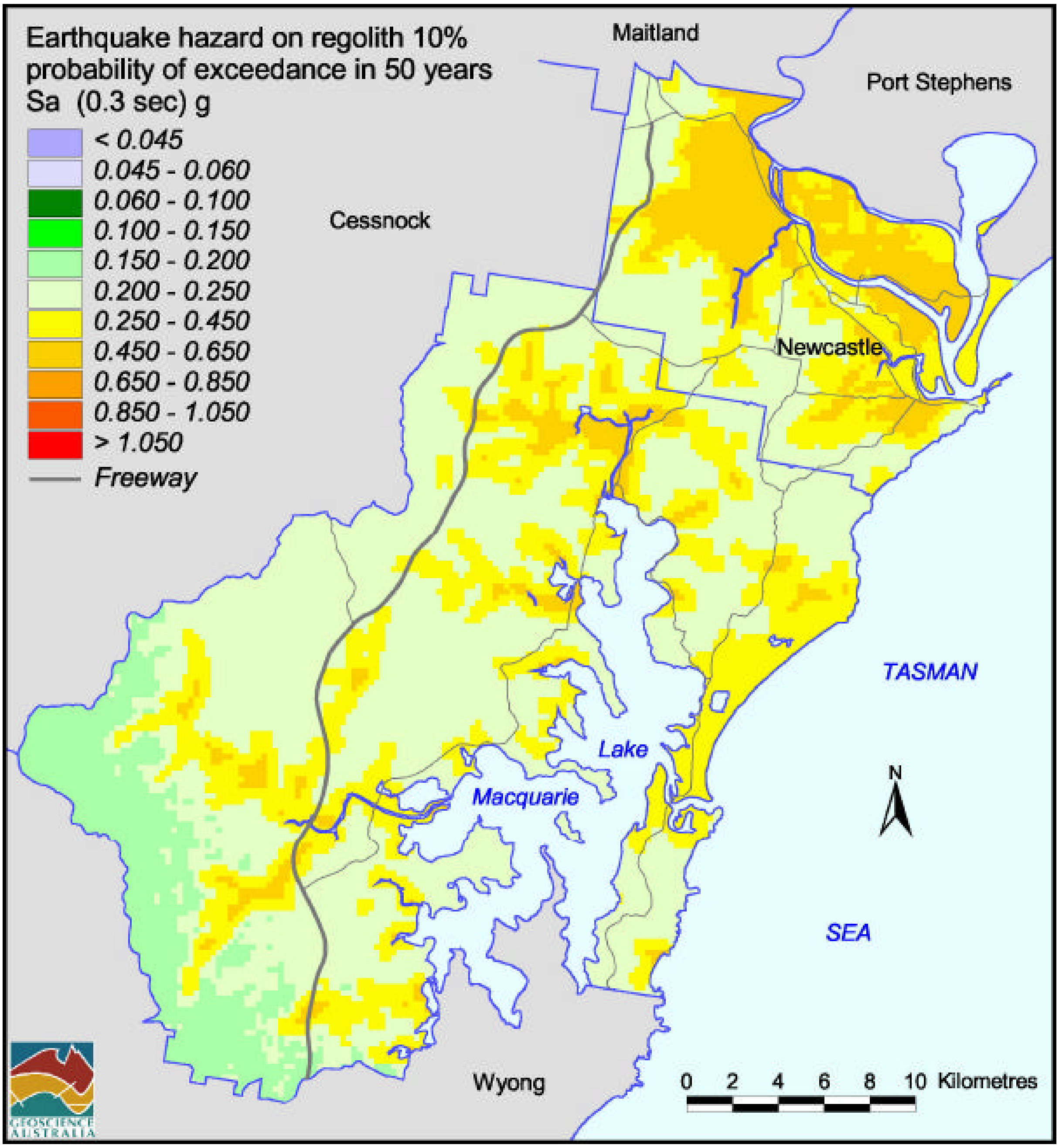

Figure 4.18: Earthquake hazard map on regolith with a 10% chance of being exceeded in 50 years. Hazard is defined by the response of idealised low- to medium-rise buildings with a natural period of 0.3 s

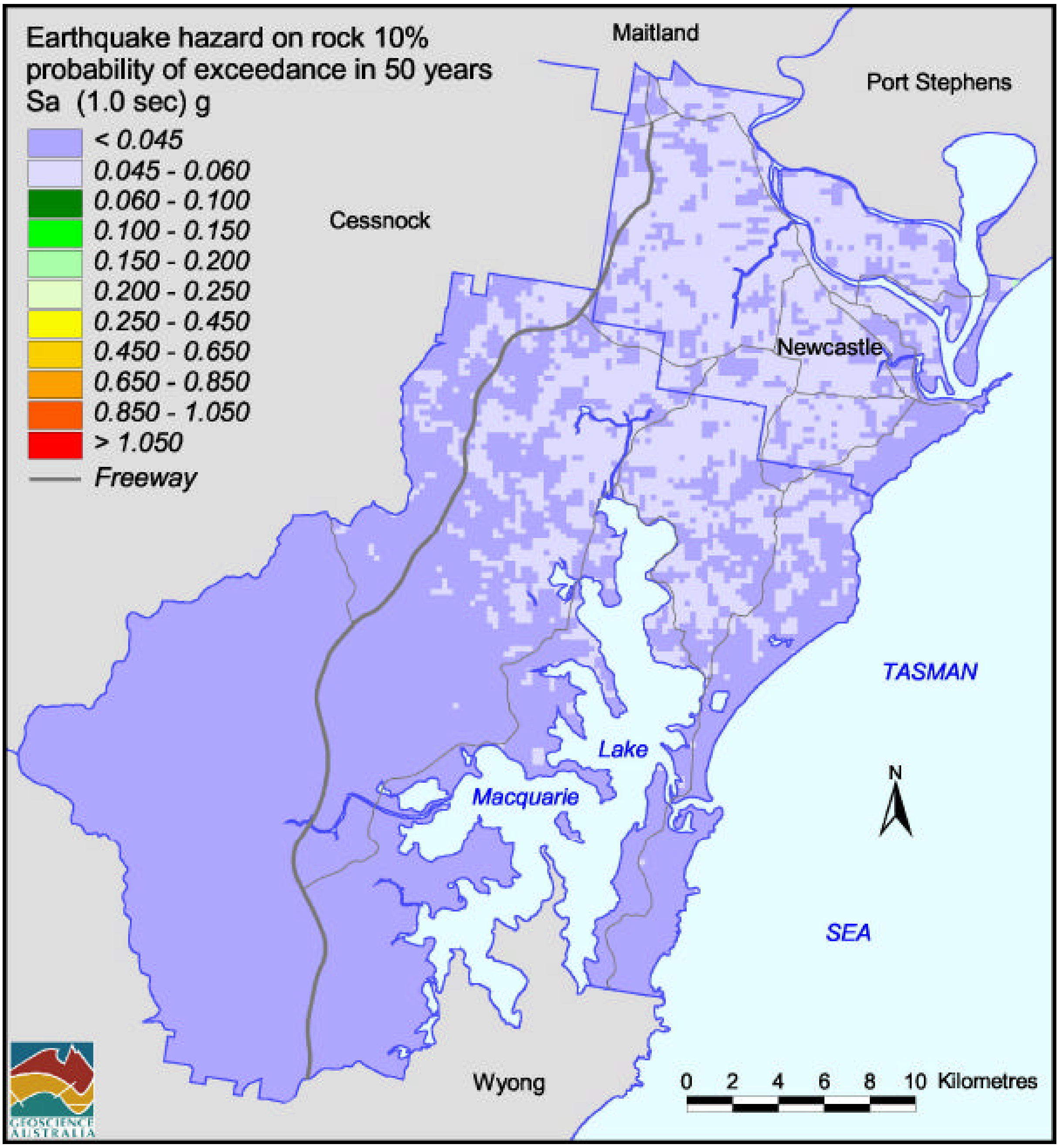

Figure 4.19: Earthquake hazard map on rock with a 10% chance of being exceeded in 50 years. Hazard is defined by the response of idealised medium- to high-rise buildings with a natural period of 1 s

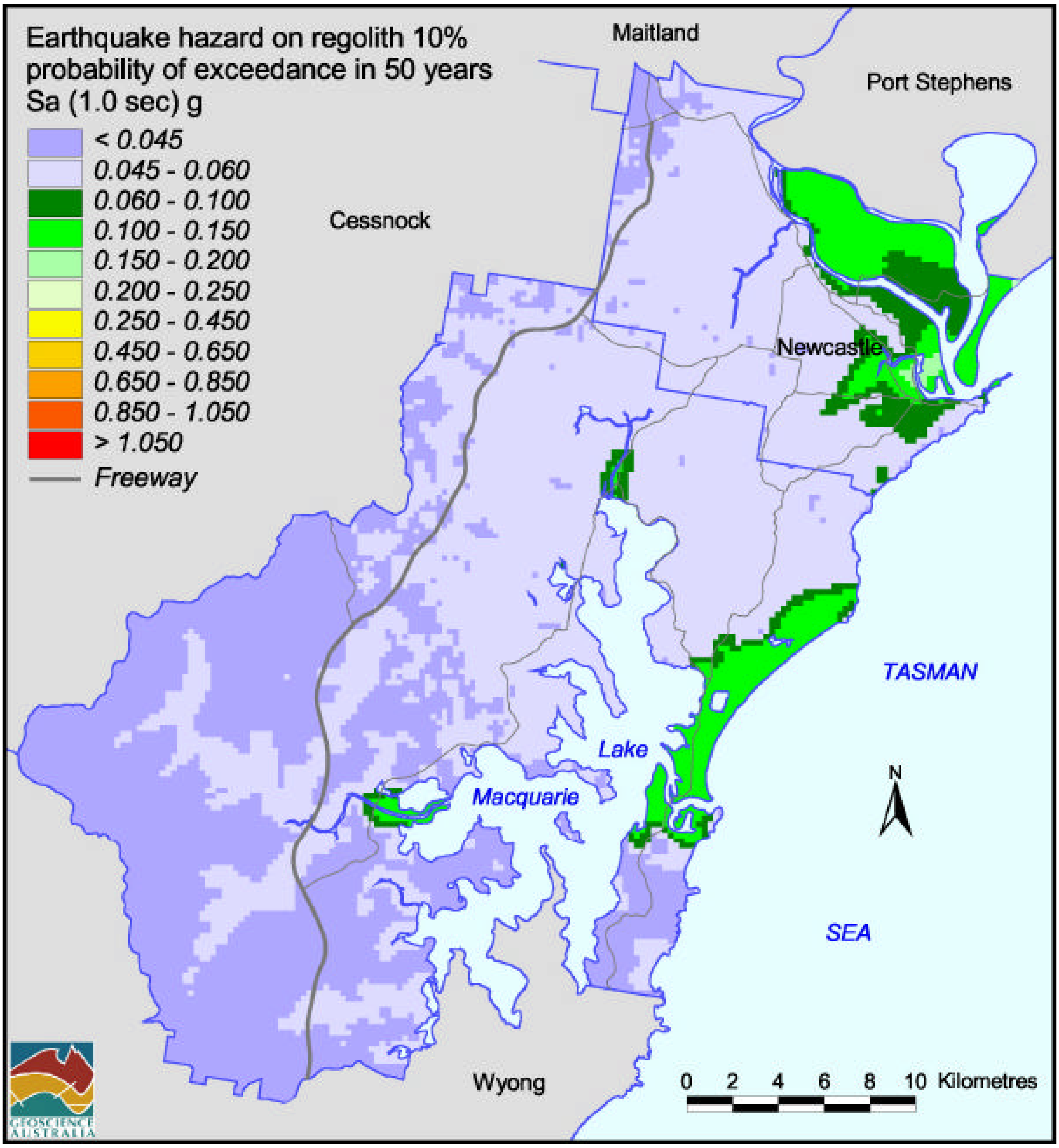

Figure 4.20: Earthquake hazard map on regolith with a 10% chance of being exceeded in 50 years. Hazard is defined by the response of idealised medium- to high-rise buildings with a natural period of 1 s

4.6.4 2% Chance of Exceedance in 50 Years (approx. 2,500 year return period)

Whilst the Australian earthquake loading code describes hazard in terms of the level of ground shaking that has a 10% chance of being exceeded in 50 years, it is often important to consider the possible effect of less likely but more damaging events. Consequently, this study has also determined the earthquake hazard that has a 2% chance of being exceeded in 50 years. This probability of being exceeded corresponds to events with a return period of approximately 2,500 years.

Earthquake hazard with a 2% chance of being exceeded in 50 years, on rock and regolith for PGA, 0.3 s and 1 s is presented in Figure 4.21 - Figure 4.26. The earthquake hazard presented in these figures is significantly greater than the corresponding hazard that has a 10% chance of being exceeded in 50 years. Despite the increase in the level of hazard, the same general trends are present in these maps of hazard as in the maps of hazard with a 10% chance of being exceeded in 50 years, specifically:

- The hazard on rock demonstrates a trend of increasing hazard to the north-east of the study region for hazard at PGA, 0.3 s and 1 s;
- The hazard on rock at PGA and 0.3 s is very similar across the entire study region, however the hazard at 1 s is significantly lower than either of these;
- The presence of regolith causes a significant increase in hazard across the study region for hazard at PGA, 0.3 s and 1 s;
- Variations in the regolith material cause variations in the hazard across the study region, especially for the hazard at 0.3 s and 1 s;
- The hazard at 0.3 s on regolith is greatest on the silts and clays of site class D, and;
- The hazard at 1 s on the silts and clays of site class D and the hazard at 1 s on the weathered rock of site class C tends to be very similar and noticeably lower than the hazard at 1 s on any of the other site classes.

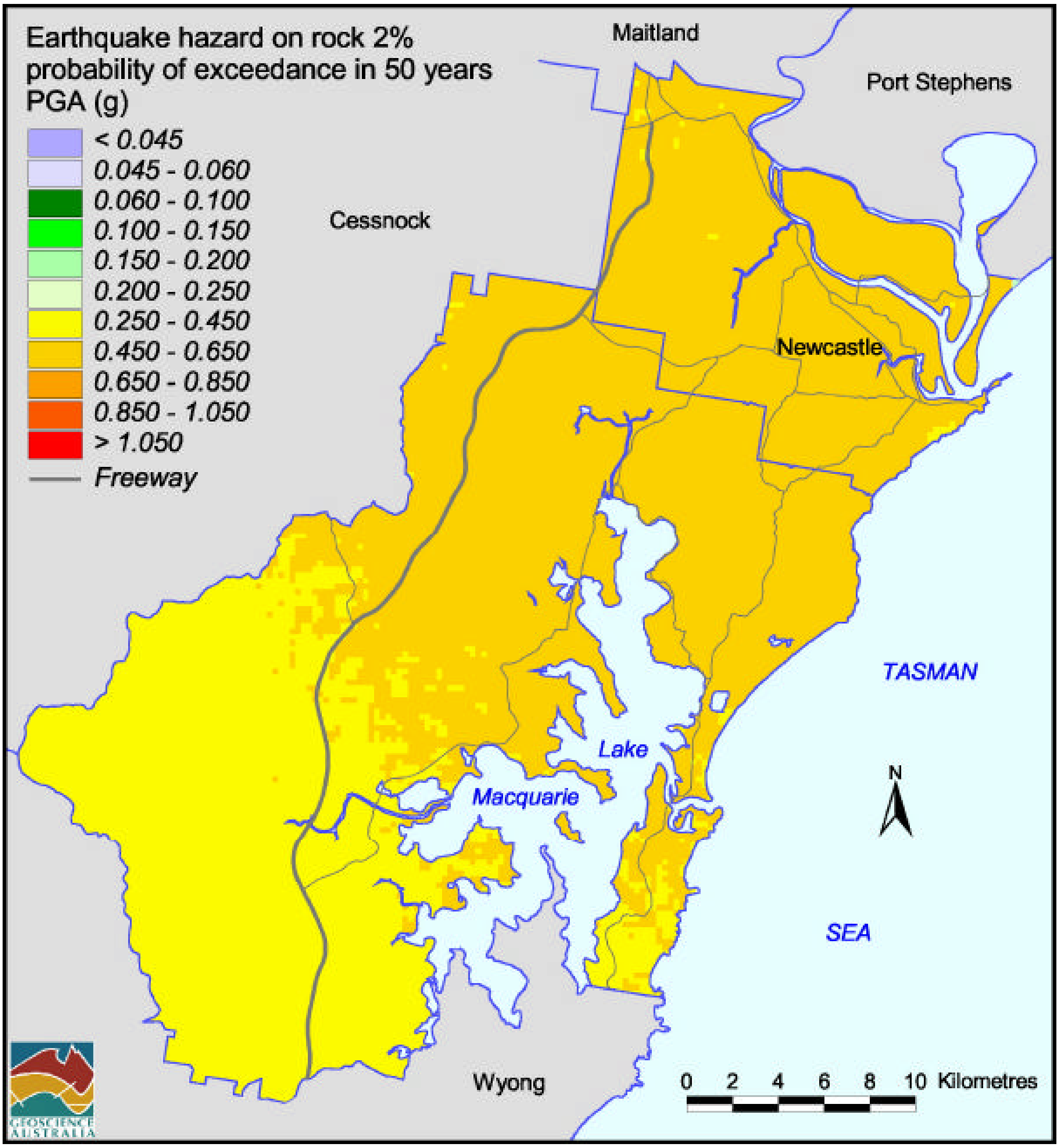

Figure 4.21: Earthquake hazard on rock in Newcastle and Lake Macquarie as suggested by the hazard assessment conducted for this study. Earthquake hazard is defined as the peak ground acceleration that has a 2% chance of being exceeded in 50 years

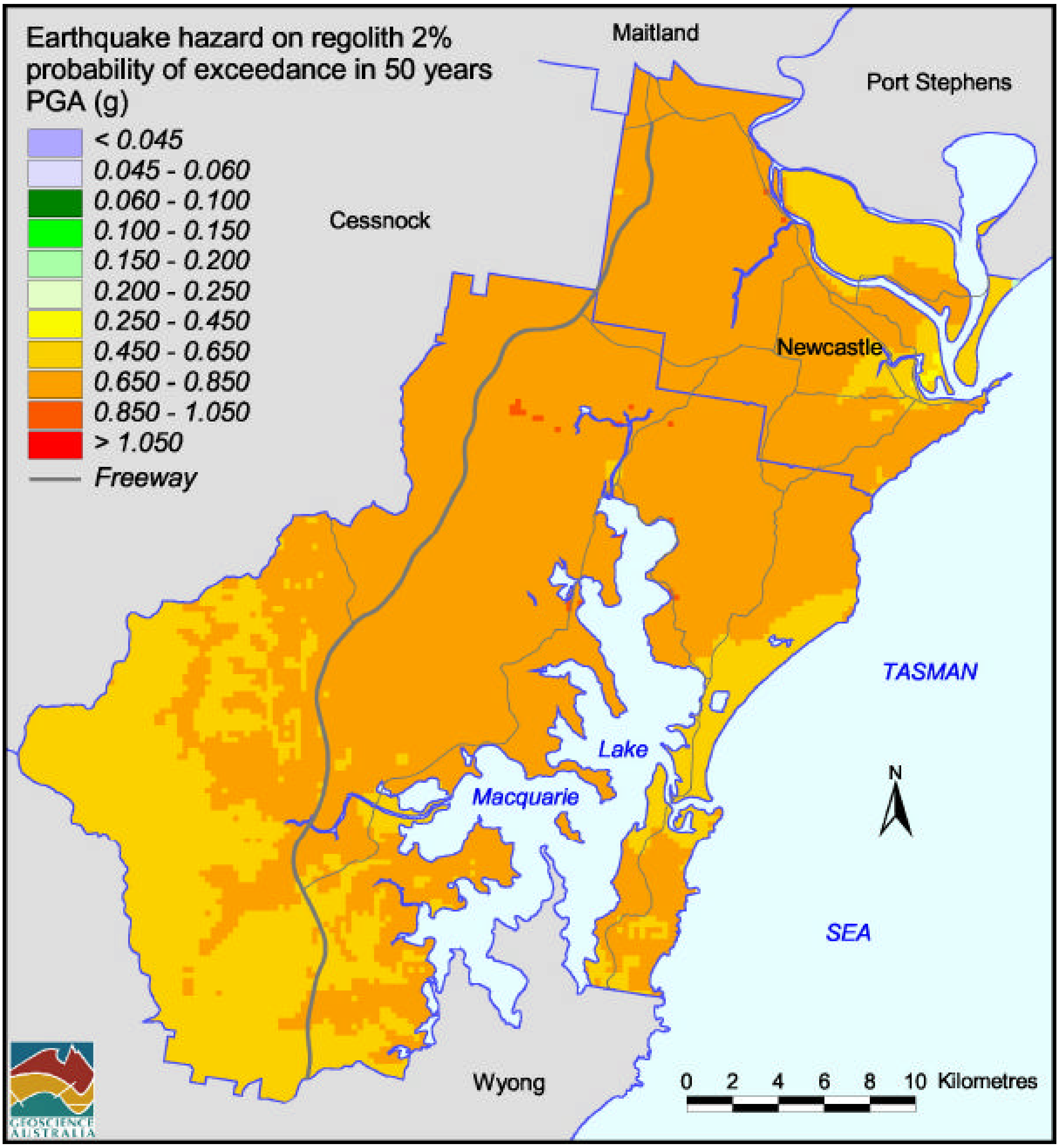

Figure 4.22: Earthquake hazard on regolith in Newcastle and Lake Macquarie as suggested by the hazard assessment conducted for this study. Earthquake hazard is defined as the peak ground acceleration that has a 2% chance of being exceeded in 50 years

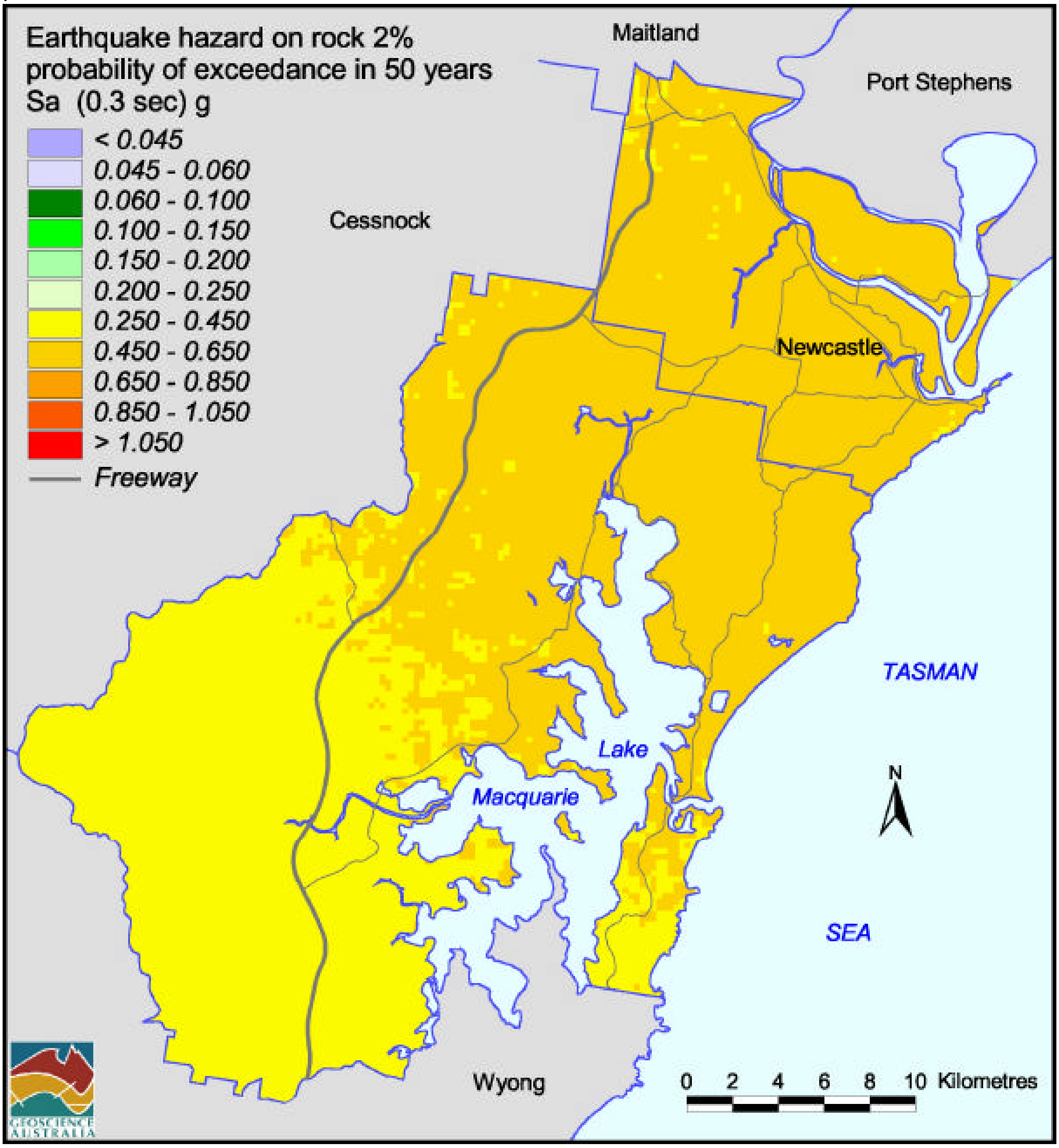

Figure 4.23: Earthquake hazard map on rock with a 2% chance of being exceeded in 50 years. Hazard is defined by the response of idealised low- to medium-rise buildings with a natural period of 0.3 s

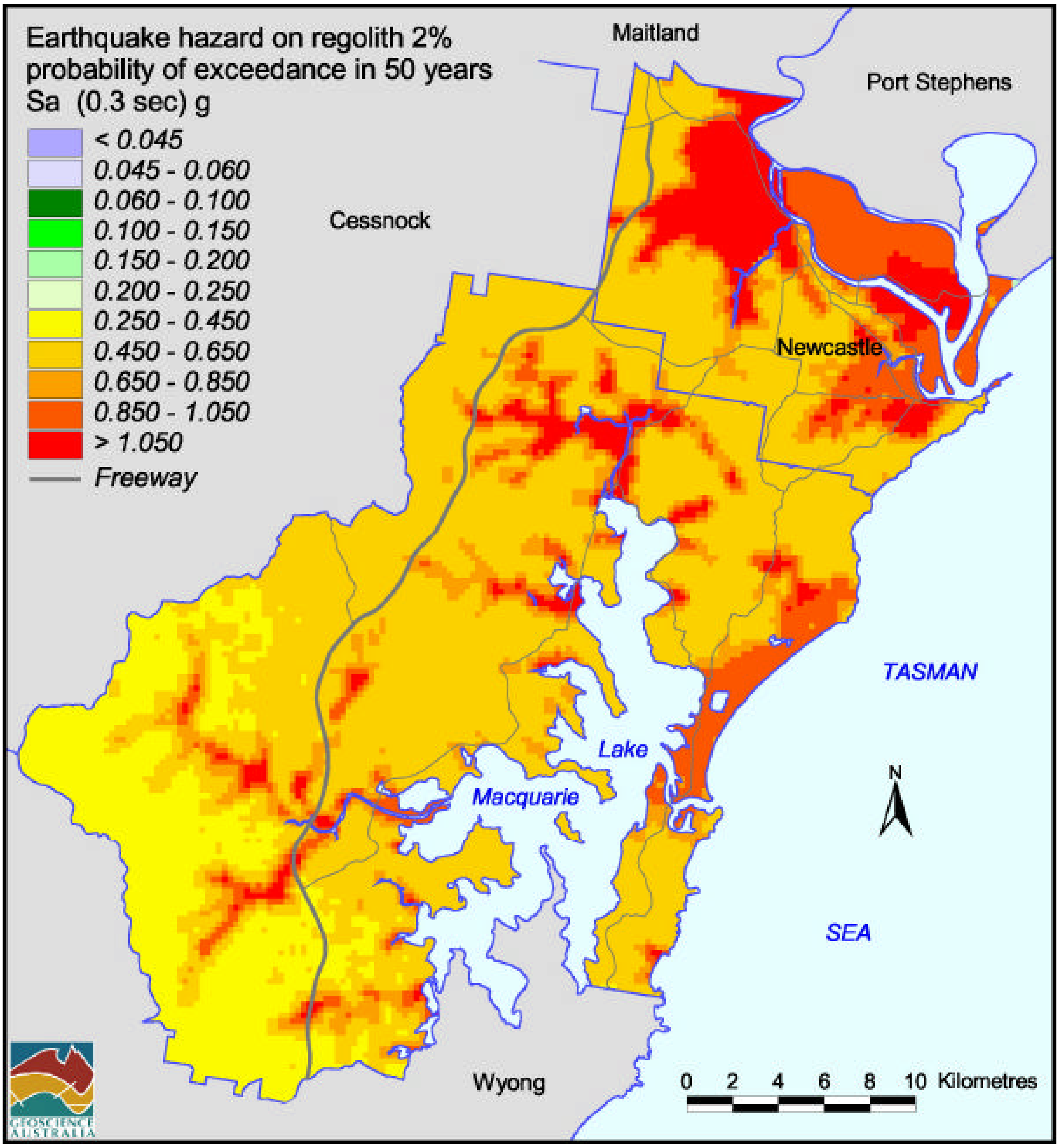

Figure 4.24: Earthquake hazard map on regolith with a 2% chance of being exceeded in 50 years. Hazard is defined by the response of idealised low- to medium-rise buildings with a natural period of 0.3 s

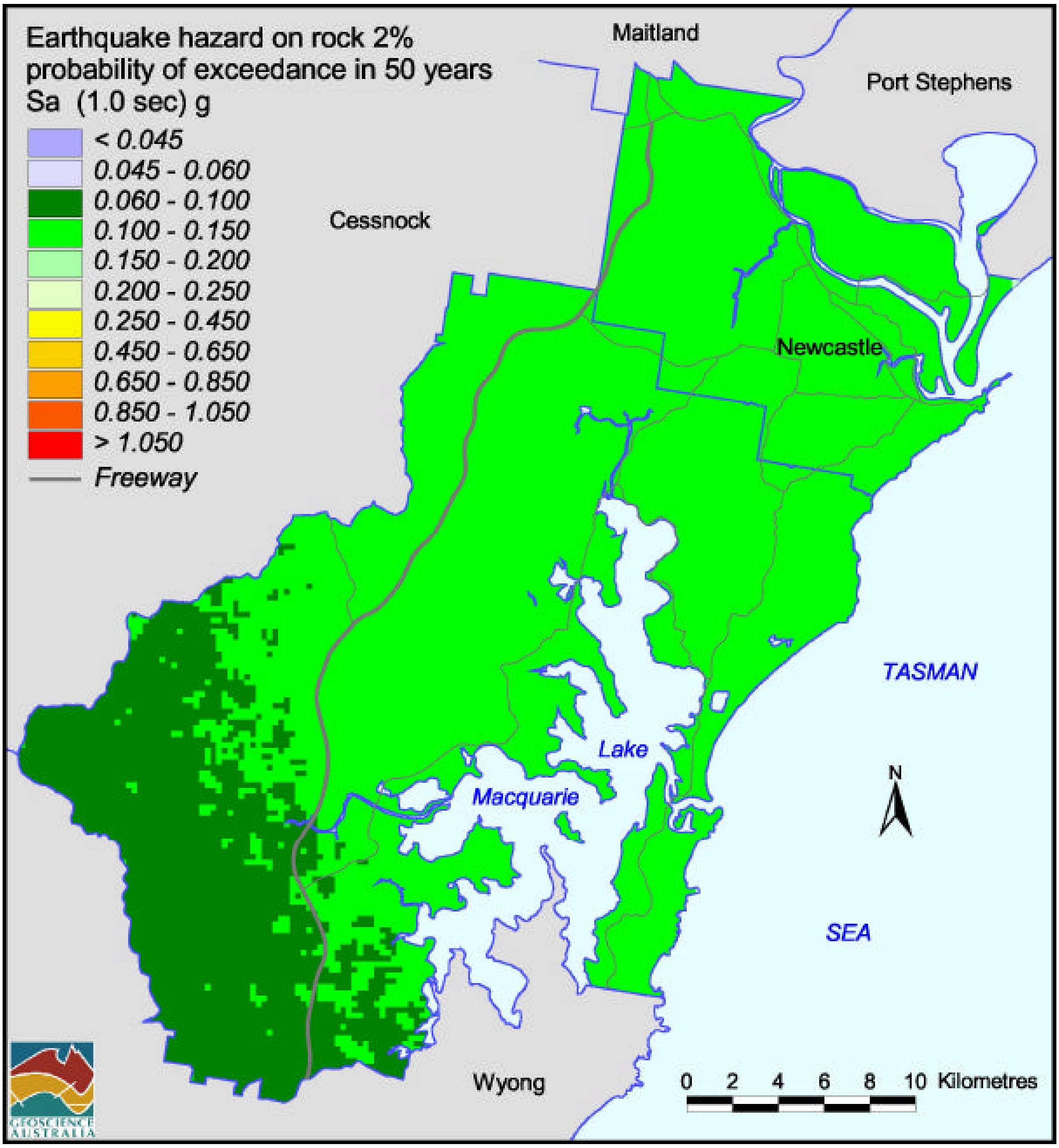

Figure 4.25: Earthquake hazard map on rock with a 2% chance of being exceeded in 50 years. Hazard is defined by the response of idealised medium- to high-rise buildings with a natural period of 1 s

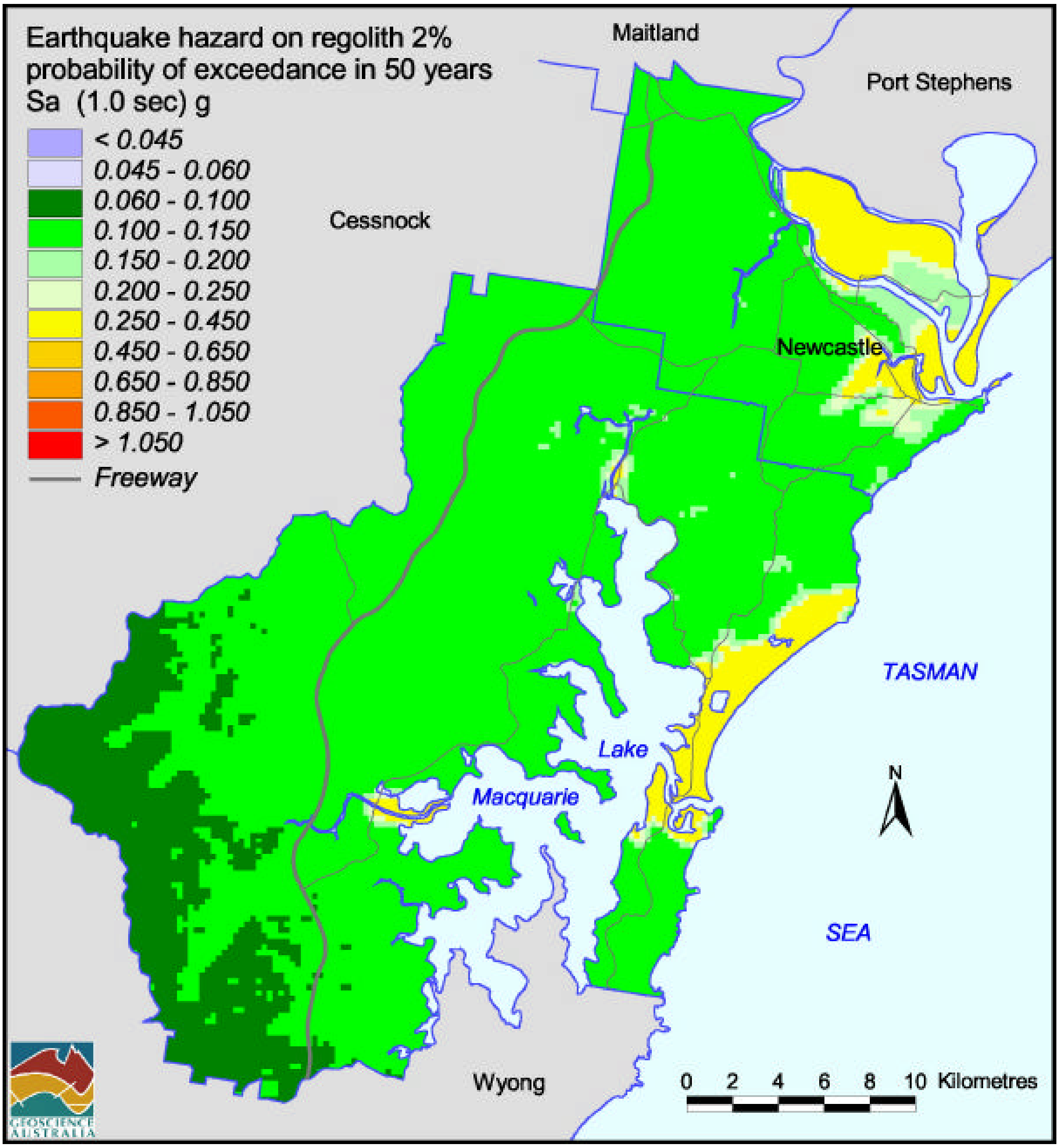

Figure 4.26: Earthquake hazard map on regolith with a 2% chance of being exceeded in 50 years. Hazard is defined by the response of idealised medium- to high-rise buildings with a natural period of 1 s

4.7 Assumptions and Uncertainties of the Earthquake Hazard Models

The earthquake hazard results in this work are based on numerous assumptions and idealisations ranging from the empirical relationships used to determine rupture dimension through to the use of an equivalent-linear methodology for modelling site response. The majority of these are thought to have minimal impact on the results presented in this Chapter. However, there are some assumptions and uncertainties that are thought to strongly influence the results that have been presented, and these are discussed below.

4.7.1 Earthquake Source Model – Assumptions and Uncertainties

There are two key issues relating to the earthquake source zones that have had a significant impact on the earthquake hazard results, specifically:

1. The Gutenberg-Richter (GR) relationships defined for the Newcastle Triangle and Newcastle Fault zones are based on datasets that have a great deal of uncertainty associated with them. The GR relationship for the Newcastle Triangle Zone is based on a historical record of seismicity that is very short and generally incomplete. The GR relationship for the Newcastle Fault Zone is based on poorly constrained estimates of rupture age and total slip for faults that may or may not be currently active. Variations in the GR relationships for either of these source zones would have a significant affect on the estimated hazard.

2. The definition of the source zones in the region has been based partly on an interpretation of the local structural geology. Variations in this interpretation would influence the GR relationships defined in the region and consequently would change the estimated earthquake hazard.

4.7.2 Attenuation Model – Assumptions and Uncertainties

The attenuation model used in this study is one of the most important inputs to the earthquake hazard analysis. Every estimate of earthquake ground shaking is based on this model’s prediction of earthquake attenuation. Consequently, a change in the attenuation model could potentially cause a significant change in the estimated hazard. As mentioned previously, the attenuation model of Toro et al. (1997) is based on the tectonic and geological conditions of central and eastern North America. To date there has been no detailed analysis of the applicability of this model to Australian conditions, and consequently there is still some question as to the appropriateness of this attenuation model.

5 The Elements at Risk in Newcastle and Lake Macquarie (J. Stehle, N. Corby, D. Stewart and I. Hartig)

A comprehensive survey of buildings was carried out in Newcastle. This Chapter outlines some of the main results of that survey. The inventory of buildings also in an important input to the risk simulation model in Chapter 6.

5.1 The Urban Setting

5.1.1 The Development of Newcastle and Lake Macquarie

Newcastle, on the Hunter River, was settled from early in the 19th Century as both a centre for coal extraction and export, initially to Sydney. It was also the seaport for trade between the growing agricultural economy in the Hunter Valley, served by river ports at Morpeth and Clarence Town, and by the expanding bullock track and then rail system into the valley and nearby coastal areas. Though a convict penal settlement was established in 1792 the first land grants in the valley, around Newcastle, were in 1823 marking the beginnings of current European style communities. Early occupation was concerned with coal mining, agricultural support, maritime exports and administration. The original settlement was able to draw on resources of this government and commercial investment and from the late 1800s significant building work was carried out in brick and masonry. These structures were for administration, commercial headquarters, warehouses and homes for the wealthy. There was also considerable timber building, much of it for worker housing in the outlying mining settlements spread across the Newcastle Basin.

Lake Macquarie was also first settled early in the 19th century, on both the eastern sand peninsular and the relatively low-lying, south-western shore. The rate of settlement was slow, driven by small scale agriculture rather than by coal extraction. Suburban expansion only commenced with coal mining at Belmont and around Teralba and Toronto late in the 19th century, following train services linking to Newcastle and the new Sydney-Newcastle railway. No major commercial centre was established before 1900, so the type and scale of building in Lake Macquarie settlements is 20th century, and much of it is of timber because of the abundant forests in the hills west of the lake.

These expressions of building form have a bearing on the vulnerability of existing building stock, and the whole community, to earthquake hazard.

5.1.2 Geographical Setting

The geological setting of the municipalities of Newcastle and Lake Macquarie is described in Appendix D. The importance of this to present communities is discussed in the following Sections. The more heavily populated suburbs of both cities sit on an area of Permian sedimentary rocks of the Newcastle and Tomago Coal Measures, which are part of the Hunter Valley Dome Belt and which are characterised by low-relief folded hills and a complex of north-west to south-east trending faults. The towns and suburbs of Lake Macquarie south of Toronto and Swansea are on the northern extremity of the younger Narrabeen/Hawkesbury sandstones of the Hornsby Plateau and are characterised by relatively higher relief but less sharply folded and less frequently faulted strata. These Narrabeen sandstones extend as a north finger along the Mount Vincent ridge to Mount Sugarloaf and also appear locally south-west of Teralba.

The surface of these sedimentary rocks is both weakened by weathering and eroded by recent wash into gullies and creeks. The terrain on which urban structures are built therefore generally comprises up to thirty-metre thickness of soils weathered from the sedimentary rock or washed from adjacent slopes. There is very little exposed competent sound rock to provide foundation for large structures at the surface.

The topographical units, which describe differences in the setting of urban settlements, are:

1) The Newcastle city foreshore and the hill suburbs backing it, The Hill;
2) The Newcastle basin, being that flat terrain on Quaternary sedimentary soils comprising suburbs from Cooks Hill and Merewether through Hamilton, Lambton and Mayfield;
3) The delta areas of Stockton peninsula, Carrington, Kooragang and Hexham which sit on low sand/silt/clay beds which also include areas of fill material human-placed to form land;

4) The hill suburbs on sedimentary rocks of the coal measures (sandstone, siltstone, conglomerates, tuff and coal) from Merewether Heights/Redhead west to Beresfield/Minmi/West Wallsend/Awaba and round the north of the lake to Toronto/Warners Bay/Belmont North;

5) The lakeside townships on Quaternary sediments in widening creek valleys as they enter the lake. These are typified by Dora Creek, Toronto, Swansea and Warners Bay and are much smaller segments of urbanisation than found in the Newcastle Basin;

6) The Belmont to Swansea coastal barrier sand strip;

7) The southern lake suburbs on Narrabeen sandstones and conglomerates from Caves Beach and Cams Wharf across to Morisset, Cooranbong and Wangi Wangi.

These topographical units describe the suburbs and townships and have had some bearing on the development of western settlement in the study area. Topography permitted access, or inhibited it to early transport systems. Water supply and streams, coal seams and soils provided the economic opportunity and spirited development of the settlements.

5.1.3 Significant Features

5.1.3.1 The Historical City

The core of the old city of Newcastle contains a mixture of small and medium sized buildings with many dating from the late 19th century, and with a wide variety and a complex mix of urban uses – administrative, commercial, retail, cultural, residential, industrial and transport. Many of these old buildings still operate with their original function. All this is set between a beach and headland at the east, the busy operating Port of Newcastle at its north and a steep cathedral topped hill behind it on the south. This city of old buildings embodies a mixture of construction types; of brick, timber, concrete, some stone and iron. Threaded through this fabric of old is a scatter of buildings of all periods of the 20th century.

In a half moon around this core lies the remainder of the original city, from Merewether to the suburbs of Lambton and Mayfield. These suburbs lie in the basin sitting on sedimentary material as described in Chapter 4. Beyond these are the hill suburbs extending out to Lake Macquarie suburbs in the south and Maitland in the west.

5.1.3.2 Social & Cultural

Major structures within the city are:

- City Hall
- Catholic and Anglican Cathedrals and major other churches
- Library and Museum
- Conservatorium of Music.

5.1.3.3 Community Service

- Police headquarters
- Royal Newcastle Hospital
- Police, Fire & Ambulance stations
- Regional Court House
- Newcastle City offices and works depot.

5.1.3.4 Educational

- Primary and secondary schools
- Pre-school centres
- TAFE College campus
- University campus.

5.1.3.5 Public Utility Infrastructure

- Telephone exchanges
- Water pump and storage facilities.

5.1.3.6 Environmentally Sensitive

- Sewage treatment works
- Oil storage tank farm.

5.1.3.7 Economic

- Newcastle CBD
- Newcastle port facilities
- Major industrial establishments.

An assessment of vulnerability requires consideration of the elements at risk. Broadly, these elements can be grouped into three categories: buildings, societal elements and lifelines.

5.2 Elements at Risk - Buildings

5.2.1 Distribution of Buildings

Building type can be inferred by various attributes such as wall type and number of storeys, which can be determined from a 'footpath survey'. The survey regime consisted of approximately a 1 in 10 sample for inner Newcastle, with coarser survey rates being adopted for outer Newcastle and Lake Macquarie regions. The survey methodology is discussed in detail in Appendix G. The information was used for the categorisation of buildings according to a "HAZUS" (National Institute of Building Sciences, 1999) structural type and a "HAZUS" usage type. These types are defined below. The categorisation approach is explained in more detail in Appendix G.

Building details often increase the vulnerability of individual buildings compared to the average performance expected for a generic building class. These building details include brick chimneys and parapets, brick gable roof ends, suspended awnings, structural irregularities (including soft-storeys and brick pier foundations) and tile roofs (which are heavy). A particular type of unreinforced masonry house, built before the 1930s, has also been identified as being particularly vulnerable. This type has its heavy tile roof supported by a single exterior skin of brickwork, and can be identified by a lack of soffit lining (see Figure 5.1). The support of the roof on an internal brick skin is considered less vulnerable since interior walls brace the internal skin.

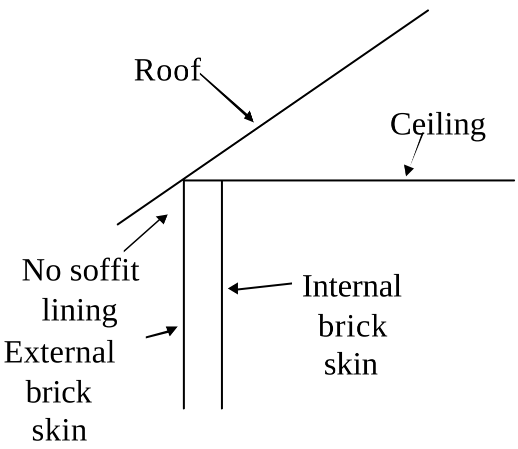

Figure 5.1: Illustration of a vulnerable unreinforced masonry building detail whereby the roof is solely supported on the external brick skin

The variation of building stock over time should be considered in a more rigorous study. In particular, the growth of a city should be considered. For example, in 1999, Lake Macquarie City Council anticipated that

19,000 new homes would be required by 2020. Such growth could increase the overall community vulnerability if the growth consists of the construction of vulnerable building types (such as unreinforced masonry structures) and if the capacity of emergency response facilities is not increased to cope with the increased population. On the other hand, Newcastle has undergone a lot of redevelopment, including some retrofitting. This often involved the replacement or structural upgrading of older (and vulnerable) unreinforced masonry structures. Hence, vulnerability can also reduce over time.

An example of the spatial distribution of some of buildings according to external wall type is shown in Figure 5.2.

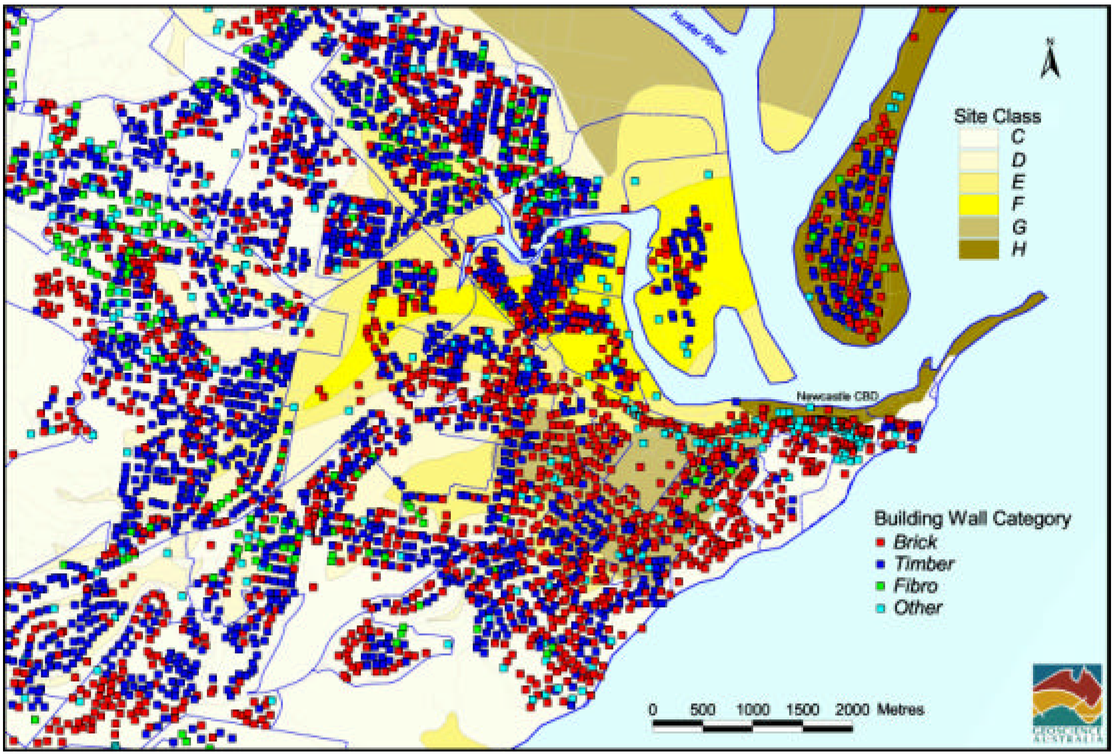

Figure 5.2: Distribution of buildings according to external wall type in the Newcastle area

5.2.2 HAZUS Construction Types

For the risk simulation modelling (see Chapter 6) buildings are classified into subgroups of building construction types. The classifications have been adopted by the methodology used by HAZUS (National Institute of Building Sciences 1999).

The main HAZUS construction types are listed in Table 5-1. There are 36 types in total, although not all types are present in Newcastle. Some of the types are further subdivided into height classes: low-, mid- and high-rise. For a full list of the HAZUS construction types see Chapter 5 of the HAZUS Technical Manual (National Institute of Building Sciences 1999). The most common construction types in Newcastle are timber frame, followed by unreinforced masonry.

Table 5-1: HAZUS classifications for building construction type, found in Newcastle

HAZUS Types	HAZUS type codes
Unreinforced masonry	URML, URMM
Timber frame	W1, W2
Reinforced and pre-stressed concrete buildings	C1L, C1M, C1H, C2L, C2M, C2H, PC1
Steel framed buildings	S1L, S1M, S1H, S2L, S2M, S2H

An example of the spatial distribution of buildings according to the HAZUS structural type is shown in Figure 5.3 (for more information see Appendix G). A more detailed description of some of the key building construction types is given below.

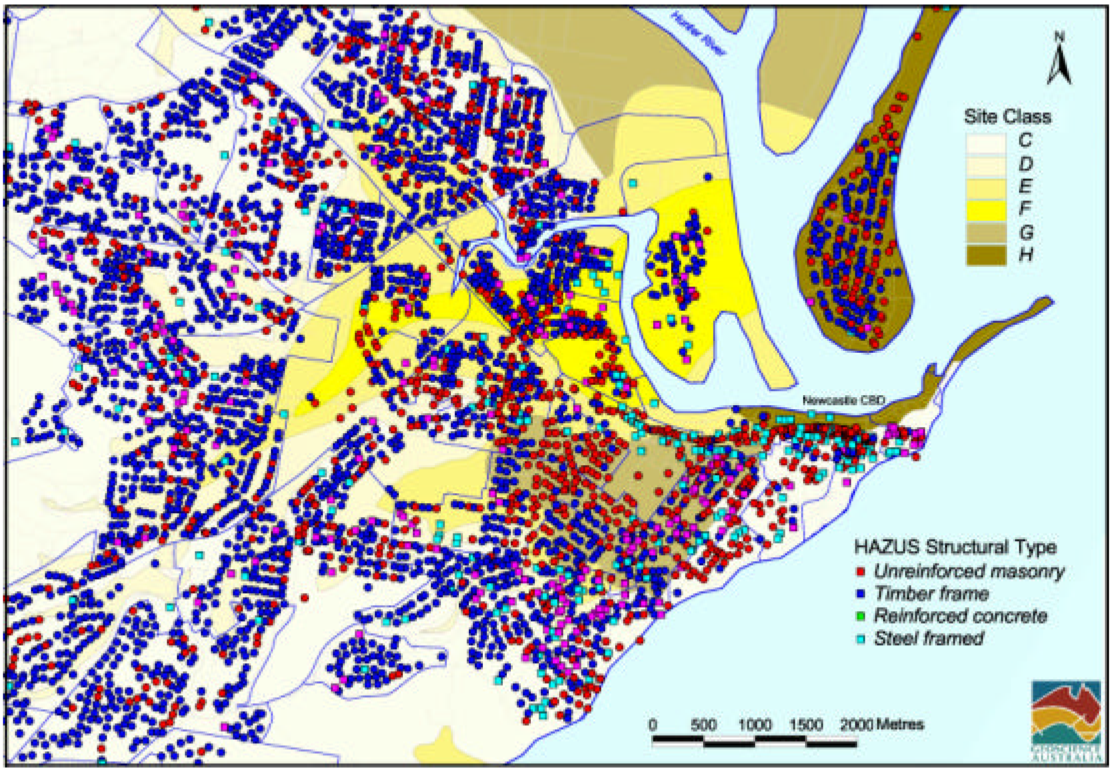

Figure 5.3: Distribution of HAZUS building structural type in the Newcastle area

5.2.2.1 Unreinforced masonry buildings

These types of buildings are very common in Newcastle, particularly for construction up until the 1960s. Older parts of Lake Macquarie also have this type of construction, though it is generally not as common. A wide range of buildings including houses, terraced houses, shops, schools, churches and hospitals are constructed of unreinforced masonry. Infill walls in reinforced concrete framed buildings are also commonly constructed of unreinforced masonry, however this is considered in Section 5.2.2.3.

Unreinforced masonry buildings have historically performed poorly in earthquakes, as witnessed in the 1989 Newcastle earthquake (Melchers, 1990). While these types of structures can perform well if designed and constructed according to current building standards, buildings which are old, decayed of poor design or construction may perform poorly during an earthquake.

A common deficiency in this type of construction is a lack of ties between the two leaves of double-brick cavity wall construction. This deficiency may be a result of corrosion or simply the lack of, or incorrect placement of, ties. Soft and eroded lime mortar joints also contribute to structural weakness and to widespread corner failures in the Newcastle 1989 earthquake (Melchers, 1990). These deficiencies commonly manifest themselves in the failure of parapets, gable roof ends, corners, chimneys and the transverse failure of walls. Cracking due to racking is another common type of damage, although this result is less dependent on construction quality.

Continuity of the structure and ductile behaviour are keys to good seismic performance. The latest Australian standard for masonry structures, AS3700, 2nd edition (AS3700, 1998) was released in 1998 and gives recommendations for design, including requirements for seismic effects to achieve adequate performance levels. This standard replaced the first edition which was issued in 1988, and paid little or no regard to seismic effects. In general, Australian Standards for buildings are enacted by Federal parliament into the Building Code of Australia. The latest version of AS3700 is referenced by way of BCA Amendment 3, and came into effect on the 1st of July, 1998.

5.2.2.2 Timber frame buildings

In Newcastle and Lake Macquarie, timber frame housing is often identified by brick veneer, timber and sometimes fibreboard cladding. Brick veneers, which can easily be confused with unreinforced masonry buildings, are more common for construction dating from the 1960s onwards. The method used for distinguishing brick veneers is presented in Appendix G. Timber frames are most common in smaller buildings such as houses.

Timber frame buildings generally perform very well in earthquakes, although nonstructural and contents damage can be significant. Brick veneer cladding, brick chimneys, plasterboard linings and cornices are commonly damaged by earthquake shaking. However, serious structural damage is perhaps most likely in the foundations, particularly where brick pier or “soft/weak storey” type foundations are used or if there is a lack of continuity.

Timber frame housing must be designed according to AS1720.1 (AS1720.1, 1997) or AS1684.1-4 (AS1684.4, 1999; AS1684.3, 1999; AS1684.2, 1999; AS1684.1, 1999), with consideration of lateral loading predominated by discussion of wind loading in these documents. The consideration of seismic effects has had practically no effect on the construction practices for this category of structure. Despite non-structural and contents components of these building types being more vulnerable than the structural components, little attention is paid to improving their performance, and this is reflected by a lack of requirements in Australian Standards.

5.2.2.3 Reinforced and pre-stressed concrete buildings

Concrete buildings form a significant percentage of large buildings in Newcastle and Lake Macquarie. These buildings are used for a wide range of purposes, including commercial, car parking, industrial, residential, education and government purposes. These concrete buildings may be normally reinforced and/or prestressed, cast *in situ* and/or precast, and consisting of slabs, moment frames and/or shear walls.

Concrete construction performs well when detailed to ensure continuity and ductility and if structural irregularities are avoided. A vertical structural irregularity, often called a ‘soft’ or ‘weak’ storey is particularly susceptible to collapse. These soft/weak storeys are common where car parking or large open spaces are located on the ground floor of a multi-storey building. Irregularities in building plan are equally undesirable since torsional effects can amplify the response for torsionally eccentric components. Soft storey construction can also be an issue for types of construction other than concrete.

The presence of unreinforced masonry infill walls in multi-storey frame buildings can inadvertently cause structural irregularities. Also, the failure or cracking of such walls in racking or out-of-plane response can be costly in terms of repair and also in terms of the hazard they present as falling debris. Falling debris from other failed non-structural components, such as glass windows, can be equally as hazardous.

“Tilt-up” forms of pre-cast concrete construction have become more popular in recent decades. However, this construction method has not been well tested by real earthquake events in Australia.

The current Australian Standard for concrete structures, AS3600, issued in 2001 (AS3600, 2001), requires special seismic design and detailing only in special cases. This version has not been modified from the 1994 version with regard to seismic detailing. Previous versions had no such requirements. In general, however, requirements for seismic effects have had practically no influence on construction practice. Non-structural and contents components are expected to be more vulnerable, although, as previously mentioned, few requirements exist in Australian Standards for these components.

5.2.2.4 Steel framed buildings

Steel framed buildings make up a significant proportion of large buildings in Newcastle and Lake Macquarie. These buildings are mainly used for industrial and recreation purposes, consisting of large shed structures.

Although steel is a ductile material, the connections between steel members can be brittle, particularly when poorly designed and/or constructed welds are used. Structural irregularities, and non-structural elements and contents are the sources for the greatest concern, as they are for concrete buildings.

Both editions of the Australian Standard for steel structures, AS4100, first published in 1990 and revised in 1998 (AS4100, 1998), contain requirements for seismic effects, whereas previous versions lacked them. In general, however, requirements for seismic effects have had practically no influence on construction practice. Non-structural and contents components are expected to be more vulnerable, although, as previously mentioned few requirements exist in Australian Standards for these components.

5.2.3 Key Facilities

Hospitals, police, fire and ambulance stations and similar facilities are extremely important for post-disaster operations. Other key facilities, such as education institutions, nursing homes, and buildings of historical and cultural importance also form critical elements of the community.

The distribution of key facilities is shown in Figure 5.4 and Figure 5.5. While an attempt has been made to capture all key facilities by field survey, some have been missed. Further work is required for a more thorough and detailed risk evaluation.

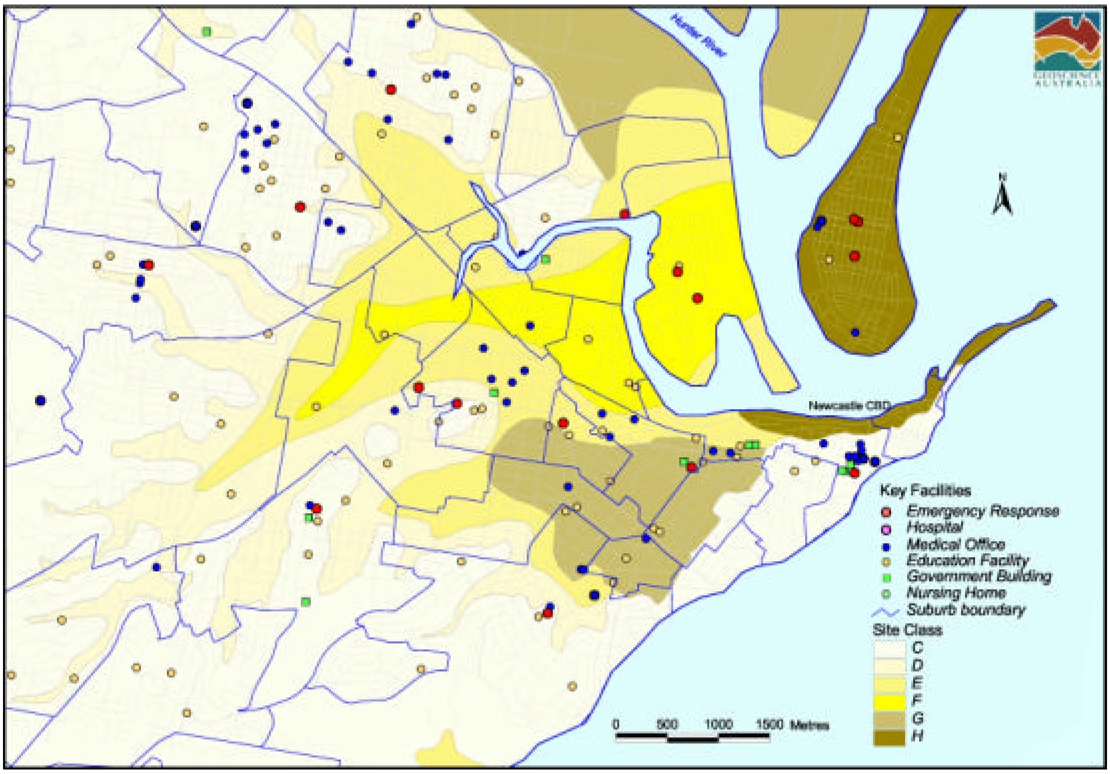

Figure 5.4: Distribution of emergency response and key facilities in the Newcastle area

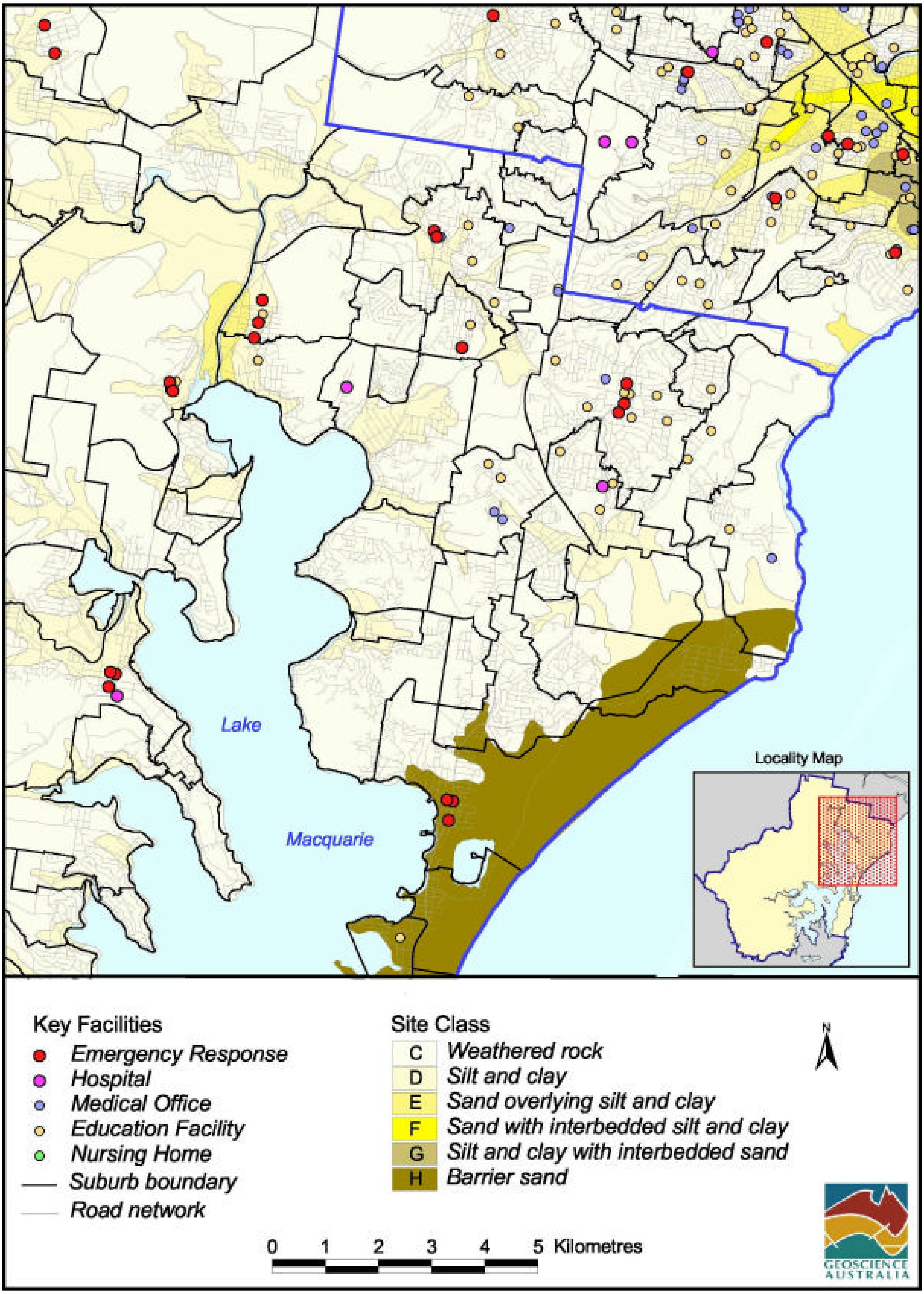

Figure 5.5: Distribution of emergency response and key facilities in the Lake Macquarie area

5.3 Elements at Risk - Societal

The social impact of an earthquake is multi-dimensional and can be measured in a number of ways. Some of the important indicators are discussed here.

5.3.1 Economic

The economic cost of an earthquake is a very important quantity, because decisions can be made for mitigation planning in a financial/risk framework. Economic cost includes the cost of direct damage as well as indirect cost, such as from lost business. The economic cost may not always be a loss for a community, but rather a gain, since economic activity may be spurned by the need to rebuild, often with an external supply of funding from governments, insurance companies and charity. However, for this study, only the economic cost of direct damage to buildings and their contents has been quantified.

5.3.2 Casualty

This includes the number of fatalities as well as the number of non-fatal casualties of varying degree, from serious to non-hospitalisation. In this study, only casualties due to building damage are determined. A key determining factor for vulnerability to injuries of deaths due to earthquakes is the population distribution.

Casualty rates depend on population distribution at the time of the earthquake. The population distribution in the study area, according to place of residence and by suburb, is shown in Figure 5.6. This plot is based on 1996 census demographic data, which are shown in Figure 5.7. Where suburb boundaries and census collection districts (CCDs) are not compatible, a judgment has been made of the division of the population (see Appendix G).

In 1999, the Lake Macquarie City Council estimated a population growth in the range of 0.48% to 0.99% per annum until the year 2020. The continual decrease in the average number of people per dwelling, falling from 3.22 to 2.36 from 1971 to 1996 (ABS, 1998), should see the shift of people from older unreinforced masonry to less vulnerable, newer, construction types.

However, the most important factor in relation to casualty risk is the location of people throughout the day. Since people spend at least one third of their lives at home, and nearly as much at work or school, the relative risk of such environments plays an important role. Further work is required to account for all of these factors.

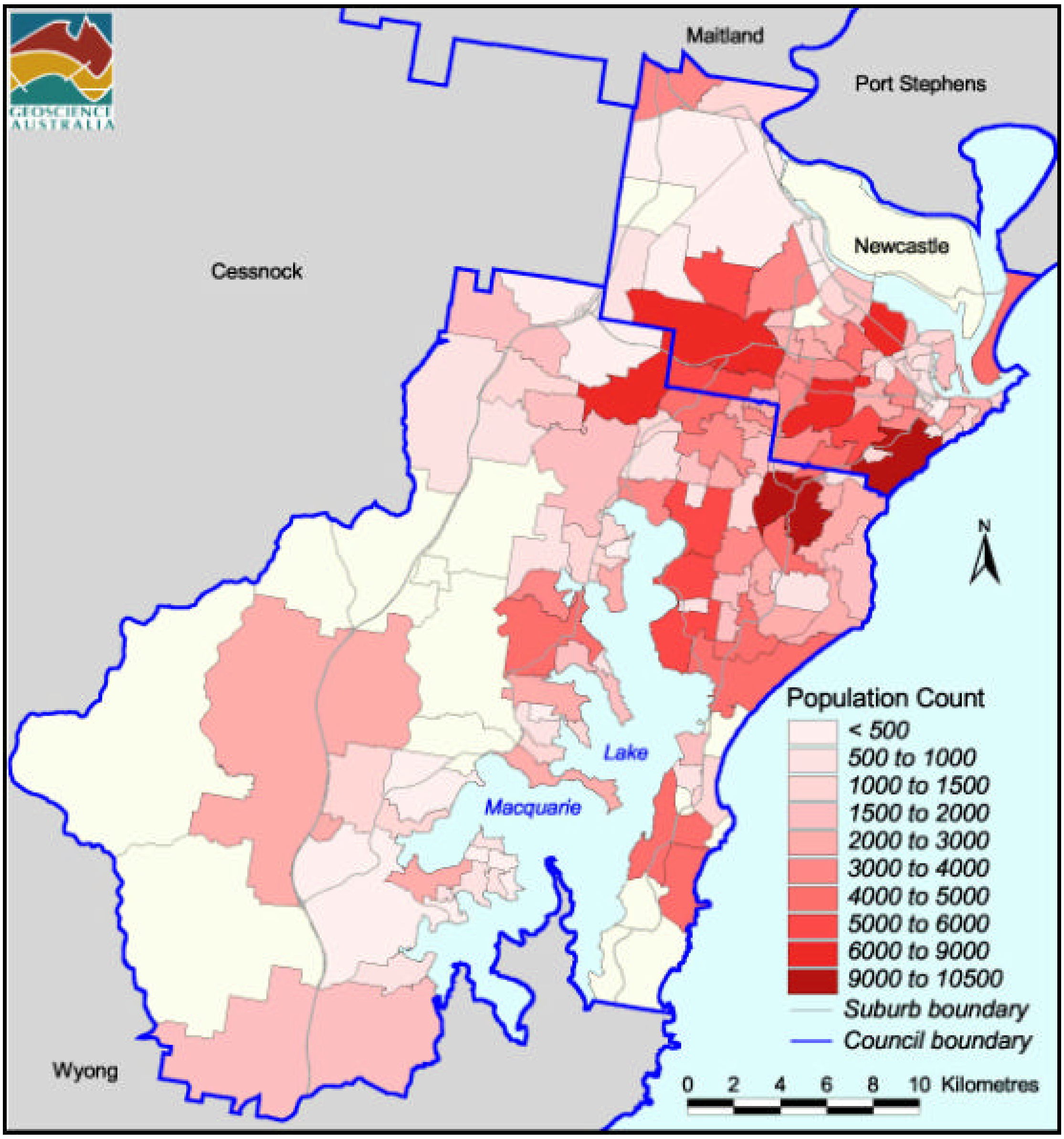

Figure 5.6: Population distribution by suburb

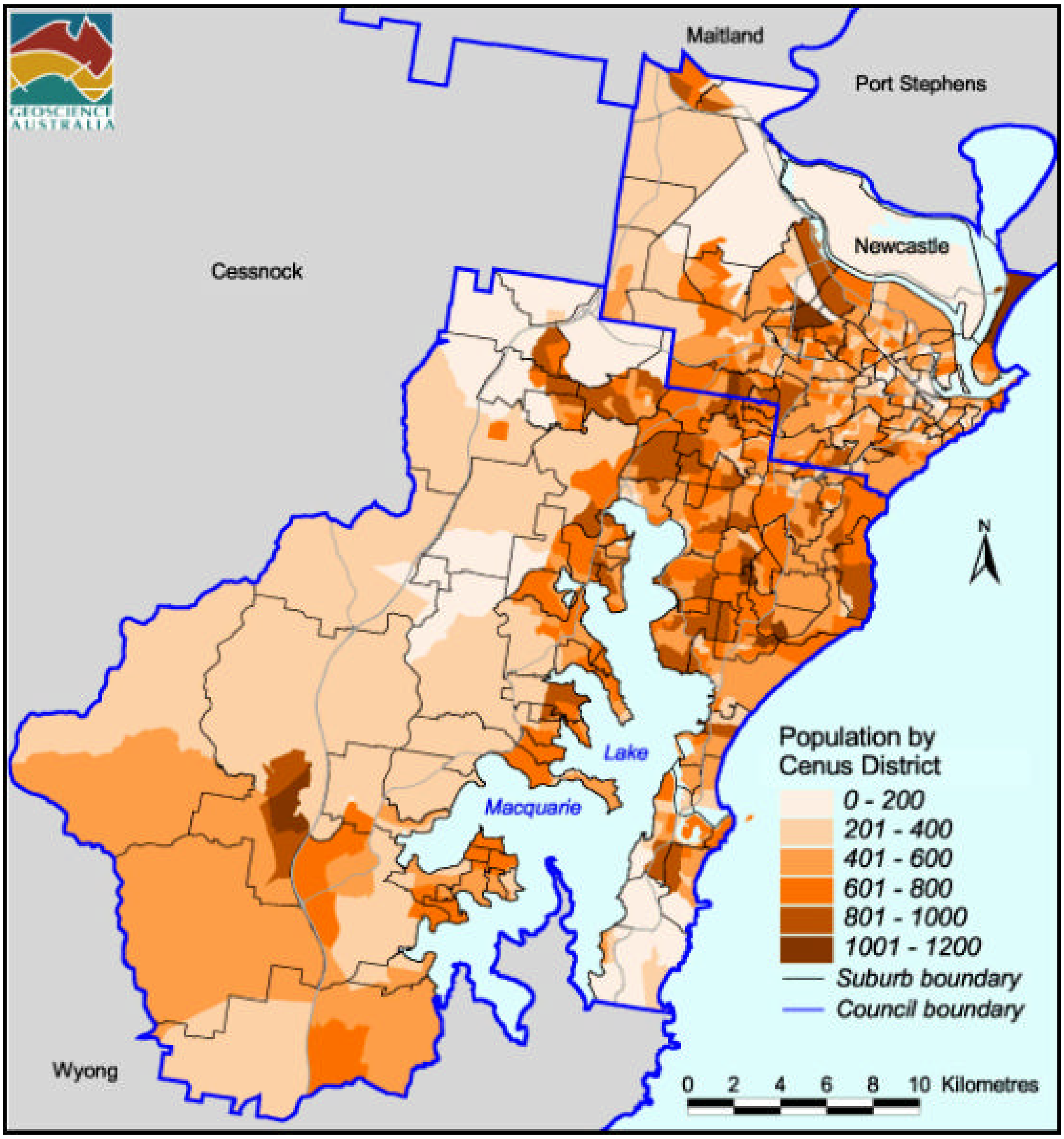

Figure 5.7: Population distribution by census collection district (CCD)

5.3.3 Shelter

The loss of shelter due to building damage is an important consideration. The resilience of the community requires consideration, as does the level of assistance that is socially acceptable and available. Age, economic status, level of insurance, physical capacity, ethnicity and culture may be important factors. However, no analysis of this aspect has been conducted in this study.

5.3.4 Trauma

It is difficult to quantify the trauma caused by an earthquake, with few studies having been performed. The psychological effects can be serious, especially if family and/or friends are killed or maimed. However, no analysis of this aspect has been conducted in this study.

5.3.5 Social Indices

A number of social vulnerability indices are of interest in terms of the ability of the community to recover from an earthquake. These indices account for population age, community support and wealth. While these indices have not been incorporated into any analysis, the distribution of index values as compared to economic risk results is of interest. Factors which have been considered include the distribution of people aged over 65 (Figure 5.8) and under 5 (Figure 5.9), the Index of Socio-Economic Disadvantage (Figure 5.10) and the Index of Economic Resources (Figure 5.11), as defined by the Australian Bureau of Statistics.

The Index of Socio-Economic Disadvantage is a combination of some 20 census statistics including personal income, educational attainment level, unemployment and jobs skill level. The Index has a mean of 1,000 across Australia, and a standard deviation of 100, with lower values indicating greater disadvantage.

The Index of Economic Resources is a combination of some 22 census statistics which reflect the income and expenditure of families, including measures of income, rent and home ownership. This index also has a mean of 1,000 across Australia, and a standard deviation of 100, with lower values indicating lesser economic resource.

Other vulnerability indices may be important in terms of earthquake risk for the community. These may include ethnicity profiles, car ownership levels and levels of unemployment. Considerable further study is required in this area and is an area of active, current research at Geoscience Australia.

It is not clear how social vulnerability indices should be considered in an overall risk assessment, since it depends on the point of view adopted. For example, more vulnerable families and individuals may initially handle a natural disaster with greater difficulty. However, these people may benefit most from the economic activity following the event caused by the influx of money through aid and insurance pay-outs. Another example is, if a person rents rather than owns their house, they do not suffer the financial cost of damage repair to the building, however, they might have to pay for contents damage. The use of vulnerability indices such as these is being activly investigated at Geoscience Australia, however they have not been addressed explicitly in this work.

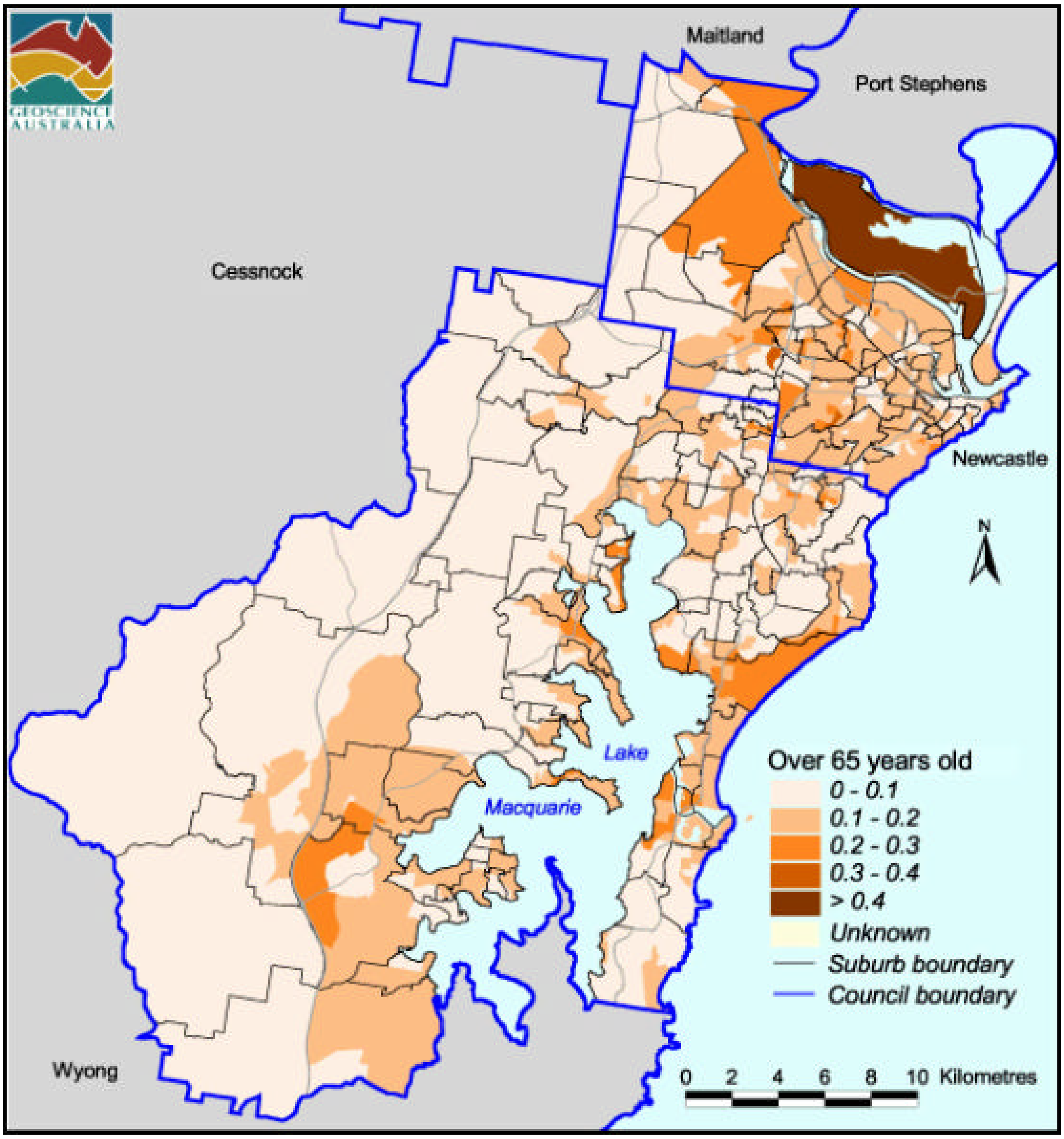

Figure 5.8: Proportion of population over 65 years old by CCD

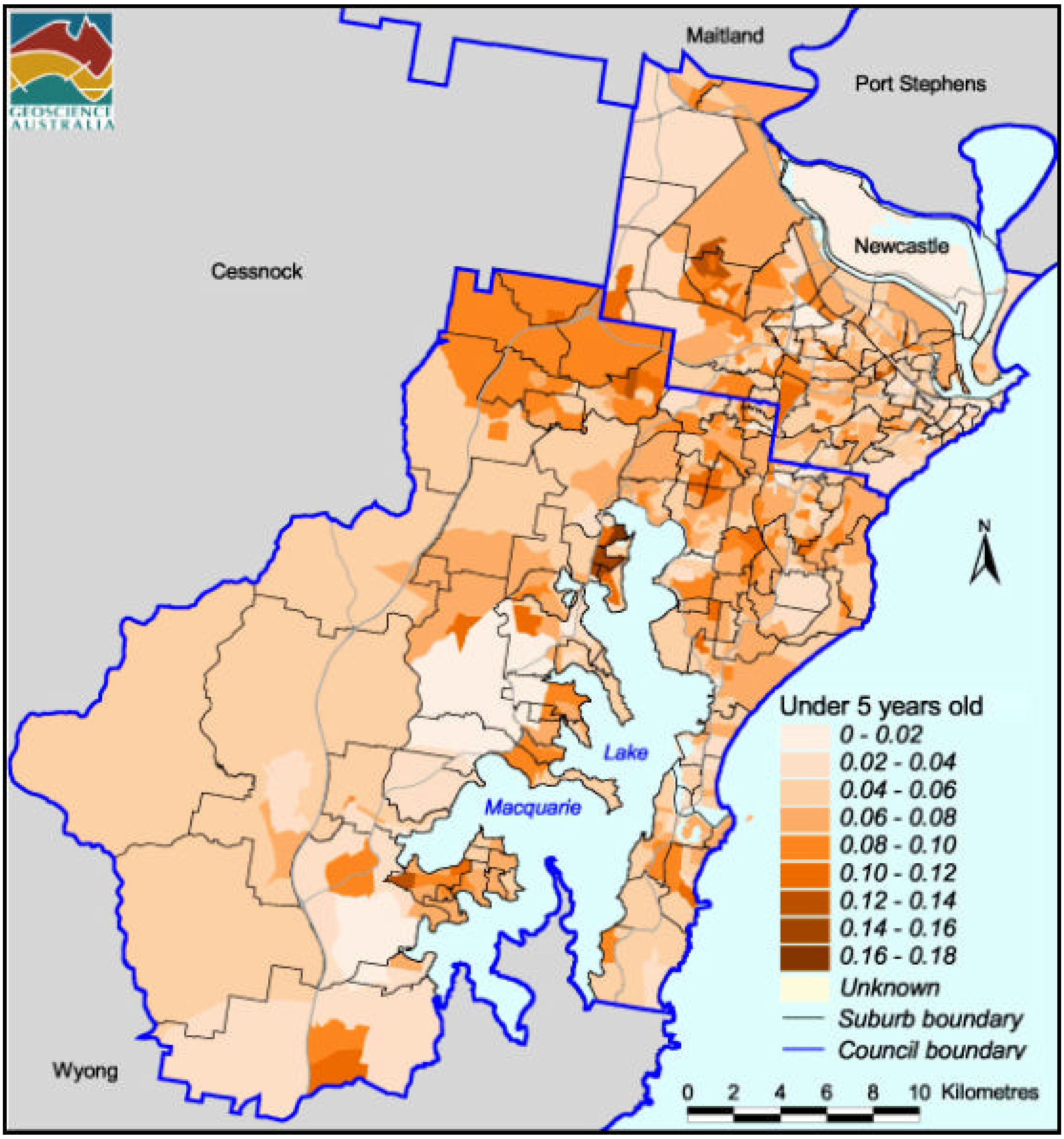

Figure 5.9: Proportion of population under 5 years old by CCD

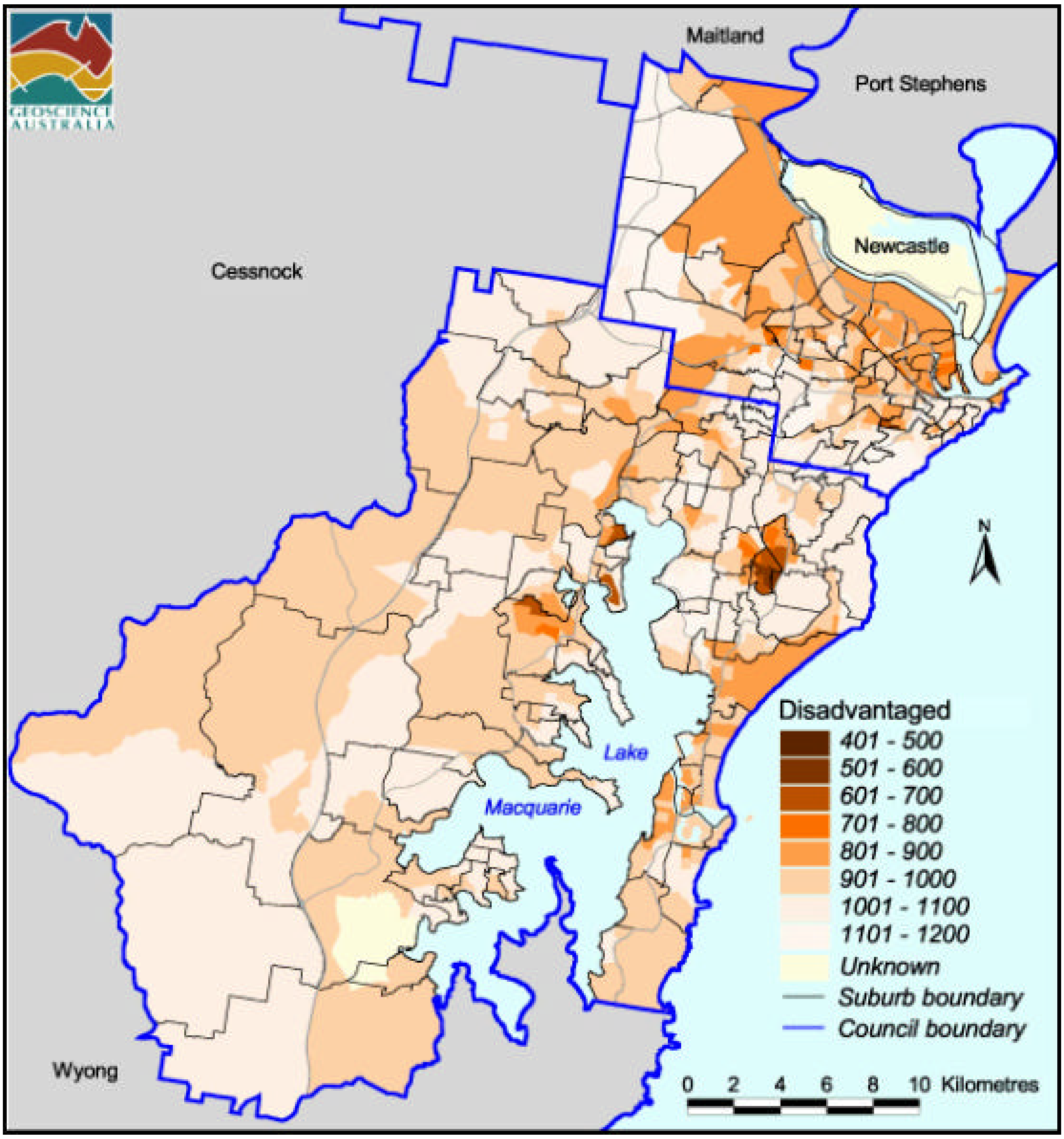

Figure 5.10: The SEIFA (ABS) Index of Socio-Economic Disadvantage

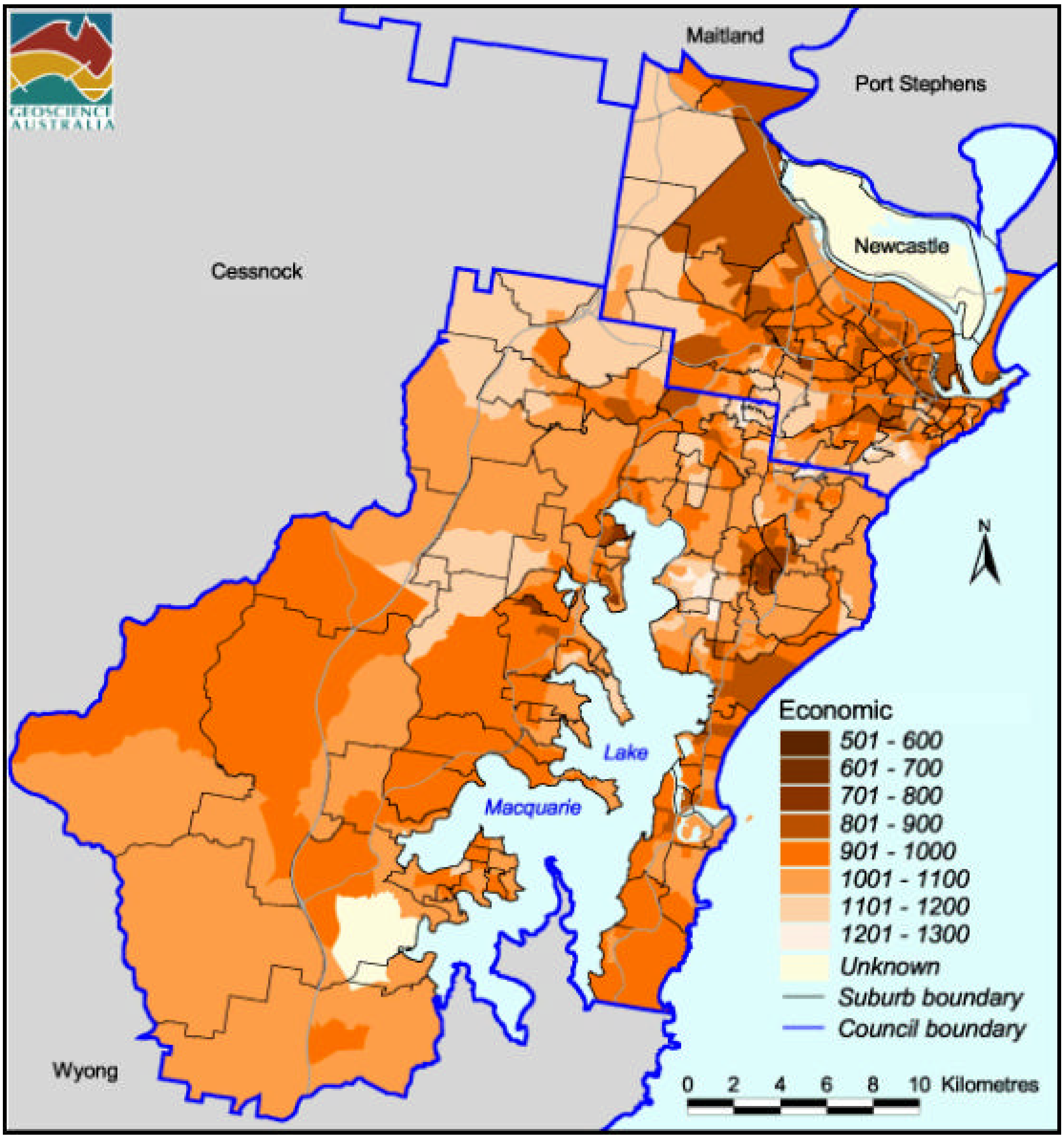

Figure 5.11: The SEIFA (ABS) Index of Economic Resources

5.4 Elements at Risk - Lifelines

Lifelines are networks that allow a community to function. An alternative definition could be “infrastructure”. Lifelines include transportation and utility networks. The vulnerability of some of the more important ones are discussed here. However, no analysis of the impact on lifelines has been conducted in this study. In Chapter 3, it is mentioned that lifelines experienced minimal disruption for the 1989 Newcastle earthquake. However, it is also noted that many lifelines were on the verge of serious disruption, which could have had a dramatic impact on the region.

5.4.1 Roads

Bridges and elevated sections of road are the most vulnerable components of road networks. Weak supporting piers and bridge abutments are commonly damaged. Road on the ground surface is generally unaffected, except close to earthquake fault surface ruptures, on slopes susceptible to earthquake triggered landslides or on soils subject to liquefaction and densification. Tunnels have historically performed well during earthquakes.

The Newcastle and Lake Macquarie region has numerous bridges which are critical for local and interstate transport. Other than these bridges, the road network is fairly redundant, as can be seen in Figure 5.12. The risk of death from bridge failure is considered to be low.

5.4.2 Rail

Railway lines are generally affected in a similar manner to roads, although rail operation is far more vulnerable to misalignment of tracks. Newcastle has an important rail connection to Sydney, which if damaged could cause significant disruption. The rail network is shown in Figure 5.12.

5.4.3 Sea Transport

Ports are particularly vulnerable if located on ground which is prone to liquefaction and lateral ground spreading. Damage to port facilities such as loading cranes may render the port inoperable. Ports in Newcastle service some heavy industrial facilities and hence their disruption could cause significant financial losses.

5.4.4 Air Transport

Generally air transport lifelines are unaffected unless runways are susceptible to damage, which is not likely unless close to a fault. Airport buildings and particularly the control tower may be susceptible to damage and so can affect the operational capacity. The study area is serviced by airports which actually lie outside the bounds of the study region. Airport disruption is considered to be a low risk.

5.4.5 Electricity

Electricity is perhaps the most important lifeline since nearly all other lifelines are dependent upon it. A particularly vulnerable component of the electricity distribution network is electricity substations. Ceramic insulators, which are important in substation operation, are very brittle and highly vulnerable to earthquakes. Only limited data on the location of buildings forming part of the electricity distribution network has been collected for this study, as shown in Figure 5.15.

5.4.6 Water and Sewerage

Dams, reservoirs and tanks have the potential for serious damage; however, historically they have performed well in earthquakes. Pipes are susceptible to damage, particularly if close to the earthquake fault and constructed of brittle material. The water and sewerage networks for Newcastle and Lake Macquarie are shown in Figure 5.13 and Figure 5.14 respectively. These figures demonstrate that the networks have a greater level of redundancy in the inner Newcastle area than in Lake Macquarie and outer-lying suburbs and townships.

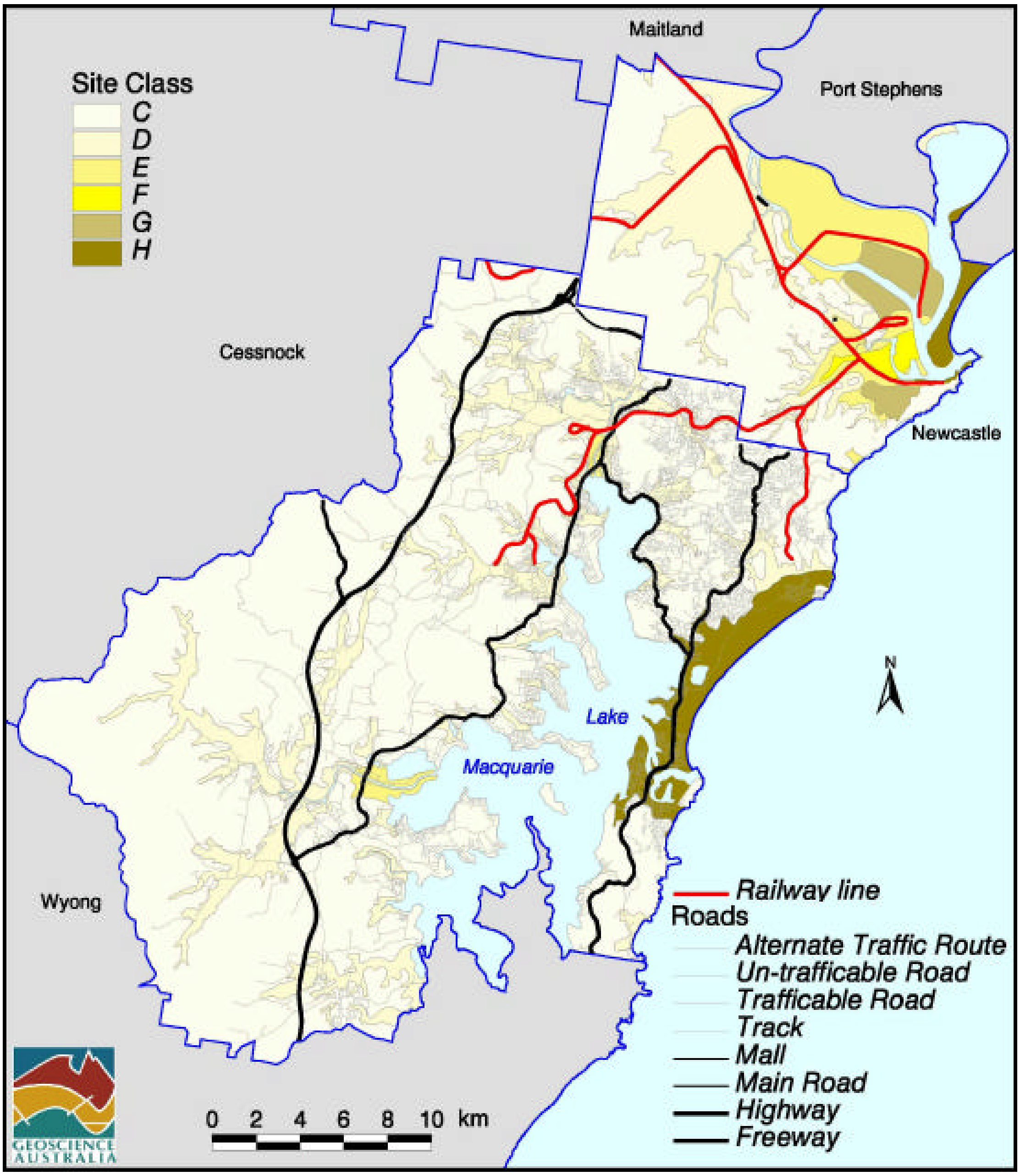

Figure 5.12: Road and rail networks for Newcastle and Lake Macquarie

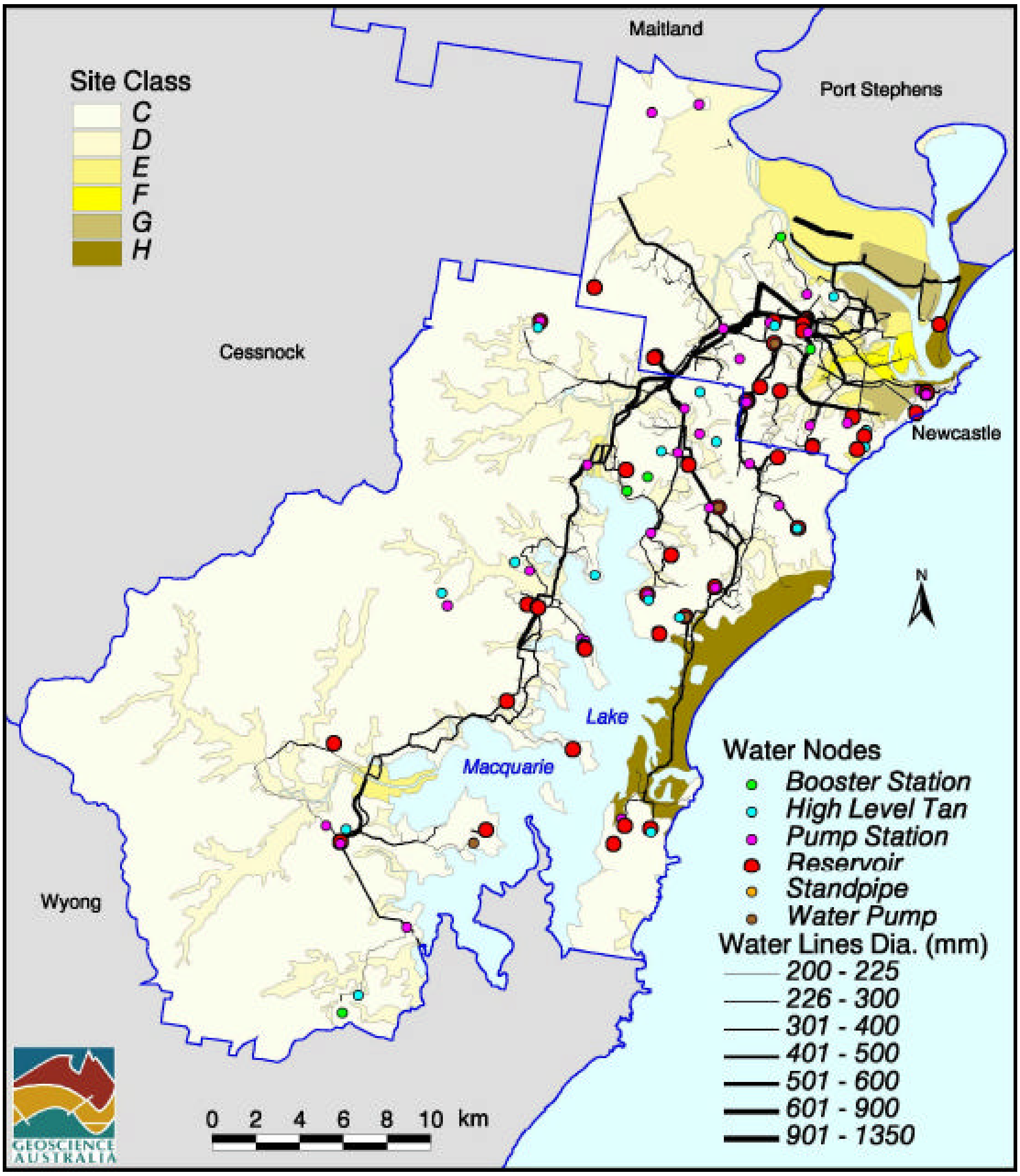

Figure 5.13: Water network for Newcastle and Lake Macquarie

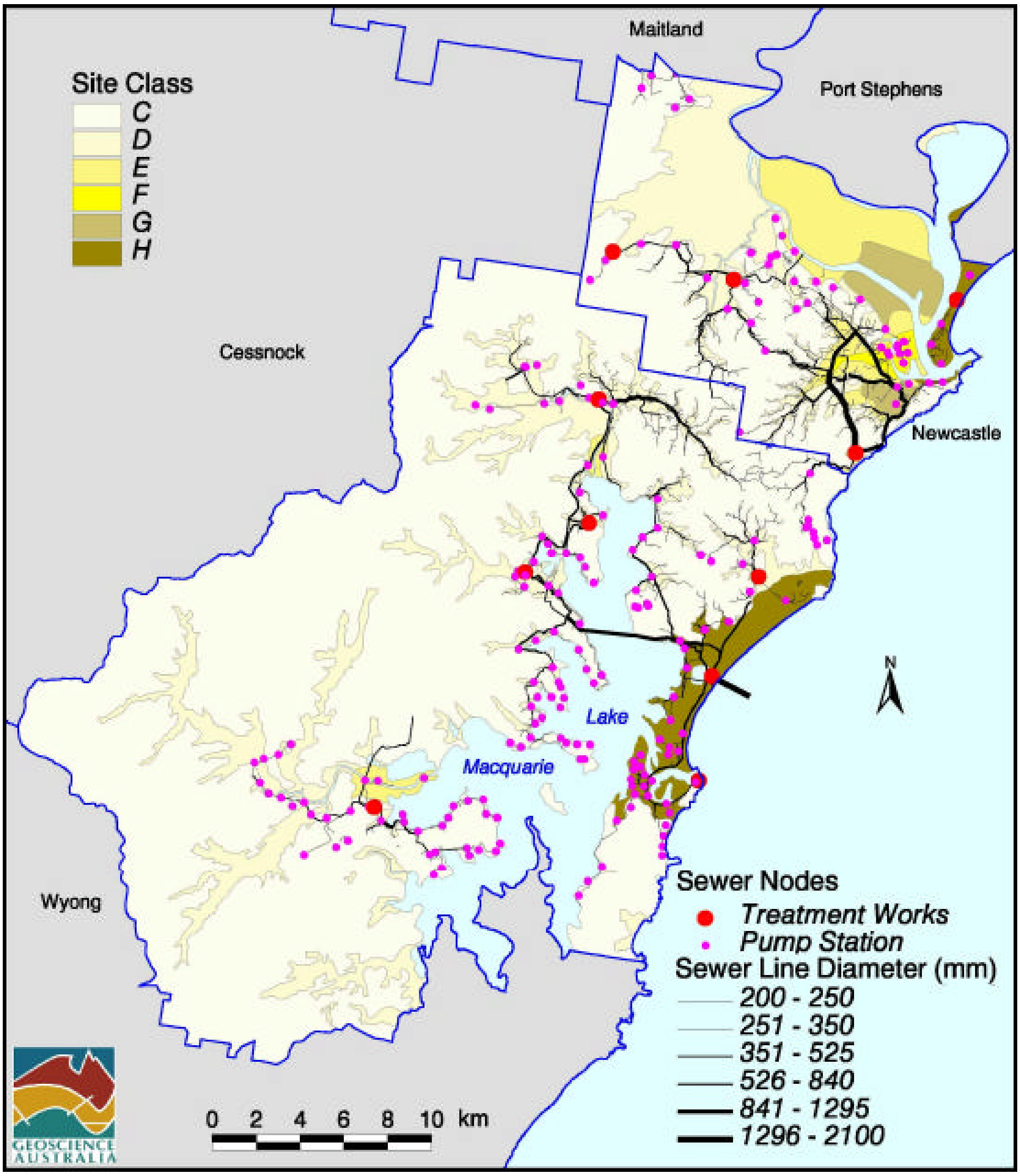

Figure 5.14: Sewerage network in Newcastle and Lake Macquarie

5.4.7 Gas and Other Fuels

Pipeline damage from earthquakes is generally less likely for these lifelines as they are usually constructed of ductile materials. However, any type of pipe which crosses a fault is likely to rupture, and in this case the consequences can be explosive and harmful to the environment. Gas pipelines and fuel facilities are expected to only present local risks of low probability. Only limited data on the location of buildings forming part of the gas distribution network has been collected for this study, as shown in Figure 5.15.

5.4.8 Communication

Communication lifelines are susceptible to damage generally only if the buildings which house telephone exchanges, or support mobile telephone transceivers or satellite dishes, etc. are susceptible to damage. These types of networks are often highly redundant as they are in the study region. Only limited data on the location of buildings forming part of the telecommunication network has been collected for this study, as shown in Figure 5.15.

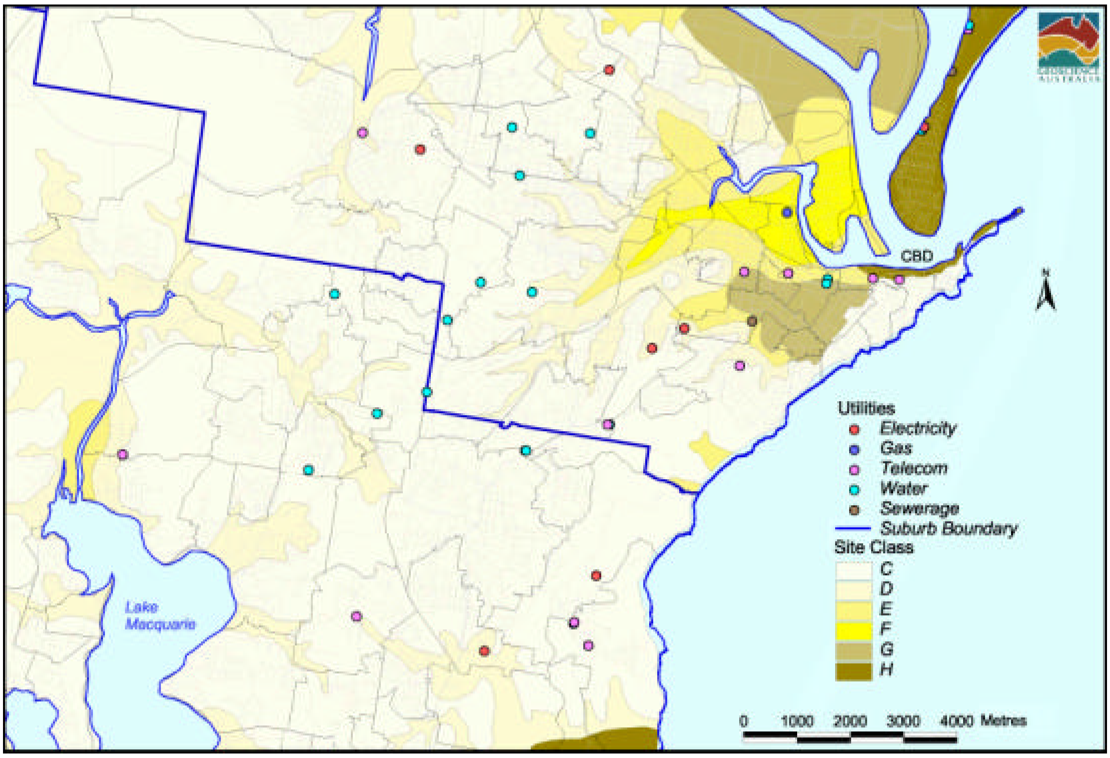

Figure 5.15: Surveyed lifelines in Newcastle and Lake Macquarie

5.5 Collected Statistics

Some statistics have been compiled for road, rail, water and sewerage networks.

5.5.1 Roads

Statistics of the road network are given in Table 5-2. It is clear that for both council areas, a significant amount of road lies upon significant amounts of regolith (site classes E, F, and G). This is the case, irrespective of the road function. While roads may be susceptible to damage from earthquake fault surface rupturing, liquefaction, densification and earthquake induced landslide the risk is not expected to be significant. However, critical bottlenecks in the network, such as bridges, warrant further detailed investigation for the risk to the road network to be properly addressed.

Table 5-2: Road network statistics

Road length (m)		Site Class						
Network[17]	Road type	C	D	E	F	G	H	Undefined[18]
Newcastle	Alternate Traffic Route	67,021	22,727	17,240	5,102	6,283	8,466	0
	Freeway	29635	0	0	0	0	0	0
	Highway	76,431	28,431	10,195	4,864	8,046	657	0
	Main Road	377	0	0	0	0	0	0
	Mall	222	0	123	0	7	175	0
	Track	17,185	5,700	2,414	319	0	1,688	0
	Trafficable Road	44,7843	97,075	68,044	31,151	55,381	32,781	0
	Un-trafficable Road	7,228	1,419	803	538	0	3	0
Lake Macquarie	Undefined	158,401	10,753	0	0	0		0
	Alternate Traffic Route	183,338	50,842	0	0	0	9,947	0
	Freeway	77,273	11,397	0	0	0	0	0
	Highway	80,154	148,75	3,255	0	0	18,171	0
	Main Road	4,906	0	0	0	0	0	0
	Mall	266	0	0	0	0	0	0
	Track	7,643	2,031	597	0	0	1,784	0
	Trafficable Road	840,778	158,829	14,458	0	0	84,272	492
	Un-trafficable Road	65,141	13,440	74	0	0	5,204	54

5.5.2 Rail

Rail network statistics are given in Table 5-3. It appears that tunnelling only occurs in less hazardous soil types. Bridges are located on soils of medium hazard, and considering that these are engineered structures should pose little risk. Further risk assessment is recommended if the governing bodies are concerned about possible impacts.

[17] *Network statistics are determined on a council area basis, since jurisdiction of the roads is generally upon this basis.*

[18] *Undefined site classes are generally for pipes located on foreshore areas, particularly in the Lake Macquarie area, and for underwater pipes. Such areas have not been given a site class.*

Table 5-3: Rail network statistics

Rail length (m)		Site Class						
Network	Road type	C	D	E	F	G	H	Undefined
Newcastle and Lake Macquarie	Railway	34,567	29,387	13,946	1,483	2,049	1,125	0
	Bridge	0	0	119	0	0	0	0
	Tunnel	1,306	0	0	0	0	0	0

5.5.3 Sea Transport

Lifeline has not been evaluated at this stage due to a lack of information.

5.5.4 Air Transport

Lifeline has not been evaluated at this stage due to a lack of information.

5.5.5 Electricity

Lifeline has not been evaluated at this stage due to a lack of information.

5.5.6 Water and Sewerage

Statistics for the sewerage and water networks, of the number and type of nodal facilities, and the size and length of pipes, according to the site class they are located on and in are presented in Table 5-4 to Table 5-6. It is expected that site classes D, E, F, G and H will be generally more hazardous locations than for site classes C. It appears that a significant number of sewerage nodes and pipes are located on the more hazardous site classes. For the water network, few node facilities are located on the hazardous site classes, although a significant proportion of pipes are located on these hazardous site classes. Critical elements of the networks; reservoirs and treatment plants are generally located on the least hazardous site class – type C. However, there are a few exceptions, and it is perhaps these exceptions which require a prompt and more thorough assessment. Risk is difficult to quantify without information on construction type and quality. Hence, further work is required.

5.5.7 Gas and Other Fuels

Lifeline has not been evaluated at this stage due to a lack of information.

5.5.8 Communication

Lifeline has not been evaluated at this stage due to a lack of information

Table 5-4: Water and sewerage network node statistics

Number of facilities		Site Class						
Network	**Node type**	**C**	**D**	**E**	**F**	**G**	**H**	**Undefined[19]**
Sewerage	Pump stations	102	43	7	8	2	33	0
	Treatment works	7	2	0	0	0	2	0
Water	Pump stations	43	2	0	0	0	1	0
	Water Pumps	30	0	0	0	0	0	0
	Booster stations	6	0	0	0	0	0	0
	Standpipes	0	0	0	0	0	0	0
	High level tanks	20	0	0	0	0	0	0
	Reservoirs	50	0	0	0	0	1	0

[19] *Undefined site classes are generally for nodes located on foreshore areas, particularly in the Lake Macquarie area. Such areas have not been given a site class.*

Table 5-5: Water and sewerage network pipe statistics

Length of pipe (m)		Site Class						
Network	Pipe diameter (mm)	C	D	E	F	G	H	Undefined
Sewerage	200	17,298	5,101	2,228	453	649	1,433	0
	225	118,420	57,535	0	6,143	3,062	20,141	0
	250	13,307	4,810	11,185	32	0	5,573	0
	280	41	0	0	0	0	42	0
	300	52,666	39,482	4,305	1,685	967	10,125	0
	325	5	0	0	0	0	0	0
	350	0	0	0	0	0	0	0
	375	25,528	18,602	2,488	0	0	11,125	17
	400	6,144	8,714	895	100	415	2,827	0
	450	14,821	12,778	3,511	184	319	1,169	0
	500	8,411	7,380	979	0	0	879	652
	525	2,255	7,642	830	268	0	159	0
	600	12,025	16,336	1,239	254	294	3,888	0
	675	790	785	970	0	0	0	0
	700	497	728	22	0	0	0	0
	735	0	0	72	0	303	0	0
	750	12,235	11,704	1,692	0	0	11,738	269
	810	0	0	0	0	0	542	0
	840	65	0	255	0	280	0	0
	900	3,133	1,782	0	0	0	1,608	0
	990	0	345	0	0	0	0	0
	1,050	1,360	1,849	1,778	0	320	0	0
	1,065	185	0	1,006	1,580	0	0	0
	1,140	0	0	304	0	0	0	0
	1,145	0	0	121	52	0	0	0
	1,200	0	360	106	822	2,048	0	0
	1,220	91	0	0	0	0	0	0
	1,295	1,207	0	0	0	0	0	0
	1,450	0	0	292	0	156	0	0
	1,650	0	211	248	148	0	219	0
	1,830	1,823	1,139	291	0	0	0	0
	2,100	63	0	252	0	0	0	0
	9,999	20	0	0	0	0	0	0

Table 5-6: Water and sewerage network pipe statistics (continued)

Length of pipe (m)		Site Class						
Network	Pipe diameter (mm)	C	D	E	F	G	H	Undefined [20]
Water	200	117,366	31,854	5,754	4,894	2,823	11,496	0
	225	93	0	0	0	0	0	0
	250	42,630	9,525	4,534	1,641	1,383	5,217	0
	280	0	0	33	0	0	0	0
	300	38,815	12,775	2,058	823	3,162	1,819	0
	375	71,,927	14,986	8,585	943	5,291	11,667	492
	400	53	0	0	0	0	0	0
	450	1636	560	67	0	5	0	0
	500	45,548	23,742	7,904	0	5,684	92	0
	600	13,631	2,601	2,459	518	401	198	0
	750	12,153	4,232	168	0	0	0	0
	900	6,458	205	15	0	0	0	0
	1050	909	340	2,848	0	0	0	0
	1200	2,563	0	0	0	0	0	0
	1350	3,120	185	0	0	0	0	0

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[20] *Undefined site classes are generally for pipes located on foreshore areas, particularly in the Lake Macquarie area, and for underwater pipes. Such areas have not been given a site class.*

6 EARTHQUAKE RISK (G. FULFORD, T. JONES, J. STEHLE, N. CORBY, D. ROBINSON, J. SCHNEIDER AND T. DHU)

The impact of earthquakes in Newcastle and Lake Macquarie and their associated risk in terms of the economic loss is analysed in this Chapter. An overview of the methodology used to calculate the building damage and the economic loss model is described in Section 6.1. Further technical details of the model can be obtained from the authors of this Chapter at Geoscience Australia. The Newcastle 1989 earthquake is then run as a scenario and compared with data from this event in Section 6.2. Finally, in Section 6.3, a probabilistic risk analysis of future earthquakes in Newcastle and Lake Macquarie, in terms of economic loss from building damage, is done.

6.1 Methodology for Vulnerability and Economic Loss

The probabilistic earthquake risk model, used in this study, is based upon a stratified Monte Carlo simulation. This involves random placement of earthquakes with random magnitudes. Building damage and economic loss modules are used to determine how much a building is damaged and the corresponding replacement costs, due to a given amount of ground shaking. A description of the ground shaking (or hazard) part of the simulation methodology has been given in Chapter 4. A building damage model which inputs to an economic loss model (see Figure 6.1) produces results that are used to analyse the risk of future earthquakes in Newcastle and Lake Macquarie.

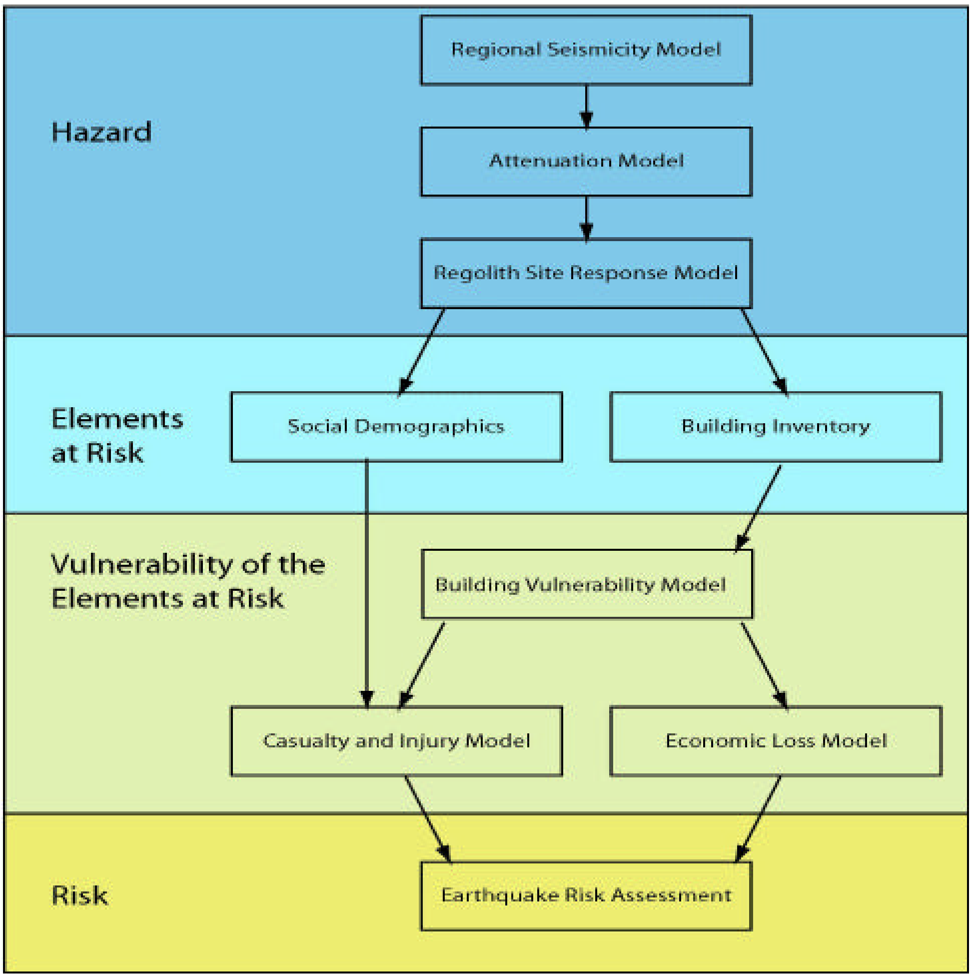


Figure 6.1: Flow-chart describing the earthquake risk assessment process as applied to Newcastle and Lake Macquarie

The overall simulation model includes the following sources of random variability: earthquake location, earthquake magnitude, attenuation, soil amplification, building capacity and building damage states.

The building damage was calculated according to the methodology known as the Capacity Spectrum Method. This methodology had also been used in the HAZUS program of FEMA in the United States (National Institute of Building Sciences, 1999). A good description is given in (Kircher et al., 1997) and in the HAZUS technical manual. The Capacity Spectrum Method determines the displacement and acceleration response of a building due to a given earthquake response spectrum.. It is based upon finding the intersection of the response spectrum (at a given building site) with a building capacity curve (commonly called a push over curve). Each building construction type has a different building capacity curve that depends on certain parameters (e.g. the building natural period, the ductility). The building capacity curve (see Figure 6.2) has a linear part, corresponding to elastic deformation, and a non-linear part corresponding to plastic deformation. The peak response displacement and acceleration for the building is determined by the location on the graph where the building capacity curve intersects the damped demand spectrum (from ground shaking) (see Figure 6.2). The original, 5% damped, elastic response spectrum (due to ground shaking) is further adjusted to account for the additional energy absorbed by the structure of the building through its increased elastic and hysteretic damping.

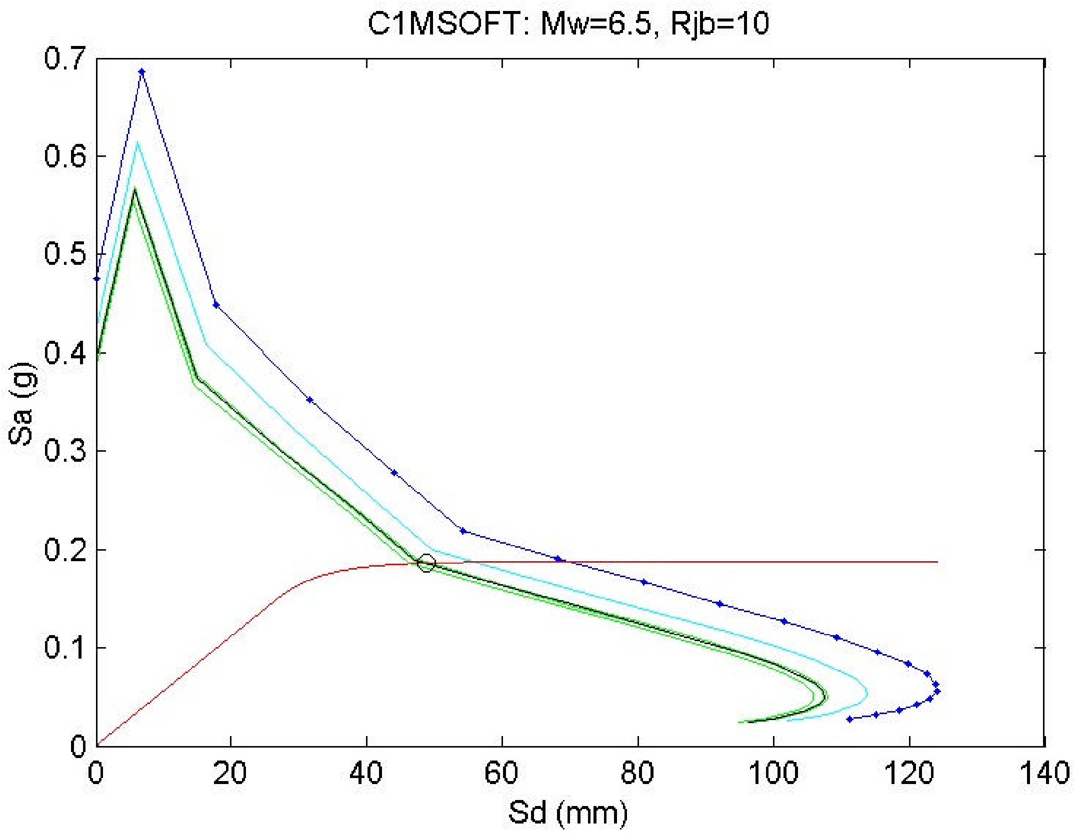


Figure 6.2: The Capacity Spectrum Method for a single earthquake event with moment magnitude 6.5 and Joyner-Boore distance of 10 km, on soft rock, for a reinforced concrete frame (soft storey) building. The building capacity curve (red) intersects with the final damped demand spectra (black) to give the peak displacement and peak acceleration of the building. The original spectral response curve (dark blue) is modified, first by elastic damping (light blue) then by hysteretic damping (green) in an iterative process that converges to the black curve

A key difference in our implementation of the Capacity Spectrum Method to that used by HAZUS is using the full response spectrum for intersecting with the building capacity curve rather than a design spectrum based on only a few building periods. For example, the HAZUS approach only uses periods of 0.3 and 1.0 seconds. Our approach has the advantage that the full shape of the response spectrum and all the available information for the soils amplification factors, at all periods, (see Chapter 4) is taken into account rather than at only two periods.

On 23 February 2001, a workshop was held at the University of Melbourne to assess the applicability of the HAZUS building capacity parameters to Australian building construction. A number of recommendations were made, including the subdivision of some of the HAZUS types into subtypes depending on wall and roof materials (See Table 6-1 for the definitions of the sub-types and Chapter 5 for a discussion of the main HAZUS construction types in Newcastle and Lake Macquarie). It was also recommended that the adjustment of the building parameters be undertaken to better suit buildings constructed according to Australian standards. Note that HAZUS gives parameter values for four different code design levels (High, Moderate, Low and Pre- code). We have assumed all buildings are Pre-code, due to lack of any other information.

Table 6-1 Sub classification of HAZUS building types, for types (W1, timber frame), C1L, C1M, C1H (low, mid and high-rise reinforced concrete frame) and URML, URMM (low and mid-rise unreinforced masonry) as recommended by the workshop (Stehle et al., 2001)

W1MEAN	Timber frame (not otherwise classified)
W1BVTILE	Timber frame, Brick veneer wall, Tiled roof
W1BVMETAL	Timber frame, Brick veneer walls, Metal roof
W1TIMBERTILE	Timber frame, Timber walls, Tiled roof
W1TIMBERMETAL	Timber frame, Timber walls, Metal roof
C1LMEAN	Low-rise reinforced concrete frame (not otherwise classified)
C1LSOFT	Low-rise reinforced concrete frame (soft story)
C1LNOSOFT	Low-rise reinforced concrete frame (non soft story)
C1MMEAN	Mid-rise reinforced concrete frame (not otherwise classified)
C1MSOFT	Mid-rise reinforced concrete frame (soft story)
C1MNOSOFT	Mid-rise reinforced concrete frame (non soft story)
C1HMEAN	High-rise reinforced concrete frame (not otherwise classified)
C1HSOFT	High-rise reinforced concrete frame (soft story)
C1HNOSOFT	High-rise reinforced concrete frame (non soft story)
URMLMEAN	Low-rise unreinforced masonry (not otherwise classified)
URMLTILE	Low-rise unreinforced masonry, Tiled roof
URMLMETAL	Low-rise unreinforced masonry, Metal roof
URMMMEAN	Mid-rise unreinforced masonry, (not otherwise classified)
URMMTILE	Mid- rise unreinforced masonry, Tiled roof
URMMMETAL	Mid- rise unreinforced masonry, Metal roof

Subsequently, Geoscience Australia contracted the University of Melbourne to further investigate the building capacity parameter values for some of the new construction sub-types, to report on their suitability and to provide new values where necessary (Edwards et al., 2002). These new and reviewed values are listed in Table 6-2. This table also shows the values for the URML and URMM types suggested in the workshop, which are different from the original HAZUS parameters. Whilst these parameters were felt to be more appropriate for Australia than the previous HAZUS parameters, they have not been broadly and rigorously reviewed, and this should be a priority for future research in the Australian engineering community.

Table 6-2 New and reviewed building parameters for subdivided HAZUS types. The W1 (timber frame) and C1 (reinforced concrete frame) building parameters have been provided or reviewed by the University of Melbourne (Edwards et al., 2002) whereas the URML, URMM types (unreinforced masonry) are from the workshop (see text). Note that the hysteretic damping coefficients are provided for short (S), medium (M) and long (L) duration earthquakes. Units are dimensionless, except where otherwise indicated.

Building type	Design Strength	Height (feet)	Period (seconds)	Weight fraction	Height fraction	Overstrength (yield)	Overstrength (ultimate)	ductility	Hysteretic damping (S)	Hysteretic damping (M)	Hysteretic damping (L)	Elastic damping
W1MEAN	0.077	13	0.275	0.9	0.7	1.75	2	7	0.001	0.001	0.001	0.08
W1BVTILE	0.063	13	0.32	0.9	0.7	1.75	2	7	0.001	0.001	0.001	0.08
W1BVMETAL	0.082	13	0.28	0.9	0.7	1.75	2	7	0.001	0.001	0.001	0.08
W1TIMBERTILE	0.069	13	0.3	0.9	0.7	1.75	2	7	0.001	0.001	0.001	0.08
W1TIMBERMETAL	0.094	13	0.26	0.9	0.7	1.75	2	7	0.001	0.001	0.001	0.08
C1LMEAN	0.2	20	0.45	0.975	0.795	1.5	1.38	3.75	0.12	0.09	0.09	0.07
C1LSOFT	0.2	20	0.45	1	0.79	1.5	1.25	3.5	0.12	0.09	0.09	0.07
C1LNOSOFT	0.2	20	0.45	0.95	0.8	1.5	1.5	4	0.12	0.09	0.09	0.07
C1MMEAN	0.1	50	0.85	0.95	0.6	1.5	1.38	2.5	0.105	0.08	0.08	0.07
C1MSOFT	0.1	50	0.85	1	0.55	1.5	1.25	2	0.105	0.08	0.08	0.07
C1MNOSOFT	0.1	50	0.85	0.9	0.65	1.5	1.5	3	0.105	0.08	0.08	0.07
C1HMEAN	0.05	120	1.6	0.925	0.55	1.5	1.38	2	0.095	0.07	0.07	0.07
C1HSOFT	0.05	120	1.6	1	0.5	1.5	1.25	1.5	0.095	0.07	0.07	0.07
C1HNOSOFT	0.05	120	1.6	0.85	0.6	1.5	1.5	2.5	0.095	0.07	0.07	0.07
URMLMEAN	0.15	15	0.15	0.75	0.75	1.5	2	2	0.001	0.001	0.001	0.05
URMLTILE	0.15	15	0.15	0.75	0.75	1.5	2	2	0.001	0.001	0.001	0.05
URMLMETAL	0.2	15	0.13	0.75	0.75	1.5	2	2	0.001	0.001	0.001	0.05
URMMMEAN	0.1	35	0.28	0.75	0.75	1.5	2	2	0.001	0.001	0.001	0.05
URMMTILE	0.1	35	0.28	0.75	0.75	1.5	2	2	0.001	0.001	0.001	0.05
URMMMETAL	0.15	35	0.23	0.75	0.75	1.5	2	2	0.001	0.001	0.001	0.05

An inventory of over 6,300 buildings was compiled (see Chapter 5) and used in the simulation. Residential type buildings were multiplied by a suitable survey factor to approximate the total number of residential buildings in Newcastle and Lake Macquarie.

The peak displacement and acceleration of a particular building was used to determine various damage states that the building falls into. There are different types of damage: structural damage, corresponding to damage to the building frame, foundations and walls; and non-structural damage, corresponding to damage to partitions, ceilings and cladding. Non-structural damage is divided into drift sensitive (displacement sensitive) and acceleration sensitive components. For each of these three types of damage, there are five possible damage states: None, Slight, Moderate, Extensive and Complete. These are defined in the HAZUS technical manual for each building construction type. The damage states are determined by thresholds, which are defined for each building construction type. For drift-sensitive damage the thresholds are obtained from drift ratios. The workshop also recommended that the values for drift ratios for non-structural damage were changed from the standard HAZUS ratios (see Table 6-3) and also that different values be used for residential and non-residential buildings.

Table 6-3: Drift ratios used to define median fragility curves for non-structural drift-sensitive damage. These values were recommended by the Engineers workshop held at the University of Melbourne

Damage state	Slight	Moderate	Extensive	Complete
non-residential	0.004	0.008	0.02	0.03
residential	0.001	0.008	0.015	0.025

6.1.1 Incorporating Variability in the Building Vulnerability Models

The HAZUS methodology uses fragility curves to determine the probability of a building being in a given damage state, given the peak displacement (or peak acceleration, in the case of acceleration sensitive damage). In HAZUS there are 12 fragility curves for each building construction type corresponding to the four damage states for each of the three types of damage (structural, non-structural drift sensitive and non-structural acceleration sensitive). The HAZUS approach only crudely takes account of the various uncertainties contributing to the ground shaking and is more suited to a scenario-based approach than the full probabilistic approach adopted in this report. We have adopted a modified approach where, in our Monte Carlo-like simulation, we generate a separate random ground motion for each earthquake. For each sampled building site a random building capacity curve is chosen from a lognormal distribution with given median curve (according to building construction type) and a variability parameter[21] of 0.3, as used by HAZUS.

The fragility curves include the variability for being in the given damage state independent of ground shaking or building type. These are chosen from a cumulative lognormal distribution with variability parameters 0.4, 0.5 and 0.6 for structural damage, non-structural damage (drift sensitive) and non-structural damage (acceleration sensitive), respectively. This study has used the values recommended by HAZUS.

6.1.2 Economic Loss Model

An important indicator of the severity of an earthquake on a community is the economic cost. We have taken a simplistic approach by including only the direct costs of replacement or repair to buildings and their contents.

The method used to determine economic impact of direct damage is based on that used by HAZUS (National Institute of Building Science, 1999) which was based upon U.S. data (the Means Square Foot Cost 1994, for Residential, Commercial, Industrial and Institutional Buildings). Buildings are classified in usage types where the costs of replacement (per square metre) are specified, together with the value of the contents. In Table 6-4 a description of the HAZUS usage types is given.

The HAZUS methodology includes a Regional Cost Modifier, which is used to scale all of the cost estimates to account for the variation in construction costs in different locations. To adapt the methodology for Newcastle and Lake Macquarie, the value of the Regional Cost Modifier is determined by assuming the total replacement cost for a normal residential building is AUD 1,000 per square metre.

Table 6-5 lists the total building replacement costs per square metre (with, and without contents) for each of the HAZUS usage types, which have been used in Newcastle and Lake Macquarie. The Regional Cost Modifier has been included, and the values are for Australian dollars, in 2002. Total building replacement cost is also sub-divided into costs for the structure, the drift sensitive non-structural components and the acceleration sensitive non-structural components. Note that some particular building usage types (e.g. universities, type EDU2; hospitals, type COM6) have contents that are more valuable than the building itself, whereas for residential types the contents comprise 50% of the value of the building. This value is quoted by HAZUS, and may be too high for Australian properties. Nevertheless, this is the only published value that the authors were aware of at the time of this study.

For structural and non-structural drift sensitive components it is assumed (following HAZUS) that complete damage corresponds to 100% of the total replacement value of that component of the building with extensive

[21] *For a random variable, with a lognormal distribution, the* variability parameter *is defined as the standard deviation of the natural logarithm of the random variable.*

damage to 50%, moderate damage to 10% and slight damage to 2%. For non-structural damage (acceleration sensitive) the ratios are 100% for complete damage, 30% for extensive damage, 10% for moderate damage and 2% for slight damage. For the replacement value for contents the ratios are 50% for complete damage, 25% for extensive damage, 5% for moderate damage and 1% for slight damage. These figures are based on the assumption that half the value of the contents can be salvaged after an earthquake. It is not clear whether this assumption, based on U.S. data, is accurate for Australia and it may be more appropriate to use a larger value (possibly 100%). Further study of existing data is necessary.

By multiplying the probabilities of being in the various damage state by the replacement costs for that damage state the economic cost for each of the four building components (structural, non-structural drift sensitive, non-structural acceleration sensitive, contents) is obtained. The total economic loss, for a single earthquake and a single building site, is the sum of these four quantities.

To obtain the total aggregated loss across Newcastle and Lake Macquarie (for a single earthquake) the loss for a single building site is multiplied by the appropriate survey factor (see Chapter 5) and summed over all the sites in the building inventory.

For very small levels of ground shaking (pga < 0.05 g) it is assumed that no measurable damage occurs, and hence the economic loss is set to $0. In addition to this, only earthquakes with moment magnitudes greater than 4.5 are considered capable of causing measurable damage.

Table 6-4: Description of HAZUS usage types used for economic loss calculations for buildings in Newcastle and Lake Macquarie

Usage Type	Description	Example
RES1	Single Family Dwelling	Detached House
RES2	Mobile Home	Mobile Home
RES3	Multi Family Dwelling	Apartment/Condominium
RES4	Temporary Lodging	Hotel/Motel
RES6	Nursing Home	
COM1	Retail Trade	Store
COM4	Professional/Technical	Offices
COM6	Hospital	
COM7	Medical Office/Clinic	Offices
COM8	Entertainment & Recreation	Restaurants/Bars
IND1	Heavy	Factory
IND2	Light	Factory
IND3	Food/Drugs/Chemicals	Factory
REL	Church	
GOV1	General Services	Office
GOV2	Emergency Response	Police/Fire Station
ED1	Schools	
ED2	Colleges/Universities	Does not include group housing

Table 6-5 Approximate replacement costs per square metre for building components for the subset of the HAZUS usage types in the Newcastle and Lake Macquarie building inventory. We have also added two further types (RES1tm, RES1db), corresponding to residential timber walled houses and residential double brick houses. The values are costs per square metre expressed in Australian dollars for the year 2002, they have been normalised relative to the RES1 building value of $1,000 m^{-2}

Usage type	Ex-contents value (per square metre)	Structural	Non-structural (drift sensitive)	Non-structural (acceleration sensitive)	Contents value (%)	Total value of building (per square metre)
RES1	1,000	234	500	266	50	1,500
RES2	703	172	266	266	50	1,055
RES3	1,250	172	531	547	50	1,875
RES4	1,266	172	547	547	50	1,898
RES6	1,187	219	484	484	50	1,781
COM1	797	234	219	344	100	1,594
COM4	1,141	219	375	547	100	2,281
COM6	1,891	266	656	969	150	4,727
COM7	1,406	203	484	719	150	3,516
COM8	1,578	156	562	859	100	3,156
IND1	797	125	94	578	150	1,992
IND2	797	125	94	578	150	1,992
IND3	797	125	94	578	150	1,992
REL1	1,344	266	437	641	100	2,687
GOV1	1,047	187	344	516	100	2,094
GOV2	1,734	266	594	875	150	4,336
EDU1	1,156	219	562	375	100	2,312
EDU2	1,562	172	937	453	150	3,906
RES1(db)	1,100	258	550	292	50	1,650
RES1(tm)	850	199	425	226	50	1,275

6.1.3 Casualty Modelling

The casualty model estimates casualties caused directly from damage to buildings only. Excluded are those due to infrastructure collapse (e.g. bridges, as well as indirect casualties such as heart attacks, psychological effects or injuries suffered post earthquake (e.g. diseases or due to clean up activities).

Casualties are classified into four levels, according to severity. Severity level 4 corresponds to immediate deaths or mortal injuries. Level 3 corresponds to severe injuries that require hospitalisation and are life threatening. Level 2 corresponds to injuries requiring hospitalisation that are not life threatening whereas Level 1 corresponds to injuries requiring only basic medical aid and not hospitalisation.

The basic casualty model, adopted from HAZUS, is an event tree model that assigns a probability of a building in a given damage state causing an injury of a particular severity level. For buildings in the complete damage state there is also a different probability for a severity level, depending on whether the building structure has collapsed or not. Table 6-6 lists these probabilities for a typical building type in Newcastle and Lake Macquarie. The probabilities for other types of buildings are listed in the HAZUS technical manual. Most of these probabilities are similar, except for unreinforced masonry, for which the values are higher. The overall probability of a certain level of injury in a building, due to a single earthquake event, is then obtained by multiplying the probability of injury by the probability of being in that damage state, and then summing over the four structural damage states. Given the probability of a certain level of injury for a given building due to an earthquake event, the expected number of injuries of that level is obtained by multiplying this probability by the number of people in the building at that time. In the current simulation model this is estimated by distributing the overall population of the city over the buildings according to floor area.

Table 6-6: Probability of an injury occurring, given that the building is in a certain structural damage state. These values are for a W1BVTILE type (low rise, timber frame, brick veneer wall and tiled roof) of building

Damage State	Severity 1	Severity 2	Severity 3	Severity 4
Slight damage	0.05%	0.005%	0%	0%
Moderate damage	0.2%	0.02%	0%	0%
Extensive damage	1%	0.1%	0.001%	0.001%
Complete damage without collapse	5%	1%	0.01%	0.01%
Complete damage with collapse	50%	10%	2%	2%

6.2 The 1989 Newcastle Earthquake

To verify the earthquake risk assessment method and the models used, the 1989 Newcastle earthquake presents a good benchmark. Using information observed from this event, comparisons can be made with model predictions.

6.2.1 Available Data

The Newcastle City damage databases contain considerable detail of the impact of the 1989 Newcastle earthquake. 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 construction 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. Only the damage rating given to each building, which indicates the structural safety of the structure, was recorded systematically. (See Chapter 3 for a map of the buildings classified into damage states). Since these do not match up with the HAZUS damage states, used in the simulation model, we made no attempt to compare these.

The Institution of Engineers report contained estimates of the economic impact caused by the 1989 earthquake (Melchers, 1990). Total economic loss estimates for the region were estimated to be of the order of $1 billion (1990 dollars), with this figure comprising mostly structural and non-structural building damage ($800 million) and contents and business disruption losses ($200 million). Many other estimates of economic loss exist, with figures even as high as $4 billion (BTE, 2001),which include losses due to business interruption.

The report by the Institution of Engineers estimated that the 1989 earthquake directly caused 12 deaths and 100 to 120 serious injuries (Melchers, 1990). Nine people died in the Newcastle Workers Club, and three died as a result of awning and parapet collapse in Beaumont Street, Hamilton. There was one further death caused by the earthquake due to cardiac arrest.

NRMA insurance records, obtained from the Newcastle City Council, are estimated to account for approximately 50% of the residential building claims in the study region. There were approximately 14,000 NRMA claims in total, some as far away as Canberra. The records included, for each claim, the suburb, the value insured, the pay-out and whether the claim was on a brick building, a timber building or on contents. The database was filtered to match the suburbs covered in the study region, reducing the number of claims to approximately 12,000 claims. There was a small number of entries with zero pay-outs. Presumably these corresponded to claims that were made but refused. For the whole study region the NRMA data gave total claims of approximately $97 million (1989 dollars) and total insured value (building plus contents) of $1,056 million (1989 dollars). This gives an estimate of approximately 9.1% of damage. However, this data is a biased sample of building damage loss as it does not include buildings for which claims were not made. The inclusion of buildings for which no claims were made would decrease this estimate of building damage. The percentage of sum paid out for claims, as compared to the total value insured, aggregated by suburb, is spatially displayed in Figure 6.3.

It was difficult to compare the NRMA insurance data directly with the modelled economic losses. First, there was uncertainty as to what percentage of the buildings in the study region were insured by NRMA. It also wasn't simple to ascertain whether owners were underinsured, or if the insurance pay-out for an individual building is a true indication of the actual loss. The records also did not indicate what the excess fees were, but these were probably negligible.

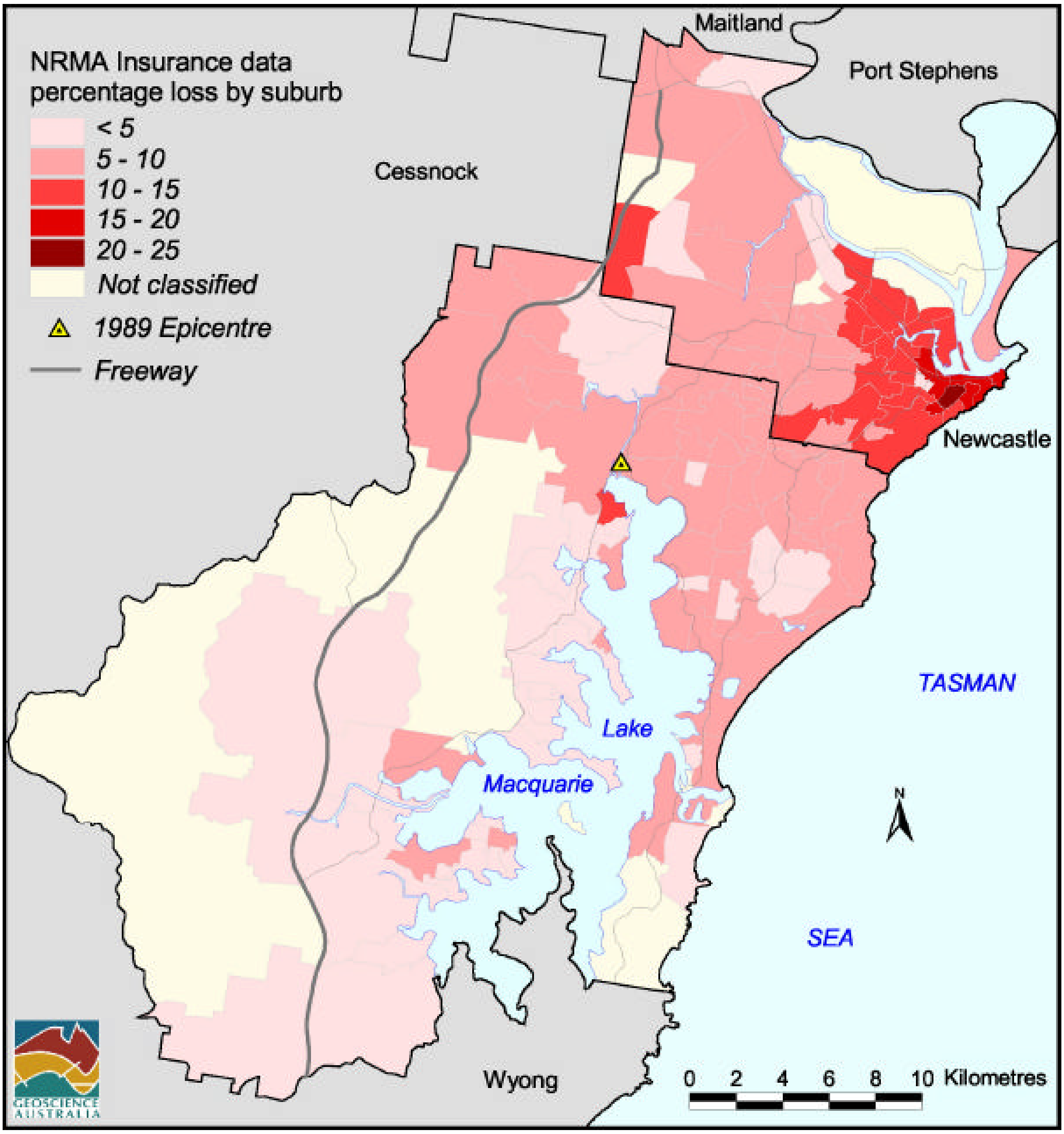


Figure 6.3: NRMA residential insurance pay-out (sum of claims for each suburb as a percentage of the amount insured) for the 1989 earthquake, according to suburb. This includes both building and contents claims

6.2.2 Results for the simulated 1989 Newcastle earthquake

The impact of the 1989 Newcastle earthquake has been modelled using the computer simulation code described earlier in this Chapter and in Chapter 4. A direct comparison of the results with recorded data however is difficult for many reasons. First, the elements at risk have changed due to population growth, and the development, demolition and renovation of buildings. The building inventory, which has been determined by a sampling process near the end of the year 2000, cannot be expected to exactly describe the nature of the inventory at the end of 1989. Buildings that are estimated to have been constructed after 1989 have been omitted from the calculation.

The spatial variability of modelled damage is a random phenomenon, so no two damage patterns can be expected to be exactly the same. The 1989 event could be viewed as a single realisation of a random process, however, we compared the 1989 event to median values in the simulation.

6.2.2.1 Economic losses

Running the simulation for the 1989 earthquake in Newcastle corresponds to fixing the location of the epicentre (or centroid of the rupture) to a position 32.95°S, 151.61°E, and the moment magnitude of the earthquake to 5.35 (based on a magnitude of 5.6 on the Richter scale and converted using the Johnston relationship described in Section 4.2). There is some uncertainty in the position of the epicentre (see Chapter 3) which hasn't been accounted for in this simulation. However, there is still variability in the attenuation, soil amplification and building damage so the result for the estimated overall economic loss for the earthquake is presented as a histogram of 1,000 simulations in Figure 6.4. The dollar estimates have been discounted from 2002 dollars to 1989 dollars.

The median value of the losses estimated from the 1,000 simulations is approximately $1.1 billion (in 1989 dollars), corresponding to a percentage loss of approximately 7.2% of total building value including contents (see Figure 6.4). Taking account of the random nature of attenuation, soil amplification and building damage produced a range of probable values of percent damage of 6.5-8%. As mentioned in Section 6.2.1, the damage data collected after the 1989 Newcastle earthquake has been used to provide estimates of the actual economic loss due to building damage from the earthquake. Melchers (1990) estimated an economic loss of approximately $0.9 billion (1989 dollars), which is slightly lower, but of the same order as our simulated loss of $1.1 billion. Using the NRMA database of claims we estimated an economic loss of 9.1% of total building value which is higher than our simulated result. Our simulated result is consistent with both of the estimates based on recorded data.

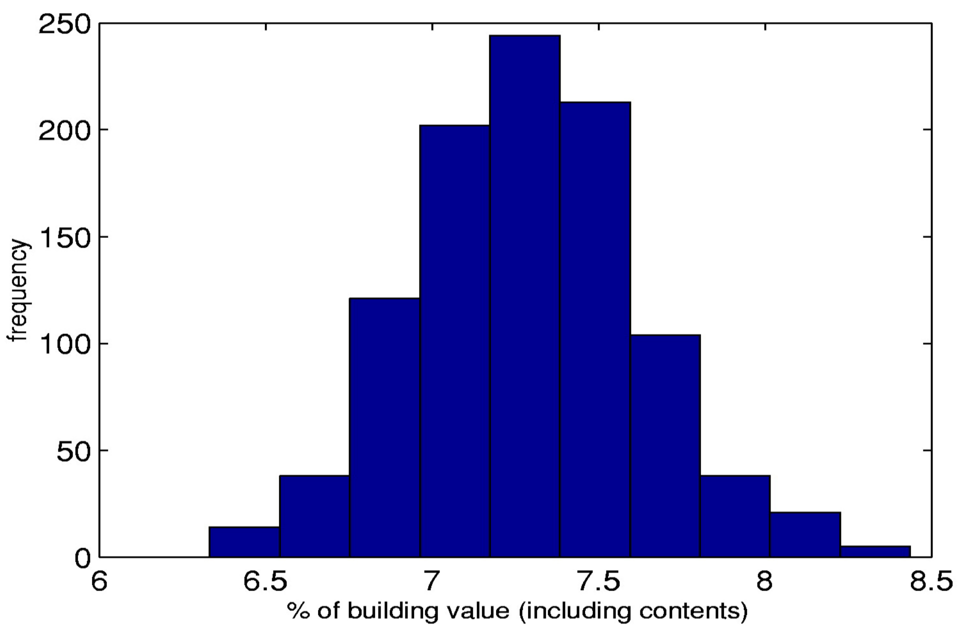


Figure 6.4: Histogram of estimated losses for 1,000 simulations of the 1989 earthquake. Aggregated losses are a percentage of total value of the building stock including contents

In Figure 6.5 a map is shown of the distribution of median values of the simulated economic loss by suburb. Here the total economic loss is calculated for all buildings in each suburb and a loss ratio is calculated by dividing the total economic loss in a suburb by the estimated total value of all buildings (including contents) for that suburb.

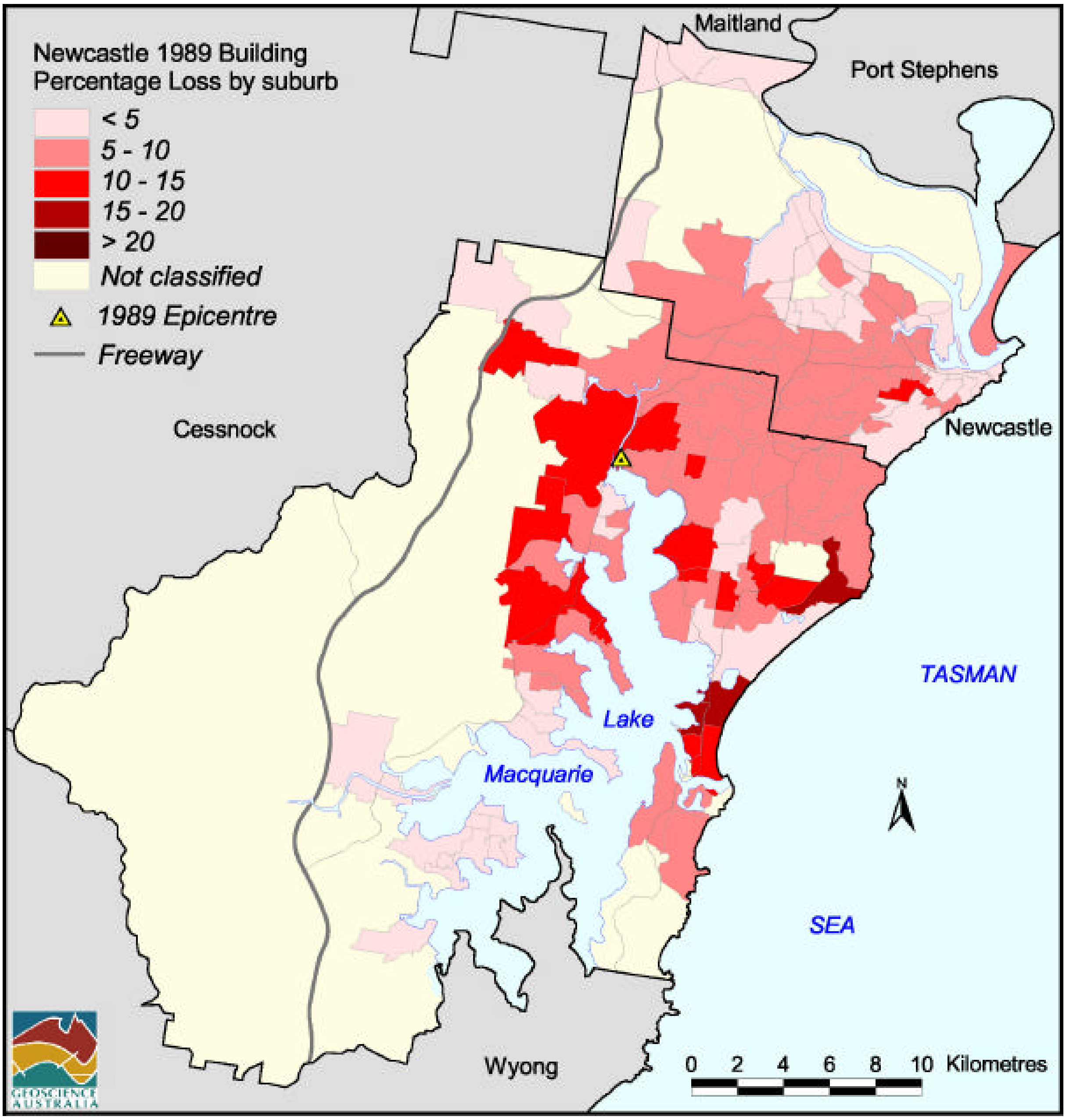


Figure 6.5: Distribution of simulated median losses (as a percentage of total building value plus contents), aggregated by suburb, for the 1989 earthquake

A comparison with the NRMA insurance data (Figure 6.3) indicates the losses are of a similar magnitude, with the main exception of the Newcastle CBD. Our simulated losses tend to have more damage near the earthquake epicentre than was actually recorded. The simulation underestimated the damage in the Newcastle CBD (approximately 20% losses indicated by the NRMA data compared to about 3% for the median result from the simulation). Given that the majority of buildings in the CBD are unreinforced masonry, one possible explanation for the discrepancy could be that the building parameters in the models require further refinement. Many of the buildings in this area are quite old. There is, currently, no provision in the building parameters for increased damage resulting from degradation of building materials over time.

It should be emphasised that the simulation represents a stochastic process and that the 1989 earthquake should be viewed as just one realisation of that process. In Figure 6.6 a map is given for a single realisation of the stochastic simulation. The spatial distribution of losses varies from the median case (by a few percent) although the overall trend is similar.

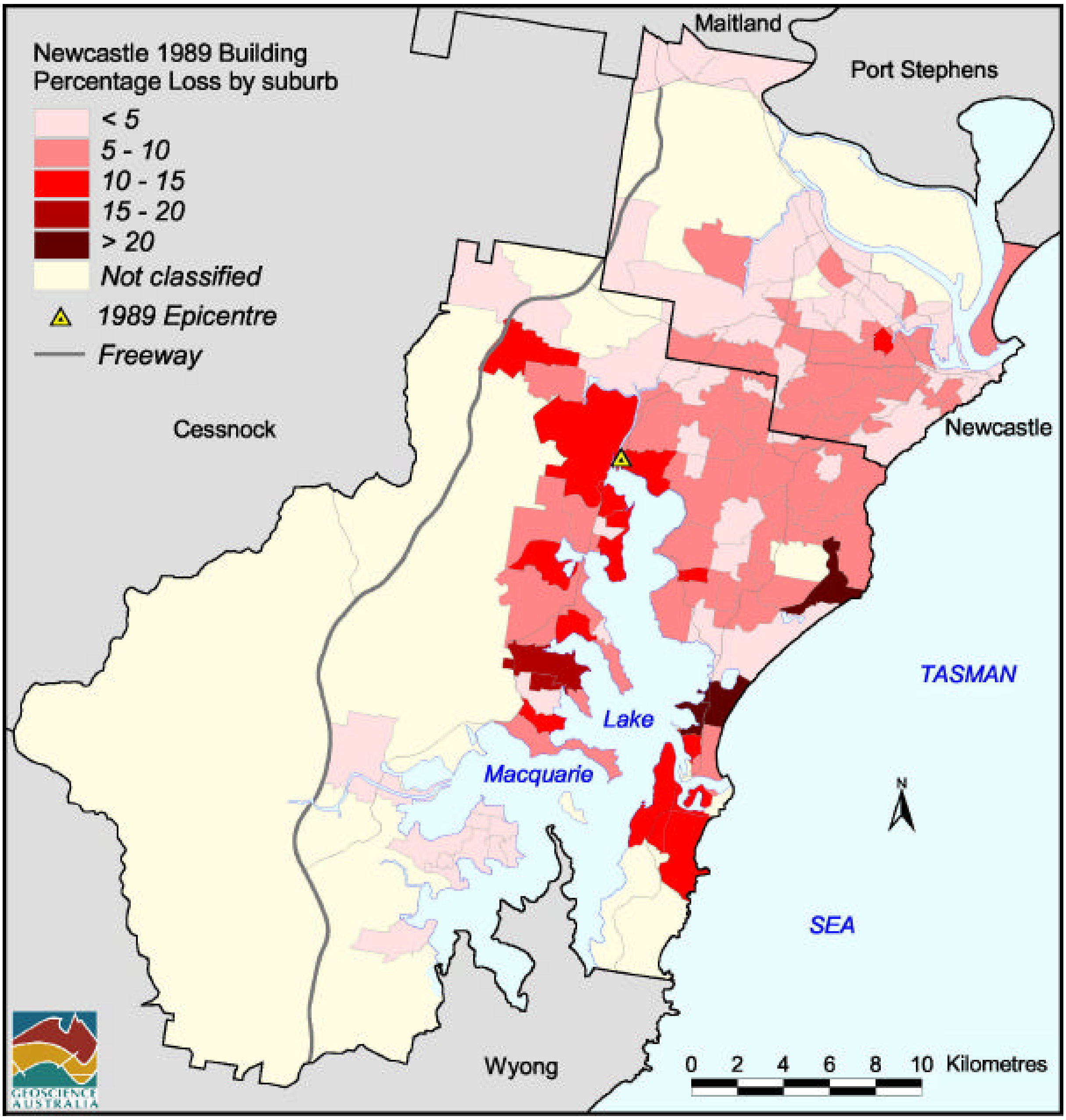


Figure 6.6: Results of a single simulation of the 1989 Newcastle earthquake. Damage ratios are a percentage of total building value plus contents aggregated across each suburb

6.2.2.2 Injuries and casualties

The total number of casualties simulated for the 1989 event can be compared to records of deaths and cases of hospitalisation. It was assumed the population in 1989, for the study region, was approximately 300,000. It was also assumed that the population was evenly distributed according to building floor area, and that 30% of people were outdoors at the time of the earthquake (it occurred mid-morning on a sunny day on 28 December). The simulation model predicted median values of approximately 44 deaths (severity level 4 casualties) and 550 less severe injuries requiring hospitalisation (severity level 2). These values are high compared with the 12 recorded deaths and 100-120 estimated severe injuries (Melchers, 1990). However, given the high levels of uncertainty involved in the assumptions of the population distribution at the time of the earthquake, these values are, at least, within an order of magnitude of the observed casualty figures.

6.2.3 Uncertainties in the Model

The considerable uncertainty in the modelling methods has not yet been fully addressed in attempting a verification of the effects of the 1989 Newcastle earthquake. Neither has the considerable uncertainty in the recorded effects of the 1989 Newcastle earthquake. For example, the effect on simulated economic losses due to the uncertainty in the hypocentral location of the 1989 earthquake could be examined by varying the epicentral location. The full range of economic losses, particularly with regard to lifelines and key facilities, has not been addressed.

The results for economic damage are sensitive to the building parameters used. It is important that further research is undertaken to develop reliable numbers for these parameters for Australian buildings, and compare damage predictions with existing data. In particular, we have less confidence in the parameters for unreinforced masonry buildings, especially old buildings of this type where the mortar will have degraded with age or where poorer quality mortar may have used.

The method for distributing the population according to total floor area of buildings could be improved. One approach would be to have a randomly varying population on a building by building basis which would better account for the high level of variability expected in modelling casualties.

The 1989 Newcastle earthquake presented a unique opportunity to learn about the effects of earthquakes and how Australian communities could be made safer. With regard to this study, it represented an opportunity to verify the modelling techniques adopted. For the impacts quantitatively considered (building damage, economic loss and casualties), this has been performed with as good a match as one could reasonably expect from such a highly uncertain and random process.

The difficulties involved in achieving a close match have been illustrated. A major problem that clouds the ability to verify the results is the lack of systematically and accurately recorded details of earthquake impact. This includes poor constraint on the earthquake source location, inconsistent and incomplete damage surveys and a lack of details regarding economic losses. Hence, it is recommended that future post-disaster data collation efforts be conducted in a more systematic way, with a high degree of detail and accuracy.

Despite some concerns, the models used in this study are able to broadly predict the overall impact of the 1989 Newcastle earthquake. This supports the notion that the adopted models are appropriate for use in this earthquake risk assessment. The results are thought to be more reliable at a scale which encompasses the entire study region, rather than the scale of individual buildings or even suburbs.

6.3 Economic Risk in Newcastle and Lake Macquarie

6.3.1 Overall Impact

In this section we present results of running the simulation with earthquakes distributed randomly in seismic zones with magnitudes determined from a Gutenberg-Richter distribution**,** as discussed in Chapter 4. The possible implications of these results are discussed in detail in Chapter 7.

For each earthquake scenario, the economic damage loss values have been determined for every surveyed building site in the study region. Approximately 1,200 earthquake scenario events were used. Each scenario earthquake had a magnitude, a location and a probability of exceedance. The hazard map calculations in Chapter 4 used 10 times more scenario earthquakes in order to get consistent statistics. For economic loss results that are aggregated across sampled sites (more than 6,000) such a large number of events is not required. A detailed analysis of the minimum required number of earthquakes needed was not conducted here, however, 1,200 events was found to be sufficient.

By considering the impact of all earthquake events on any one or group of buildings sites, an annual probability of exceedance – loss curve can be generated. The probability of a loss level being exceeded and the annualised loss are of particular interest for risk management decision making. These results have been evaluated for the study region as a whole and on a survey site basis, in terms of economic and casualty losses.

A curve showing the estimated economic loss due to building damage for the entire study region is given in Figure 6.7. This curve describes the probability of the study region incurring various minimum levels of economic loss within a single year. Economic loss is expressed as a percentage of the total value of all buildings and their contents in the study region.

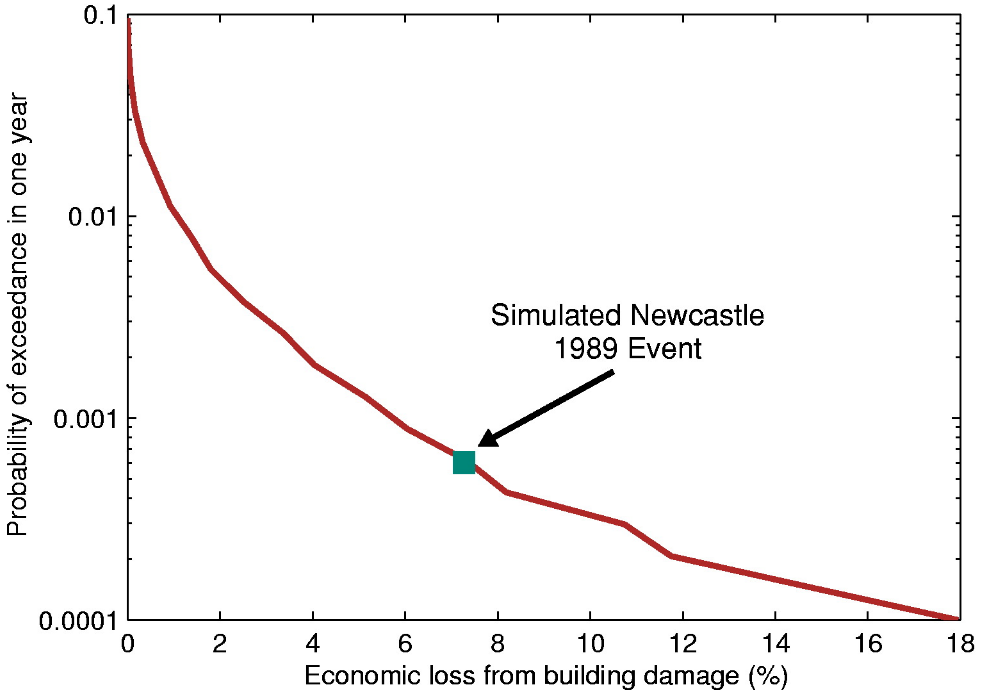


Figure 6.7: Probable maximum loss curve for the Newcastle and Lake Macquarie region

The simulated 1989 Newcastle event had a loss on the order of 7.2% of the total value of the building stock and associated contents (see previous Section). Locating this point on the risk curve suggests that this level of loss has a probability of about 0.0006 of being exceeded in any single year. This annual probability corresponds to a return period of around 1,500 years for the 1989 Newcastle earthquake, and for other events that would have a similar impact on Newcastle and Lake Macquarie.

The integration of the area under the annual probability of exceedance-economic damage loss curve gives the annual expected economic damage loss (or annualised economic loss). This is a useful measure of risk for planning purposes. For example, how much should be spent annually on mitigation efforts such as building improvement, emergency response facilities, insurance premiums, etc. Annualised economic loss can be determined for any one or group of building sites, depending on the interests of the stakeholder. For example, federal and state governments may be interested in the whole study area, local governments in their own local area, and emergency management agencies in their own districts. Also, insurance companies may be interested in their portfolio of sites distributed over the region, and residents might be interested in their own properties. (However, comprehensive risk assessments for individual buildings are best conducted by experienced professionals). Annualised economic loss values are also useful for making comparisons to other hazards, particularly if rankings of impact intensity are dependent on the return period selected. The annualised economic loss for the whole study region, varying according to the maximum return period of events considered, is shown in Figure 6.8.

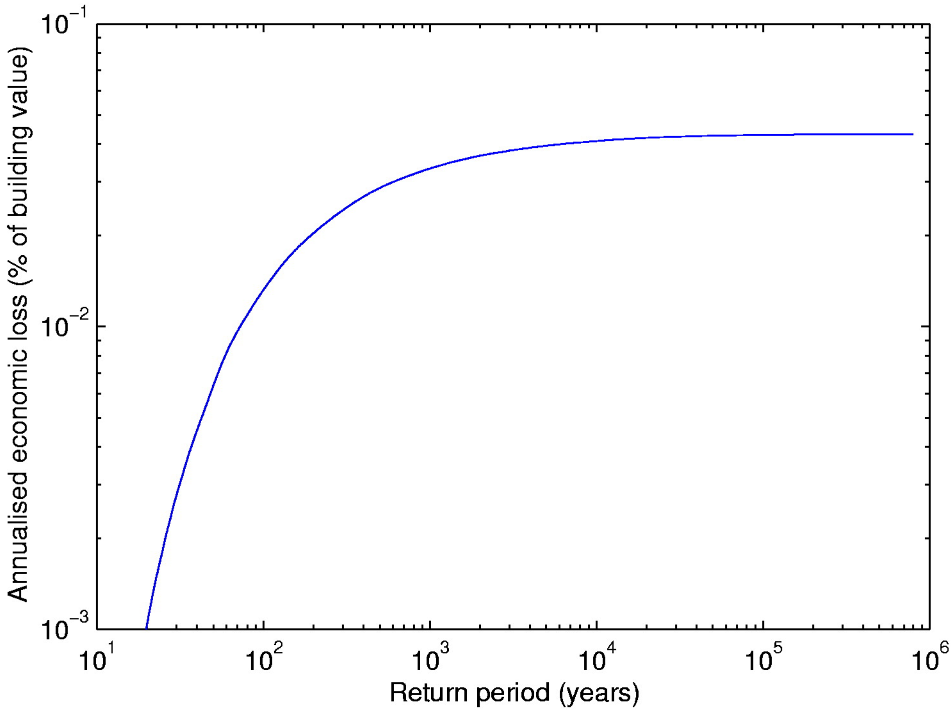


Figure 6.8: Annualised economic loss versus maximum return period considered, for the whole study area

The results of this study suggest that, on average, the Newcastle and Lake Macquarie region will suffer an estimated economic loss of around 0.04% per year. This corresponds to an annualised loss of the order of $11 million per year. This value has been calculated on the basis of the total value of buildings in the study region which is estimated by our models to be approximately $26.5 billion.

The majority of the earthquake risk in the study region is from events that have probabilities of occurrence in the range of 0.02 to 0.001 (return periods of 50-1,000 years). This suggests that the risk to the region is primarily from relatively infrequent events with low or moderate impacts. In contrast, very frequent events will have low impacts, and consequently they pose little risk to Newcastle and Lake Macquarie. Very high impact events could also occur in the region. These events are extremely rare and hence contribute little to the annualised risk, however, should they occur the impact could be catastrophic.

Events with return periods of 500 years or less contribute approximately two thirds of the total annualised losses. A return period of 500 years is similar to a 10% probability of occurrence in 50 years (return period of approximately 475 years) that is described in AS1170.4-1993. The 1989 Newcastle earthquake was estimated to have an impact with a return period of approximately 1,500 years. Events which are less severe than the 1989 earthquake contribute an annualised economic loss of approximately 0.035%, representing around 82% of the total annualised risk. Thus, events like the 1989 earthquake, or even more catastrophic events, make only a small contribution to the earthquake risk in the region.

It is possible to determine the relative contributions to annualised risk from earthquakes of varying magnitudes and distances from each sampled building site. The distance here is the Joyner-Boore distance, which is the closest horizontal distance from the site to the rupture plane of the earthquake (see Chapter 4). In Figure 6.9 a histogram is given for the contribution of overall annual risk for a number of moment magnitude and distance combinations.

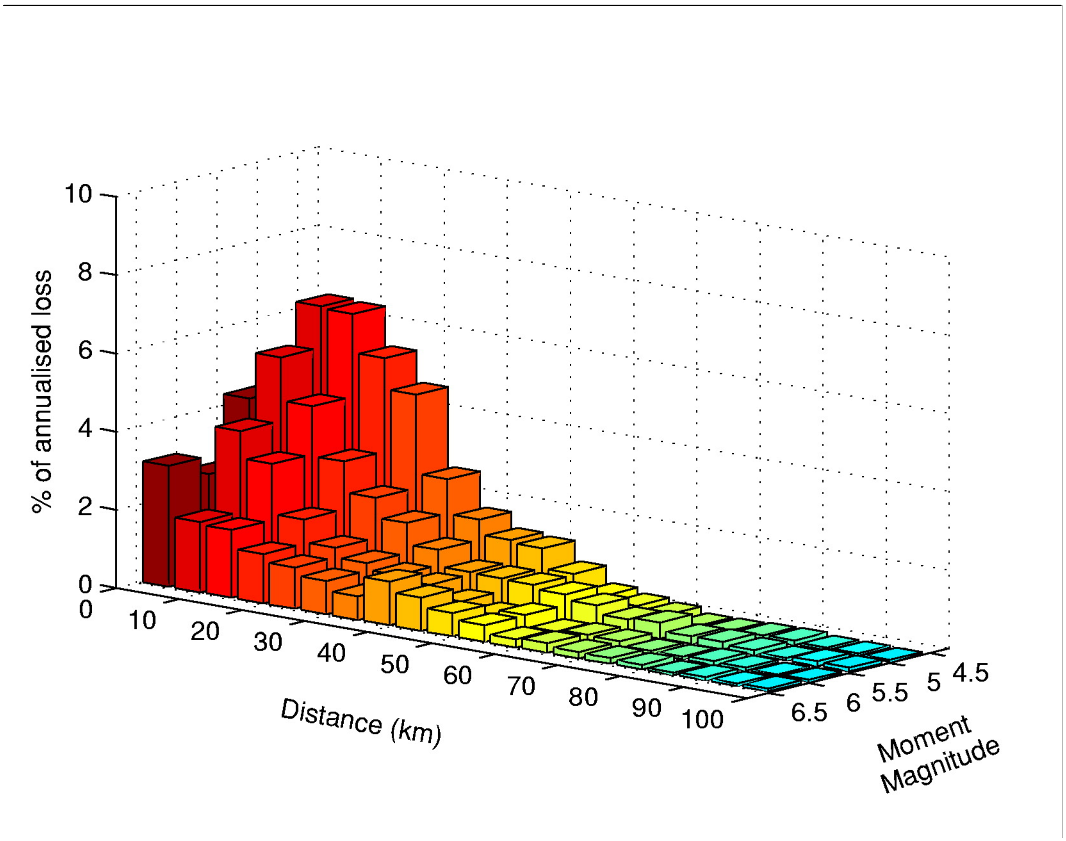


Figure 6.9: Contributions to the earthquake risk in Newcastle and Lake Macquarie from earthquakes of different magnitudes at varying distances to the building stock

Over half the earthquake risk in the study region is due to earthquakes with moment magnitudes around 5 at distances of less than 30 km. This result further suggests that the majority of the risk in the region can be attributed to moderate-impact, relatively infrequent events rather than high-impact, but extremely rare, events.

Most of the annualised risk for building usage type (see Table 6-4 for a description of usage types) is for the residential types (91%) with the next most common being commercial (4%). This is mainly because residential buildings make up the overwhelming majority of buildings in the study area, and comprise the majority of the total estimated value of all buildings in the study area. However, any problems with the data inventory, such as incomplete or incorrect classification of buildings, are expected to affect these relative contributions to risk.

It should be noted that the annualised loss varies quite significantly from building type to building type. For example, buildings constructed from unreinforced masonry (cavity brick construction) tend to have a higher annualised loss than any other building type in the study region (Figure 6.10). This is based on a per-building basis (i.e. by calculating the annualised loss for all buildings of that type, as a percentage of the total value of all buildings of that type). However, there are many more timber frame buildings in the study area than unreinforced masonry buildings. Consequently, timber frame buildings make a greater contribution to the total risk in the study region than unreinforced masonry buildings.

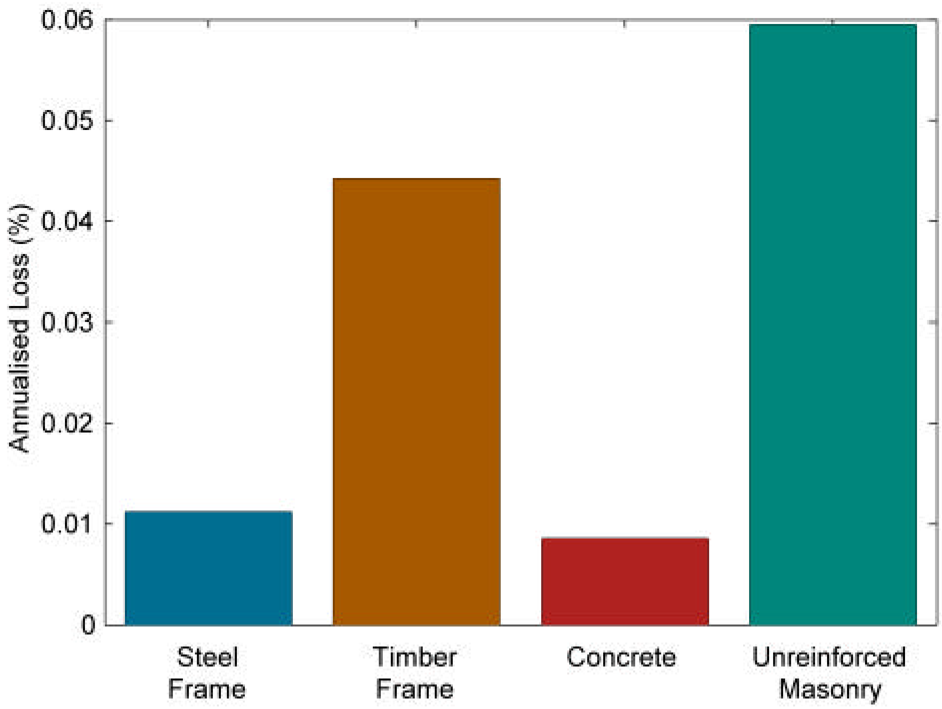


Figure 6.10: Annualised risk for a selection of building types in the study region. The annualised loss for a specific building type is described as a percentage of the total value of that building type in the study region

In Table 6-7 results for annualised risk are given for the sub-divided building construction types for the two most common classes of buildings in Newcastle and Lake Macquarie; timber frame and unreinforced masonry (see Table 6-1 for definitions of the subtypes). Timber frame, with brick wall and tiled roof, contributes nearly half of the total annualised risk for Newcastle and Lake Macquarie although this type of building makes up only about one third of the building stock in Newcastle and Lake Macquarie. On the other hand, timber frame with timber walls (tiled and metal roof) contribute more than a third of the number of buildings yet less than 12% of the total risk. If the vulnerability parameters were modified then the relative proportion of risk would vary. For example, if the model for unreinforced masonry was modified to account for older or degraded structures, the relative risk from unreinforced masonry buildings may well increase.

The annualised risk of a given building type expressed as a percentage of the total value of all buildings (including contents) of that type, gives a measure of risk that allows different construction types to be compared without the influence of the relative numbers of buildings. Table 6-7 shows that the buildings with the highest risk are generally unreinforced masonry (URML and URMM) which have values ranging from 0.038 to 0.067. The timber framed buildings (W1) are generally lower, with the exception of timber frame buildings with brick walls which have values of around 0.06. This suggests that the presence of brick walls on timber framed houses may cause these buildings to have similar risks to unreinforced masonry buildings.

The implications of these results and recommendations for future work that could improve the models that are the basis of these results are discussed in Section 7.4.

Table 6-7: Annualised risk for building construction types

Building construction Type	Estimated number of building (% of total)	Estimated total value of buildings of that type (% of total)	Annualised risk (% of total annualised risk)	Annualised risk (% of building value)
W1MEAN	18.36	17.12	12.4	0.031
W1BVTILE	30.34	35.17	48.8	0.060
W1BVMETAL	1.82	5.37	7.6	0.061
W1TIMBERTILE	22.94	12.61	6.0	0.020
W1TIMBERMETAL	15.76	7.64	5.0	0.028
URMLMEAN	0.28	1.05	1.6	0.067
URMLTILE	7.23	7.92	10.9	0.059
URMLMETAL	2.29	2.74	4.2	0.066
URMMMEAN	0.08	0.80	0.8	0.046
URMMTILE	0.03	0.35	0.3	0.038
URMMMETAL	0.03	0.59	0.7	0.048

6.3.2 Localised Impact and Risk

Of key interest to this study is the spatial variation of risk and a determination of which suburbs are most at risk, for whatever reasons. By calculating the annualised risk for each suburb in the study region as a percentage of the total annualised risk for the entire study region it appears that some locations are more at risk (on average) than others. For example, the suburbs Charlestown, Mayfield, Belmont South and New Lambton each contribute 4% or more to the total annualised risk, whereas many other suburbs contribute less than 1%. However, this higher contribution to the risk can be partly attributed to the fact that these suburbs contain a greater number of buildings than other suburbs and consequently contribute a greater amount of risk to the total annualised risk.

Perhaps a better measure of the economic vulnerability of a suburb is the annualised loss for the suburb, expressed as a percentage of the estimated total value of buildings in that suburb. For this measure of risk, the four suburbs with the highest percentage values are Estelville, Belmont South, and Redhead (greater than 0.12%), however, the percentage values are less heterogeneous across the region than for the percentages of total annualised risk. It should also be noted that the suburbs Estelville and Redhead had only a small number of sampled buildings, so the results may be significantly different for these suburbs, and other suburbs (mostly in Lake Macquarie) that were only sparsely sampled. A map of the annualised economic loss due to building damage has been determined on a suburb by suburb basis in Figure 6.11.

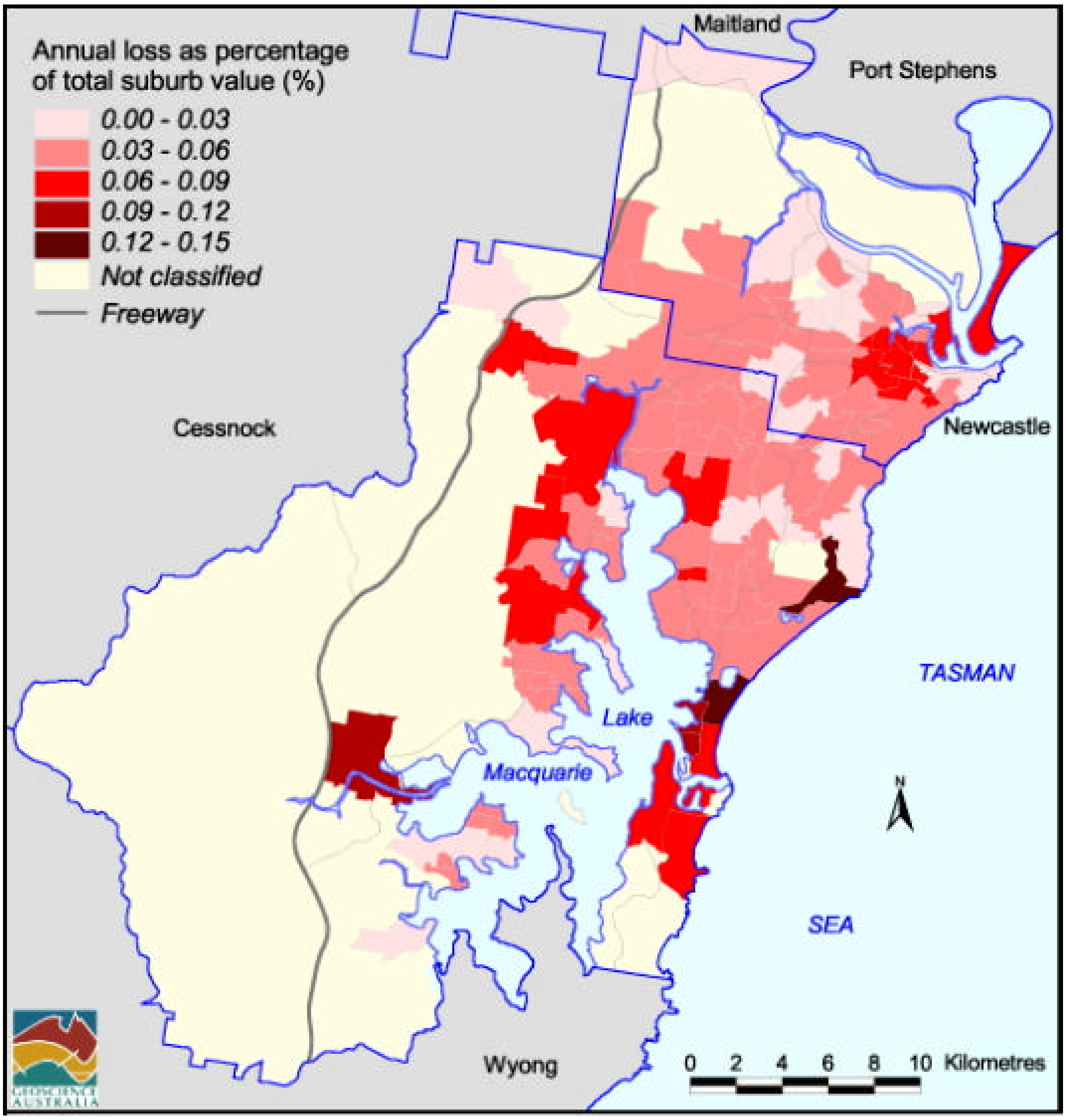


Figure 6.11: Annualised risk by suburb. The annualised risk in each suburb has been calculated as a percentage of the total value of all the buildings within the suburb. Note that some suburbs have not been classified due to the relatively low number of buildings surveyed

This figure clearly demonstrates that risk varies spatially across the study region. The variation in annualised risk can be partially attributed to differences in building stock across the study region. However, the underlying regolith also affects the annualised losses, and areas that are built on substantial thicknesses of regolith, such as parts of the Newcastle municipality, have a noticeably higher annualised risk. The map of observed building damage from the 1989 earthquake, from the Newcastle City Council, from Chapter**3**, also shows a strong correlation of high building damage with regolith thickness. Changes to the building parameters used, as well as improvements to the building inventory, as discussed in Section 7.4, could change this spatial distribution. For example, changes to unreinforced masonry parameters to account for degradation and age may well increase the annualised risk in suburbs containing older buildings, such as the Newcastle CBD. Also, the sampling rate in many Lake Macquarie suburbs was low, and consequently may have been biased towards a specific regolith class. Improvements to the sampling procedure and the building inventory in Lake Macquarie would alter the spatial distribution of annualised risk.

6.3.3 Uncertainties in the Modelling

The simulation model takes account of natural uncertainties by using random variables with assumed probability distributions. These include uncertainties in the earthquake location and magnitude, variation due to the degree of ground shaking observed between two adjacent sites, and natural variation between buildings of identical type at the same location. However, there are also further uncertainties associated with the choice of those distributions, along with the choices of models used. For example, the attenuation model used, and the choice of the building capacity method used, also contribute to overall variability. Taking account of these may tend to increase the risk. Conversely, further research that can improve the models can reduce the risk.

Results for casualty risk are not presented. The results for casualties from the 1989 earthquake simulation indicate that the casualty model needs further refinement. However, it is expected that a major casualty loss is unlikely.

As discussed in the next Chapter, the results of this risk assessment are useful to assess overall trends. They can be used to influence future planning decisions from the point of view of determining the most effective measures that can be taken to minimise the likely economic losses should another earthquake occur. However, there is a need to perform a detailed sensitivity analysis on the model, to determine whether changes in inputs such as earthquake magnitude and frequency parameters, attenuation parameters or building damage parameters cause significant changes in economic loss estimates.

7 Discussion and Conclusions (T. Jones, G. Fulford and T. Dhu)

7.1 Discussion

7.1.1 Earthquake Hazard

The earthquake hazard calculated for rock foundation in this study for the Newcastle and Lake Macquarie region is higher than the hazard suggested by the Australian earthquake loading standard, AS1170.4-1993. Our techniques to estimate hazard are an improvement over previous techniques used to estimate hazard in the Hunter region (e.g., Gaull et al., 1990). A detailed earthquake source zone model has been prepared that is based both on historical data and on expert opinion from structural geologists and seismologists. More than 10 years of new earthquake catalogue data was available since the assessment of Gaull et al. (1990). The attenuation relation for the decay of peak ground acceleration that was used in this study (Toro et al., 1997) gives similar results to the relation used by Gaull et al. (1990). The calculations were carried out to a much finer scale of resolution than, for example, Gaull et al. The new earthquake hazard results are presented for periods of vibration of 0.3 seconds and 1 second, in addition to peak ground acceleration. The hazard at other periods of vibration of interest can also be generated. However, in this study, considerable allowances were made for variability in the regional hazard model. These allowances will tend to increase the estimated hazard. Whilst we are confident that our methodology and input models are an improvement of the previous work included in the Australian earthquake loading standard, we believe that more testing is needed prior to these values being adopted.

The regolith site class model for Newcastle and Lake Macquarie also produces amplifications of earthquake ground shaking for all regolith sites 'softer' than weathered rock that are significantly higher than the specifications in the Australian earthquake loadings standard AS1170.4-1993. For example, for site classes D to H (Figure 4.9) the peak median ground shaking amplification factors range from 2.3 to 2.7 when considering a magnitude 5.5 event with a PGA of 0.25 g (Table 4-4). By contrast, the 'site factor' S in AS1170.4-1993 has a maximum value less than 2 for the soil types that compare best with these site classes. The amplification factors for site classes D to H peak at various periods of vibration in the range 0.3 to 1.1 s. These periods of vibration approximate the natural periods of vibration of almost all buildings in Newcastle and Lake Macquarie, and are the periods at which buildings will be most affected by earthquake shaking.

The site amplifications in this study were developed specifically for localised conditions in Newcastle and Lake Macquarie. By contrast, the amplification factors presented in AS1170.4-1993, by necessity, apply generally to all of Australia.

The site classes and period-dependent amplification factors could replace those in Table 2.4 (a) and Table 2.4 (b) of AS1170.4-1993 and the relevant parts of the successor to AS1170.4-1993. AS1170.4-1993 notes (p. 23) that:

> *'For the purposes of this Standard, it is not intended that a detailed site investigation be carried out for any structure to determine a soil profile over large depths. Most major centres and regional areas have basic information available on the likely strata which should be used to assess the site factor (S).'*

Although the site class maps and related amplification factors produced in this study are generalised to local level and are not specific to an individual building nevertheless, in the absence of a 'detailed site investigation', they are an excellent guide to the dynamic properties of regolith in Newcastle and Lake Macquarie, and especially in Newcastle, where the research was mainly directed. The regolith site classes developed in this study are a valuable aid to developers and the two local governments.

7.1.2 Vulnerability of the Building Stock to Earthquakes

The predictions of damage and economic loss depend not only on the parameters that are used in the models, but also on the building inventory database that has been used. Geoscience Australia undertook a comprehensive field survey in order to document the characteristics of buildings in the study region that contribute to the building's vulnerability during an earthquake. This survey obtained vital information on vulnerability parameters for more than 6,300 buildings in the study region. In addition to surveying a sample of the general building stock, an effort was made to survey all essential service facilities such as hospitals, and ambulance and fire stations. Extrapolations were made from this sample to generate a building inventory for the entire study area. Although we consider that the building inventory we have constructed is a good reflection of the composition of building construction types and usages in Newcastle and Lake Macquarie, differences between our inventory and the actual building stock will cause variations in the estimations of earthquake risk. Our building inventory is probably more accurate for Newcastle than for Lake Macquarie, especially southern and western Lake Macquarie.

The building vulnerability models used to calculate potential damage and losses in this study were developed specifically for Australian building types by structural engineering experts. These models cover 28 structural and 18 usage types of buildings found in Newcastle and Lake Macquarie. The models provide estimates of damage and loss for both the structural and usage types. However, they do not produce estimates of damage to specific structural and non structural sub-components, often related to masonry, such as parapets, gable ends and chimneys. The models also do not predict specific types of failure such as out of plane failure of masonry walls. For low rise structures the models do not differentiate between single storey, two storey or three storey structures.

The field survey team collected information on these sub-component attributes for all of the buildings surveyed. They also collected information on soft storey construction. Some researchers found that these attributes played a significant role in the damage from the 1989 earthquake (Chandler et al., 1991; Murphy and Stewart, 1993). For example, Chandler et al. (1991) found that, in the parts of Newcastle with some of the highest damage, damage to masonry and timber frame structures with two or more storeys was approximately double that for single storey structures.

7.1.3 Earthquake Risk

In this report we have mainly used annualised loss as a measure of risk. This measure of risk is useful as it allows the reader to compare the risk from earthquakes against the risks from many other hazards, both natural and otherwise, that can impact on the community. Other indicators of risk, such as the probability of occurrence and consequence of catastrophic events, are also of interest to communities, politicians, emergency managers and the insurance and reinsurance industries.

The majority of the earthquake risk in the study region is from events that have annual probabilities of occurrence in the range of 0.02 to 0.001. These events have equivalent return periods of 50 to 1,000 years (Table 7-1). The information in this table is derived from Figure 6.8. This suggests that the risk to the region is primarily from relatively infrequent events with low or moderate impacts.

In contrast, very frequent earthquake events, with return periods of 50 years or less, will have low impacts, and consequently they pose little risk to Newcastle and Lake Macquarie. They contribute approximately 15% of the total annualised risk under the model assumptions. The ground shaking levels generated in Newcastle and Lake Macquarie by these events will be mild, and the consequent degree of simulated damage is slight. In real earthquake scenarios with these levels of ground shaking, the restoration cost per building may be of the order of hundreds of dollars or less, and many building owners may not make insurance claims to recover costs. For relatively frequent events such as these, and depending on the insurance deductibles, insured losses are expected to be significantly less than the total damage losses.

Events with return periods of less than 500 years comprise about two thirds of all annualised risk. This return period approximates the return period for loadings for normal buildings in the Australian earthquake loading standard. Events with return periods of less than 1,000 years contribute around 77% of the total annualised risk.

Very high impact events can also occur in the region. However, because these events are rare they only contribute relatively small amounts to the annualised risk to Newcastle and Lake Macquarie. For example, events with impacts at least as severe as the Newcastle 1989 event only contribute about 18% of the total annualised risk. These events have return periods of greater than 1,500 years, and their impacts will be greater than 7.2% of the total value of all the building stock, including contents. Note that these events, with return periods greater than 1,500 years, have a greater than 6% probability of occurring in any 100 year period.

Table 7-1: Percentage of total annualised risk against maximum return period considered. Annualised risk is a percentage of the total value of the building stock and contents. The percentage of the total annualised risk increases as events with increasing return periods are considered

Maximum return period considered (yr)	Annualised risk (%)	Percentage of total annualised risk
10	< 0.001	< 1
50	0.006	15
100	0.013	30
500	0.029	66
1,000	0.033	77
2,500	0.038	87
5,000	0.040	92
> 100,000	0.043	100

The average annualised losses are estimated to be approximately 0.04% or $11 million per year. For an 'average' residential building and contents of value $250,000, this annualised loss equates to a figure of approximately $100 per year.

If this 'average' building is considered to have a nominal 50 year lifespan, then in its lifetime it is expected to suffer losses of approximately $5,000 in today's dollars. However, many buildings in Newcastle are at least 100 years old or are expected to reach this age. An 'average' $250,000 residential building and contents with a nominal 100 year lifetime is expected to suffer losses approaching $10,000, in today's dollars, in its lifetime.

Although the annualised risk figures may suggest otherwise, the buildings and people in the study area are unlikely to experience a significantly damaging event in their lifetime. For example, in a 100-year period, events with a return period of 100 years or longer have approximately a 63% chance of occurring (see Chapter 2). The loss for an 'average' building from an event with a 100 year return period or greater is approximately 1% of the building and contents value. This percentage is equivalent to a loss of approximately $2,500 for a nominal value of $250,000 for building and contents. This sum may seem an acceptable loss in a 100-year lifetime of a house.

More severe events are much less likely to occur in a nominal 100-year 'lifetime'. For example, the impact on an 'average' residential building from events with return periods of 1,000 years or greater is approximately 5.7% of the total value, or $14,250 for the same 'average' residential building and contents. This sum would appear far less acceptable. However, events with impacts with return periods of 1,000 years or greater have only about a 9.5% chance of occurring in a period of 100 years.

The gulf between relatively small amounts of annualised risk, and realisation of that risk in single, rare, events, points out a problem with managing the risk from earthquakes in Newcastle and Lake Macquarie, and in other parts of Australia. The argument also applies to other, intraplate, areas of the world that have similar rates of seismicity to Australia.

The annualised risk may not be realised for many years, not even in the lifetime of many structures and most people. Thus, it is possible for politicians, emergency managers, the finance industry, business owners and householders to be complacent about earthquake risk. There is a good chance that they will not suffer from this assumption. However, even extremely rare, catastrophic events do have a chance of occurring at any time Although this issue is clearly of importance to the insurance and reinsurance industries, it may be less well recognised by the broader community.

Annualised risk varies considerably across Newcastle and Lake Macquarie. It depends strongly on the nature of the underlying regolith. In general, areas that are built on substantial thicknesses of geological sediments having noticeably higher annualised losses than other areas. The annual risk also depends on the building construction types, building usages and total floor areas in local areas. Figure 6.11 shows the annualised risk by suburb.

The suburbs most at risk in Newcastle and Lake Macquarie are shown in Table 7-2 and Table 7-3 respectively. The annualised risk in Table 7-2 and Table 7-3 is expressed as a percentage of the total value of buildings and contents in the suburb. Nine of the ten Newcastle suburbs considered most at risk are situated entirely on the geological sediments near the Hunter River (Figure 6.11). ***The reader should note the many variabilities and uncertainties inherent in the models used to calculate these results (see Chapter 4 and Chapter 6).***.

Lake Macquarie suburbs Estelville, Redhead, Dora Creek, Killingworth, Holmesville, and Toronto also had high estimates of annualised risk, but the results are less reliable for these suburbs because field survey rates were low, and the regolith site modelling in Lake Macquarie is inferior to that in Newcastle.

The annualised risk also varies with building construction type. Brick buildings are estimated to have higher average risks per building than other construction types. Brick veneer buildings and unreinforced masonry buildings have similar average risks per building. Timber frame buildings with timber or fibro wall cladding are estimated to have annualised risks slightly less than half of the risks for brick structures, when considered as a percentage of the value of the building.

Table 7-2: Suburbs most at risk in Newcastle

Newcastle Suburb	Annualised risk (% of value of buildings and contents)
Hamilton South	0.09
The Junction	0.08
Hamilton East	0.08
Carrington	0.08
Stockton	0.08
Hamilton North	0.07
Broadmeadow	0.07
Hamilton	0.07
Warabrook	0.06
Islington	0.06
Wickham	0.06
Maryville	0.06

Table 7-3: Suburbs most at risk in Lake Macquarie

Lake Macquarie Suburb	Annualised loss (% of value of buildings and contents)
Belmont South	0.12
Pelican	0.11
Marks Point	0.10
Blacksmiths	0.08
Caves Beach	0.07
Swansea	0.07
Teralba	0.06

The vulnerability model used for masonry was designed for new masonry compliant with the earthquake loadings standard (engineers workshop, AS1170.4-1993). However, there is plentiful evidence from the 1989 Newcastle earthquake that many masonry buildings did not perform to the expected standards of AS1170.4-1993 because of weak lime mortars, corroded or absent wall ties, and poor restraint of details such as parapets (Page, 1992; Melchers and Page, 1992). Thus, the vulnerability model we have used for unreinforced masonry structures may significantly underestimate the risk to some masonry structures, especially old masonry structures.

The spatial distribution of damage in the simulations of the 1989 earthquake and the estimates of annualised risk would be affected by such variability in the model. Suburbs with significant numbers of masonry buildings, especially old masonry buildings, may have unexpectedly low estimates of annualised risk in relation to other suburbs. Newcastle, Newcastle East and Newcastle West may be three such suburbs.

Our models show that dwellings including houses, hotels/motels and mobile homes have a higher annualised risk than buildings used for retail trade, professional offices, hospitals, medical offices and clinics, heavy and light industrial buildings, government buildings, schools and university buildings in Newcastle and Lake Macquarie. In this context, annualised risk is measured as a percentage loss of all buildings of a particular usage type in Newcastle and Lake Macquarie. The results may not accurately reflect the relative annualised risks to individual buildings.

The following question arises from an analysis of the annualised risk to suburbs in Newcastle. If 11 out of the top 12 suburbs most at risk in Newcastle are located on significant amounts of regolith, why do adjacent suburbs have significantly less annual risk? The suburbs in question are Newcastle West and Cooks Hill, and they are also situated on this regolith. The answer may lie in building usages and in the construction types of the buildings. For example, both of these suburbs contains a relatively high proportion of non-residential buildings that, according to the models, have lower annualised risks than most dwelling types.

The risks of death and serious injury are small. However, the acceptance of death or severe injury due to rare disasters such as earthquakes appears to be lower than the acceptance of more common causes of casualties such as heart disease and vehicle accidents.

7.1.4 Effect of Variability on Results

It should be emphasised that a great deal of variability was included in the models used to generate these results. To some degree this variability was incorporated to account for our lack of knowledge about the various models used in the study. A detailed description of how natural variability has been incorporated into this study can be found in Chapter 4 and Chapter 6.

The effect of high levels of variability is to increase the estimates of risk. Future studies on the earthquake risk in the region should focus on improving the models that have been used. This will allow for the variability in the models to be decreased, which will most probably result in a decrease in the estimated risk.

7.2 Conclusions

We emphasise that this report should be regarded as the best and most recent assessment of earthquake risk in Newcastle and Lake Macquarie. However, we acknowledge that there are limitations in the models and data we have used, and that we have an incomplete understanding of the natural variability inherent in ground shaking and building response.

The results, interpretations and conclusions could change with the incorporation of new data and with different model assumptions.

Therefore, the reader should not take action based on information in this report alone.

Our conclusions from this study are:

- The calculated earthquake hazard in the Newcastle and Lake Macquarie region is higher than the hazard suggested by the Australian earthquake loading standard, AS1170.4-1993;
- The regolith in the study region causes a significant increase in the earthquake hazard, and differences in the regolith thickness can cause quite dramatic variations in the hazard and risk across the study region;
- The annualised loss for the study region is of the order of 0.04% or $11 million per year;

- The majority of the annualised earthquake risk in the study region is from events that have annual probabilities of occurrence in the range of 0.02 to 0.001 (return periods of 50 - 1,000 years);
- Brick veneer buildings contribute about half of the total risk. This is partly because they comprise a large proportion of buildings in Newcastle and Lake Macquarie. Timber frame buildings with timber, fibro and other light wall claddings contribute approximately one-quarter of the risk. A further one-sixth of the risk is contributed by unreinforced masonry buildings;
- Damage to residential buildings contributes the vast majority of the risk (approximately 91%). This is largely because residential buildings comprise the vast majority of all buildings in Newcastle and Lake Macquarie;
- The 1989 Newcastle earthquake had an economic impact with a return period of the order of 1,500 years. According to our models, approximately 82% of all annualised risk in Newcastle and Lake Macquarie is due to events with lesser economic impacts than the 1989 earthquake. Thus, events like the 1989 earthquake, or even more catastrophic events, make only a small contribution to the earthquake risk in the region when considered on an annualised basis. However, rare but catastrophic events are very important to emergency managers and the insurance and reinsurance industries;
- Annualised risk varies considerably across Newcastle and Lake Macquarie. It depends on the nature of the underlying regolith, the composition of the building stock and building usage in particular areas. Our results suggest that the suburbs most at risk in Newcastle, determined by a percentage of the total value of buildings and contents in the suburb, are Broadmeadow, Carrington, Hamilton, Hamilton East, Hamilton North, Hamilton South, Islington , Maryville, Stockton, The Junction, Warabrook and Wickham. In Lake Macquarie the suburbs most at risk are Belmont South, Blacksmiths, Caves Beach, Marks Point, Pelican, Swansea and Teralba. Further research into the building parameters for unreinforced masonry construction types may change these conclusions, especially in older suburbs such as Newcastle, Newcastle East, Newcastle West and Cooks Hill. Other Lake Macquarie suburbs such as Cooranbong, Dora Creek, Estelville, Fassifern, Holmesville, Killingworth, Redhead, Toronto and Warners Bay also had high annualised risk in our results, but the results are less reliable because survey rates were low in these suburbs, and the regolith site modelling is inferior to that in Newcastle;
- Over half of the earthquake risk is from moderate-magnitude earthquakes, with moment magnitudes around 5, that occur less than 30 km from the study area. This conclusion has implications for emergency management in the lower Hunter. It may be appropriate to prepare for the possible impacts of such events rather than on catastrophic events that have an extremely small probability of occurring;
- In general, the risk of casualties from earthquakes is low. However, we do not rule out the possibility that casualties in future events could be caused by damage to a single building, or a small number of buildings. It is extremely unlikely that any event capable of causing widespread casualties will occur in the study region;
- The results also have implications for the earthquake risk facing larger Australian cities such as Sydney, Melbourne and Adelaide. This is due to a number of factors, including similarities between the earthquake hazard in Newcastle and Lake Macquarie and other parts of Australia, and similarities between the urban environments, particularly the composition of the building stock;
- The earthquake risk to Newcastle and Lake Macquarie may be reduced gradually over time by improved building construction practices, attrition of vulnerable building stock such as unreinforced masonry, and by reducing vulnerability of existing buildings through renovations constructed to modern code standards;
- Good building practice may be the single, most important, long-term factor in reducing economic losses and casualties from earthquakes in Newcastle and Lake Macquarie.

7.3 Suggested Mitigation Options

- Newcastle City Council and Lake Macquarie City Council should consider adopting the site class maps and the associated, period-dependent median amplification factors in their land planning regulations. The amplification factors could replace the site factor S in AS1170.4-1993 in determining earthquake loadings for structures in Newcastle and Lake Macquarie. The amplification factors that refer to a peak ground acceleration on rock of 0.25 g from a magnitude 5.5 earthquake (Table 4-4) are appropriate, for normal structures, for earthquake loadings with a 10% probability of occurrence in 50 years.

- Enforce the compliance of all new structures with current earthquake loading standards. Two important areas where improvements could be made are in ensuring that mortar quality and wall tie placement and specifications comply with code specifications.
- Provide adequate insurance against earthquakes. Householders, small business operators and corporations should ensure that their earthquake insurance is adequate. The cost of repair or replacement of heritage buildings can be significantly higher than the corresponding costs for modern buildings and so there is potential for heritage buildings to be underinsured to a greater extent than other buildings.
- Protect facilities such as police, fire and ambulance stations and hospitals, which provide essential services following any earthquake event. These facilities could be examined by suitably qualified engineers on a site-by-site basis to assess their performance under earthquake loadings. The survey of essential facilities carried out during this study found that many of these facilities were built on regolith site classes that dramatically increased earthquake hazard and/or were of vulnerable construction types.
- Review earthquake loading standards. In this study, certain levels of building damage were estimated as a result of certain levels of ground shaking. The levels of damage may be more or less than what engineers would have expected from the input ground motions. If the damage predicted by the models is higher than would have been expected by expert engineers, then design standards may need to be made more rigorous. The damage models need to be rigorous for this review of design standards to be meaningful.
- Collect future post disaster damage, economic, social and insured loss data in a systematic, pre-planned way with a high degree of detail and accuracy so that risk assessments will be improved and the amount of variability reduced.
- Collect information on building parameters that contribute to vulnerability to earthquakes on a systematic basis and maintain databases containing this information. This need not be a tedious task if it is combined with similar related information gathering as for example through development approval processes. The information may also be useful for other purposes, for example, as estimating the vulnerability of the community to other hazards such as fire and wind, and would be valuable to the insurance industry. This long term strategy would assist risk assessments and risk management in the future.

7.4 Future Directions for Earthquake Risk Assessment

Many improvements and additions can be made to improve the techniques used in this study. Improvement can be made through new scientific, engineering and socio-economic research, by expanding the scope of the risk assessment to capture other sources of risk outside of what has been assessed so far, and by collecting, compiling and assessing new information to assist these initiatives. Chapters 4 and 6 each contain a discussion of the sources of earthquake hazard and risk variability.

Some important measures to improve earthquake risk assessment in Newcastle and Lake Macquarie are suggested below. The list is not comprehensive.

In this study, we have assessed direct economic losses due to building damage. Our study has not addressed the direct losses from business interruption or the indirect losses to other communities resulting from earthquakes in Newcastle and Lake Macquarie. An assessment of these losses would give a more complete estimate of the total risk due to earthquakes in Newcastle and Lake Macquarie.

The importance of the impacts of earthquakes on ‘lifelines’ such as electric power and water supply needs to be investigated. In Chapter 5, a preliminary analysis was undertaken of the exposure of sewer and water facilities due to their location on the various regolith site classes. Further investigation is required to assess the risk to lifelines in Newcastle and Lake Macquarie. This investigation needs to address the impact that earthquakes could have on lifeline function, as well as the consequent impact on the broader community due to impaired lifeline functioning.

The socio-economic implications of earthquake impacts on Newcastle and Lake Macquarie also need to be assessed. In the first instance, the simplest socio-economic vulnerability models would relate structural damage to the impact on all community activities and the time taken to restore the community to its normal state. Geoscience Australia has assembled some relevant information that could assist such investigations in future, and is working to develop socio-economic loss models for natural hazards.

The methodology used in the modelling approach is a significant improvement over previously published earthquake risk assessment models applied to Australia. However, Geoscience Australia’s model will benefit from further validation, which will need to be carried out with the support and cooperation of others.

The engineering vulnerability models need to be checked, modified and produced as necessary to make them appropriate for Australian building stock. This requires a long-term, engineering research effort. Models for some construction types including timber frame buildings were developed by GA and structural engineering experts based on Australian design and construction practice were used in this study. Models for other building types such as some steel frame buildings have been adopted without alteration from US models. The efforts to improve the models should concentrate on the construction types that are the most important contributors to risk, as they have done so far. For Newcastle and Lake Macquarie, these are timber frame structures (especially brick veneer structures) and unreinforced masonry structures. Details such as tile or steel roof, masonry gable ends, parapets and chimneys, number of storeys in low rise buildings, soft storey, are important components of the vulnerability models. Other structural types may be important because, even though they are relatively few in number in the study area, such buildings may be classified as 'important' buildings or house essential services. Concrete frame buildings are one example of such building construction types.

Part of the assessment process for the building vulnerability models is to examine the degrees of structural, non-structural and contents damage, and economic losses, that are predicted by the models for certain levels of input ground shaking. The vulnerability and economic loss models need to be further reviewed by the structural engineering community to improve confidence in the results produced by them. For example, upon further analysis, the results of our modelling may show that significant simulated economic losses are due to acceleration effects rather than lateral displacements. These outcomes should be compared with the expectations of the structural engineering community and the model parameters adjusted if necessary.

The degree of damage and economic loss predicted by the models can be used to assess the appropriateness of earthquake loading standard specifications. For example, is the economic loss predicted by ground shaking with a 10% probability of occurrence in 50 years acceptable to the loading committee, the insurance and construction industries, and to government?

Sensitivity tests should be run by varying parameter values in the models to give alternative estimates of risk. The results may point to areas where efforts should be made to improve the models or collect new data. Reduced variability in the models will lead to more accurate and reliable estimates of risk.

Assessments of future risk based on projections of changes in building stock and demographics would be valuable to the assist decisions on the development of Newcastle and Lake Macquarie. A cost/benefit analysis of the effectiveness of introducing various mitigation measures would also assist the rational development of the cities. Assessments of future risk, and cost/benefit analyses, would be aided by masonry vulnerability models that accounted for building condition.

7.5 Final Remarks

Geoscience Australia is actively developing new techniques and revising its methodologies. Other workers in planning, emergency management, engineering, the insurance industry, the utility corporations, sociology and the finance industry are also putting increasing efforts into risk management for natural hazards including earthquakes. It is our hope that this study will assist these workers, the people of Newcastle and Lake Macquarie, and the broader Australian community, in reducing earthquake risk.

As a final note it should be remembered that, in the aftermath of the 1989 earthquake, there were many studies and recommendations on what should be done to mitigate the effects of future earthquakes. However, thirteen years on, few of the recommendations have been implemented. We urge the relevant authorities to review the recommendations made in this report and previous reports such as that conducted by the Institution of Engineers (Melchers, 1990) and to take appropriate action, so that ultimately we will have safer and more prosperous communities.

Appendix A - MODIFIED MERCALLI (MM) SCALE OF EARTHQUAKE INTENSITY (AFTER DOWRICK, 1996)

A.1 MM I

People

Not felt except by a very few people under exceptionally favourable circumstances.

A.2 MM II

People

Felt by persons at rest, on upper floors or favourably placed.

A.3 MM III

People

Felt indoors; hanging objects may swing, vibrations may be similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.

A.4 MM IV

People

Generally noticed indoors but not outside. 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.

Fittings

Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.

Structures

Walls and frame of building are heard to creak, and partitions and suspended ceilings in commercial buildings may be heard to creak.

A.5 MM V

People

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

Fittings

Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Hanging pictures knock against the wall. Open doors may swing. Cupboard doors secured by magnetic catches may open. Pendulum clocks stop, start, or change rate.

Structures

Some windows Type I cracked. A few earthenware toilet fixtures cracked.

A.6 MM VI

People

Felt by all. People and animals alarmed. Many run outside. Difficulty experienced in walking steadily.

Fittings

Objects fall from shelves. Pictures fall from walls. Some furniture moved on smooth floors, some unsecured free-standing fireplaces moved. Glassware and crockery broken. Very unstable furniture overturned. Small church and school bells ring. Appliances move on bench or table tops. Filing cabinets or “easy glide” drawers may open (or shut).

Structures

Slight damage to Buildings Type I. Some stucco or cement plaster falls. Windows Type I broken. Damage to a few weak domestic chimneys, some may fall.

Environment

Trees and bushes shake, or are heard to rustle. Loose material may be dislodged from sloping ground, e.g. existing slides, talus slopes, shingle slides.

A.7 MM VII

People

General alarm. Difficulty experienced in standing. Noticed by drivers of motorcars who may stop.

Fittings

Large bells ring. Furniture moves on smooth floors, may move on carpeted floors. Substantial damage to fragile contents of buildings.

Structures

Unreinforced stone and brick walls cracked. Buildings Type I cracked with some minor masonry falls. A few instances of damage to Buildings Type II. Unbraced parapets, unbraced brick gables, and architectural ornaments fall. Roofing tiles, especially ridge tiles, may be dislodged. Many unreinforced chimneys damaged, often falling from roof-line. Water tanks Type I burst. A few instances of damage to brick veneers and plaster or cement-based linings. Unrestrained water cylinders (Water Tanks Type II) may move and leak. Some windows Type II cracked. Suspended ceilings damaged.

Environment

Water made turbid by stirred up mud. Small slides such as falls of sand and gravel banks, and small rock-falls from steep slopes and cuttings. Instances of settlement of unconsolidated or wet, or weak soils. Some fine cracks appear in sloping ground. A few instances of liquefaction (i.e. small water and sand ejections).

A.8 MM VIII

People

Alarm may approach panic. Steering of motor cars greatly affected.

Structures

Buildings Type I, heavily damaged, some collapse. Buildings Type II damaged, some with partial collapse. Buildings Type III damaged in some cases. A few instances of damage to Structures Type IV. Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down. Some pre-1965 infill masonry panels damaged. A few post-1980 brick veneers damaged. Decayed timber piles of houses damaged. Houses not secured to foundation may move. Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment

Cracks appear on steep slopes and in wet ground. Small to moderate slides in roadside cuttings and unsupported excavations. Small water and sand ejections and localised lateral spreading adjacent to streams, canals, lakes, etc.

A.9 MM IX

Structures

Many buildings Type I destroyed. Buildings Type II heavily damaged, some collapse. Buildings Type III damaged, some with partial collapse. Structures Type IV damaged in some cases, some with flexible frames seriously damaged. Damage or permanent distortion to some Structures Type V. Houses not secured to foundations shifted off. Brick veneers fall and expose frames.

Environment

Cracking of the ground conspicuous. Landsliding general on steep slopes. Liquefaction effects intensified and more widespread, with large lateral spreading and flow sliding adjacent to streams, canals, lakes, etc.

A.10 MM X

Structures

Most Buildings Type I destroyed. Many Buildings Type II destroyed. Buildings Type III heavily damaged, some collapse. Structures Type IV damaged, some with partial collapse. Structures Type V moderately damaged, but few partial collapses. A few instances of damage to Structures Type VI. Some well-built timber buildings moderately damaged (excluding damage from falling chimneys). Dams, dykes, and embankments seriously damaged. Railway lines slightly bent. Cement and asphalt roads and pavements badly cracked or thrown into waves.

Environment

Landsliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes. Landslide dams may be formed. Liquefaction effects widespread and severe.

A.11 MM XI

Structures

Most Buildings Type II destroyed. Many Buildings Type III destroyed. Structures Type IV heavily damaged, some collapse. Structures Type V damaged, some with partial collapse. Structures Type VI suffer minor damage, a few moderately damaged.

A.12 MM XII

Structures

Most Buildings Type III destroyed. Many Structures Type IV destroyed. Structures Type V heavily damaged, some with partial collapse. Structures Type VI moderately damaged.

A.13 Construction types

Buildings Type I Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete, or composite materials (e.g. some walls timber, some brick) not well tied together. Masonry buildings otherwise conforming to Buildings Type I–III, but also having heavy unreinforced masonry towers. (Buildings constructed entirely of timber must be of extremely low quality to be Type I).

Buildings Type II 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. Such buildings not having heavy unreinforced masonry towers.

Buildings Type III Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed in detail to resist earthquake forces.

Structures Type IV Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid 1930s to c. 1970 for concrete and to c. 1980 for other materials).

Structures Type V Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c. 1980 for other materials.

Structures Type VI Structures dating from c. 1980 with well defined foundation behaviour, which have been especially designed for minimal damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high (value) contents, or new generation low damage structures.

Windows

Type I – Large display windows, especially shop windows.

Type II – Ordinary sash or casement windows.

Water tanks

Type I – External, stand mounted, corrugated iron water tanks.

Type II – domestic hot-water cylinders unrestrained except by supply and delivery pipes.

Appendix B - REGIONAL SEISMICITY

B.1 List of Earthquakes with ML 3 3.0 in the Investigated Region

To estimate rates of occurrence, dependent events (foreshocks and aftershocks) were removed from the catalogue. To decluster the earthquake data set, the identifiable foreshocks and aftershocks were removed according to the procedure described by (McFadden et al., 2000). An event was considered to be a foreshock or an aftershock if it was within a distance, d km, of the main shock, defined below and, if it occurred within 10 years of a mainshock of magnitude 7, within 1 year of a magnitude 6 event, within 3 months of a magnitude 5 event, and within 10 days of a magnitude 4 event.

$$d = 10^{\frac{M_L - 4.11}{1.65}} \text{ km}$$

Geoscience Australia's QUAKES Database retrieval parameters:

preferred solutions

date between 18410101 and 20010101

lat between -34.9 and -30.9

long between 149.75 and 153.75

depth between 0 and 33 km

Magnitude between 3 and 9

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
AUST	18410127	215500	-32.8	151.6	10		4.9	MCCU
AUST	18421027	193000	-32.6	151.6	10		5.3	MCCU
AUST	18680618	140000	-32.8	151.6	10		5.3	MCCU
AUST	18721018	185000	-33.7	150	15		5.3	MCCU
AUST	19020228	122000	-34.3	150.8	5		4.1	
AUST	19160610	1751	-32.25	152.5	0		4.6	
BURKE	19190815	102121	-33.5	150.7	0		4.6	RIV
MCCUE	19251218	104710	-33	151.6	10	4.5	5.3	MCCU
BURKE	19341110	234740	-34.9	150	0	4.2	4.8	RIV
BURKE	19341111	104632	-34.9	150	0		3.5	RIV
BURKE	19351208	30807	-34.5	150.5	33		3	RIV
DESU	19591012	212340	-31	151.5	0		4.7	RIV
CAN	19600717	255	-34	150.25	10		3	
CAN	19610521	214003	-34.547	150.503	19		5.6	RIV

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
CAN	19620208	52548.8	-34.55	150.51	4		3.3	CAN
CAN	19620502	135355	-33.9	150.1	8		3	CAN
CAN	19620710	64405.6	-34.2	150.43	8		3.2	CAN
CAN	19620928	204717	-34.47	150.01	27		3	CAN
CAN	19620929	13134.5	-34.48	150.03	26		4.2	RIV
CAN	19680708	115013.5	-34.57	150.51	13		4.5	CAN
CAN	19681018	175112.4	-34.52	150.45	13		3.1	ISC
CAN	19700309	121617	-32.8	152.42	0		3	CAN
AUST	19720430	171123.9	-31.01	150.15	0		3.9	CAN
CAN	19730301	321	-33.57	151.95	0		3	CAN
CAN	19730301	424	-33.78	152.12	0		3.4	CAN
CAN	19730309	190914.7	-34.17	150.32	21	5.3	5.5	CAN
CAN	19730309	192159.1	-34.15	150.37	38		3.7	CAN
CAN	19730309	192750.3	-34.18	150.34	16		3.2	CAN
CAN	19730309	192848.5	-34.14	150.28	13		3.1	CAN
CAN	19730309	193221.6	-34.18	150.35	15		3.4	CAN
CAN	19730309	195347.5	-34.17	150.33	13		3	CAN
CAN	19730309	200628.7	-34.15	150.32	12		3	CAN
CAN	19730309	201212	-34.13	150.35	9		3.2	CAN
CAN	19730309	204146.6	-34.16	150.32	12		3.5	CAN
CAN	19730309	205418.1	-34.17	150.36	4		3.3	CAN
CAN	19730309	210110.8	-34.19	150.37	25		3.4	CAN
CAN	19730310	41137.2	-34.18	150.34	26		3.5	CAN
CAN	19730310	81450.9	-34.19	150.34	20		3	CAN
CAN	19730310	124705.6	-34.17	150.35	26		3.2	CAN
CAN	19730310	125310.2	-34.17	150.35	25		3.3	CAN
CAN	19730310	125354.4	-34.16	150.34	26		3.6	CAN
CAN	19730310	132947.1	-34.18	150.34	22		3.1	CAN
CAN	19730310	180412.1	-34.18	150.35	24		3.1	CAN
CAN	19730311	30922.8	-34.18	150.37	13		3.1	CAN
CAN	19730312	144202.5	-34.18	150.35	12		3.1	CAN
CAN	19730313	61445	-34.16	150.34	24		3.5	CAN
CAN	19730314	60602.4	-34.2	150.33	22		3.9	CAN
CAN	19730314	95534.6	-34.18	150.32	21		3.2	CAN
CAN	19730315	214849.4	-34.17	150.34	18		3	CAN
CAN	19730316	14802.2	-34.17	150.34	27		3.7	CAN

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
CAN	19730317	170529.9	-34.16	150.36	24		3.4	CAN
CAN	19730319	25610.3	-34.19	150.33	16		3.5	CAN
CAN	19730321	143959.1	-34.18	150.33	12		3.4	CAN
CAN	19730325	12546.6	-34.18	150.34	14		3.2	CAN
CAN	19730327	105210	-34.18	150.35	15		3	CAN
CAN	19730328	165913.3	-34.17	150.32	17		3	CAN
CAN	19730414	210602.6	-34.18	150.31	12		3.4	CAN
CAN	19730507	115753	-34.17	150.4	0		3	CAN
CAN	19760109	43028.9	-34.21	150.63	7		3	CAN
CAN	19770413	215742.5	-33.51	150.17	20		3.4	CAN
AUST	19780123	71222.3	-33.62	151.17	30		4	CAN
CAN	19780822	103732.3	-32.87	151.42	20		3.4	CAN
CAN	19781211	23111.3	-33.89	151.69	21		3.3	CAN
CAN	19790204	132604.1	-33	151.4	29		3.2	CAN
CAN	19790226	82123	-34.58	151.77	0		3.2	CAN
CAN	19790302	180512.2	-32.99	151.41	13		3	CAN
CAN	19790413	152414.5	-32.99	149.85	7		3	CAN
CAN	19790416	13416.7	-33.94	150.53	18		3	CAN
CAN	19790506	130922	-32.1	149.83	0		3.3	CAN
CAN	19800424	41701	-33.76	150.09	19		3	CAN
ISC	19800907	95539.8	-34.155	150.698	18		3.3	CAN
CAN	19801215	150614.1	-32.76	151.41	16		3.4	CAN
CAN	19810222	131233.5	-32.98	150.51	10		3.4	CAN
CAN	19810225	52902.3	-32.78	151.46	21		3.6	CAN
CAN	19810907	24514	-32.46	150.99	19		4.2	CAN
AUST	19811115	165810.8	-34.249	150.897	14	3.9	4.6	AUST
ASC	19811119	121852.8	-34.227	150.886	12		3.3	ASC
CAN	19820713	93019	-34.25	152	0		3	CAN
CAN	19820909	42823	-33.6	151.96	15		4.1	AUST 4.3
CAN	19820915	43042	-34.75	150.87	0		3	CAN
CAN	19820915	43349.9	-34.75	150.87	26		3.3	CAN
CAN	19821225	164840	-33	151.9	0		3.5	CAN
CAN	19830206	231351.5	-31.08	151.33	25		4.6	CAN
CAN	19830209	42930	-33.83	151.76	0		3	
CAN	19830322	133935.3	-34.35	150.4	19		3.5	
CAN	19830414	151636.2	-33.46	150.6	29		3	

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
CAN	19830429	165104.8	-32.56	151.39	10		3.6	
CAN	19830518	84252.1	-33.98	150.65	22		3.5	
CAN	19830617	25940.3	-32.44	150.92	20		3.5	
CAN	19830924	72551.9	-33.6	150.13	16		3.6	
CAN	19831101	5009	-33.9	150.45	0		3.1	
CAN	19840720	215620.2	-32.52	151.37	21		3.9	
AUST	19850213	80122.8	-33.49	150.18	7		4.3	AUST
CAN	19850213	115944.4	-33.38	150.14	12		3.2	CAN
AUST	19850510	2544.8	-33.63	150.13	0		3	AUST
CAN	19850713	214655.2	-33.56	150.08	14		3.2	CAN
CAN	19850713	230624	-33.63	150.11	0		3.1	CAN
AUST	19850822	141618	-32.6	152.4	0		3.1	AUST
AUST	19860220	214355.3	-33.33	150.604	2		4	AUST
AUST	19870624	145319.2	-33.47	150.17	0		3.1	AUST
AUST	19870624	150455.2	-33.432	150.149	5		4.3	AUST
AUST	19870624	153236	-33.41	150.1	13		3.4	AUST
AUST	19870624	154706.8	-33.46	150.18	0		3.5	AUST
AUST	19870826	13833.9	-32.732	151.168	0		3	
AUST	19870904	71535.9	-32.09	152.58	0		3.4	AUST
AUST	19880430	170012.4	-33.5	150.15	1		3.2	AUST
AUST	19891216	2856.1	-34.7	150.67	23		2	
AUST	19891227	232657	-32.946	151.607	11	4.6	5.5	AUST
MEL	19900330	113300	-34.25	150.83	0		3	
MEL	19900522	63928	-32.026	150.332	10		3.4	
AUST	19910717	23411.1	-32.54	150.9	3		3.2	AUST
AUST	19931023	123241.5	-32.914	151.299	7		3	AUST
AUST	19940806	110351.6	-32.924	151.288	2		5.3	AUST
AUST	19950503	42423	-33.17	150.24	14		3.2	AUST
AUST	19950520	112911.8	-33.86	150.07	6		3.6	AUST
AUST	19950528	231258.4	-32.518	151.408	4		3.5	AUST
AUST	19950707	65324.5	-32.928	151.318	1		3.2	AUST
AUST	19951121	170214.1	-32.884	151.269	2		3.1	AUST
AUST	19961001	214222	-33.819	150.405	5		3.4	AUST
AUST	19961210	125426.1	-34.158	150.53	5		3.3	AUST
AUST	19961210	125835.4	-34.141	150.503	6		3.2	AUST
AUST	19970708	100122.4	-31.594	153.06	10		3.7	AUST

Source	Date	UTC	Lat	Long	Depth	Ms	ML	auth unsp
AUST	19980309	124042.9	-32.143	150.003	3		3.1	AUST
AUST	19990317	15810.6	-34.234	150.77	8		4.8	AUST
ASC	19990818	1451.1	-33.888	152.302	2		3.3	
ASC	19990818	1915.9	-33.901	152.175	0		3	

Seismic Parameters:

Source: contributing agency

Date: date of earthquake

UTC: Universal Coordinated Time

Lat: decimal latitude

Long: decimal longitude

Depth: focal depth in km

Mb: body wave magnitude

Ms: surface wave magnitude

MD: duration magnitude

MN: Nuttli magnitude

ML: local magnitude

Auth: agency that assigned the magnitude

- MCCU
- RIV
- CAN
- ISC
- AUST
- ASC
- AUST 4.3

Unsp: unspecified magnitude

Mw: moment magnitude

Obs: number of observations

Stat: number of stations

B.2 List of Significant Earthquakes in the Study Region

Date	Time (UTC[22])	Lat (ºS)	Long (ºE)	Place	M_L[23]	I_{max}[24]	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	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

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

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

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

B.3 Isoseimal Maps

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.

The reports of damage and other "felt" effects are quantified in terms of assigned intensities (MM values) and the compiled isoseismal maps for each earthquake and are presented as a contour map of the individual intensities. Isoseismal maps were published in three BMR/AGSO Atlases (Everingham et al., 1982; McCue, 1995; Rynn et al., 1987). The Modified Mercalli (MM) scale, the basis of modern intensity estimates, is described in Appendix A.

The results have been obtained from the files and computer data lists of Geoscience Australia (GA) formerly known as the Australian Geological Survey Organisation, Canberra. Geoscience Australia maintains the Australian National Earthquake Data Centre, where information on all located earthquakes occurring in the Australian region is recorded and updated.

The details of five earthquakes for which isoseismal maps are shown in Figure B - 1 to Figure B - 6 are listed in the following table: These details were taken from GA's earthquake database, which contains earthquake parameters obtained from all sources. The selection of hypocentres and magnitudes for the atlas earthquakes is based on a careful examination of all available data and an appraisal of published information on the earthquakes.

Table B - 1: List of earthquakes with magnitude 5 or greater in the Study Region

Source	Date	UTC	Lat	Long	Depth	M_b	M_s	M_L	auth	M_w	stat
AUST	18421027	193000	-32.6	151.6	10			5.3	MCCU		
AUST	18680618	140000	-32.8	151.6	10			5.3	MCCU		0
MCCUE	19251218	104710	-33	151.6	10		4.5	5.3	MCCU		2
AUST	19891227	232657	-32.946	151.607	11	5.7	4.6	5.5	AUST	5.6	17
AUST	19940806	110351.6	-32.924	151.288	2	5.3		5.3	AUST		

For earthquakes that occurred before 1958, instrumentally determined hypocentres are either not available or have been inaccurately determined because instrumental recordings were rare and timing was inaccurate by modern standards. In fact, until the mid-1950s only five recording stations (Brisbane, Adelaide, Perth, Melbourne, and Sydney) were in continuous operation on the Australian continent. Hence, most of the early earthquake maps show epicentres that have been determined from macroseismic observations; the epicentres are plotted in the zones of highest intensities.

Determinations of epicentres and depths for earthquakes after the late 1950s are more accurate than for earlier earthquakes and their accuracy can vary less. By the end of 1983, many more seismographic stations had been installed but there were still significant gaps in the coverage of northern New South Wales. The most accurate results have been obtained for those earthquakes with epicentres located within networks of stations, and those which have been closely studied because they were felt over a wide area. The focal depths of some earthquakes have been determined by using local network results or reliable depth phases recorded as teleseisms.

Each magnitude was investigated to ensure that it was reliably determined from instrumental data because earthquake lists frequently record magnitudes that have been determined from intensity data or have been determined by non-standard methods. Local magnitude (M_L) was the most commonly determined magnitude, and therefore generally preferred by researchers. Reliable magnitude values for several of the earlier earthquakes could not be determined instrumentally from seismograms, so their magnitudes were calculated according to the following formula for macroseismic data (McCue, 1980):

M_L (I) = 1.01 ln Rp (111) + 0. 13,

where Rp(l11) is the radius or perceptibility to the MM III contour and ln is the natural logarithm. Magnitudes determined by this method should be treated as approximate values which may be revised as a result of further research.

These isoseismals maps are smoothed versions because they enclose all intensity observations equal to or greater than a given intensity, but ignore some intensity reports which did not fit the general pattern. Because of the sparseness of instruments to record strong ground motion in Australia we will have to continue to rely 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 future earthquakes and possible revisions of existing isoseismal maps will be included.

A significant event which occurred in the study region within the last 100 years occurred on 18 December 1925 and had a magnitude of ML 5.0 determined from the Mainka seismograms recorded at Riverview, whilst that derived from the radius of perceptibility was ML(I)=5.3. The isoseimal map was compiled from newspapers reports in the Sydney Morning Herald, Northern Daily Leader, Lithgow Mercury, Queanbeyan Age and Goulburn Herald. At Newcastle two severe shocks were felt and there was panic in a picture theatre. In Sydney a sharp shock was felt. The earthquake was also felt by a miner 600 feet below the surface in West Maitland.

Figure B - 1: Isoseismal map for the Newcastle earthquake, 27 October 1842

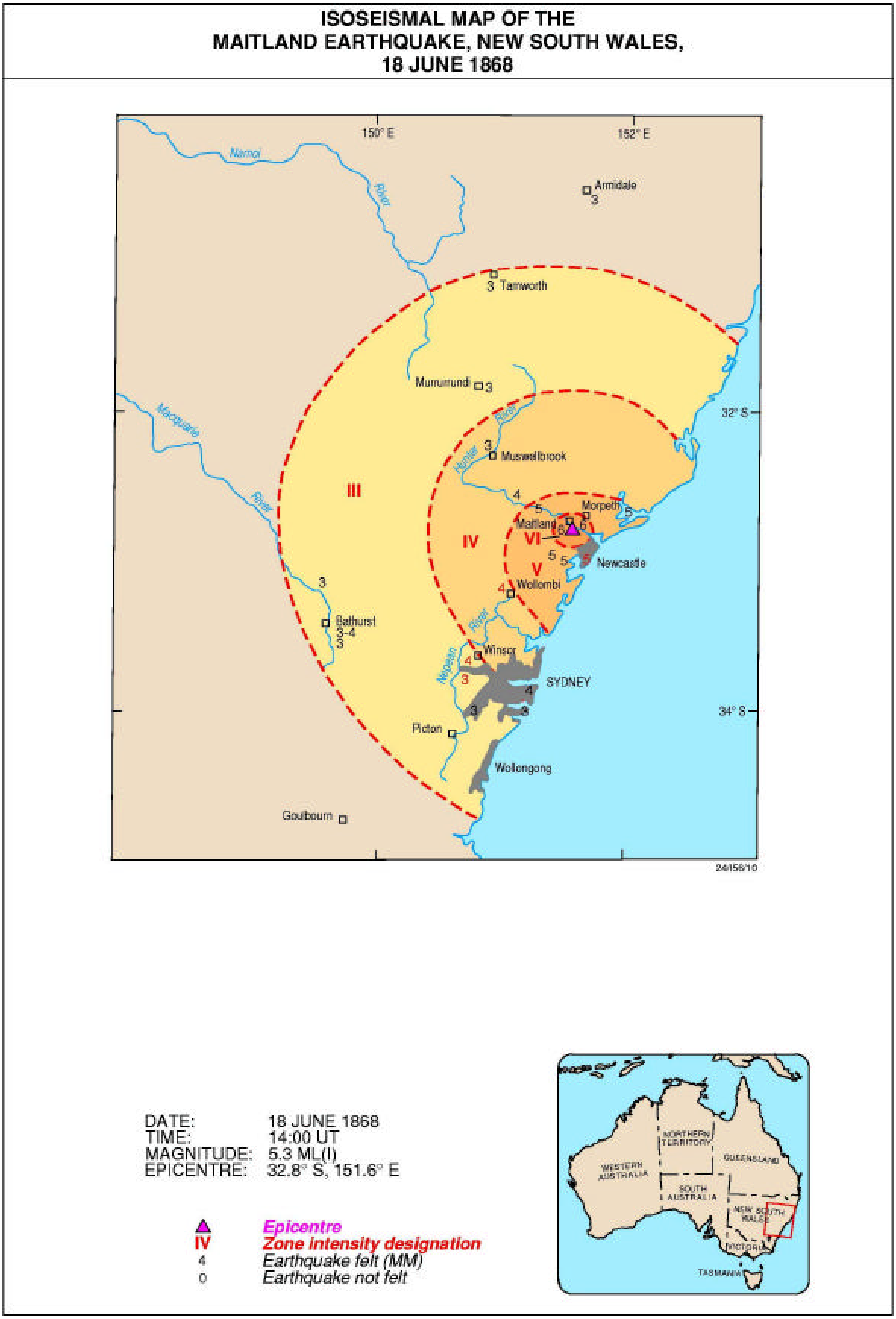


Figure B - 2: Isoseismal map for the Maitland earthquake, 18 June 1868

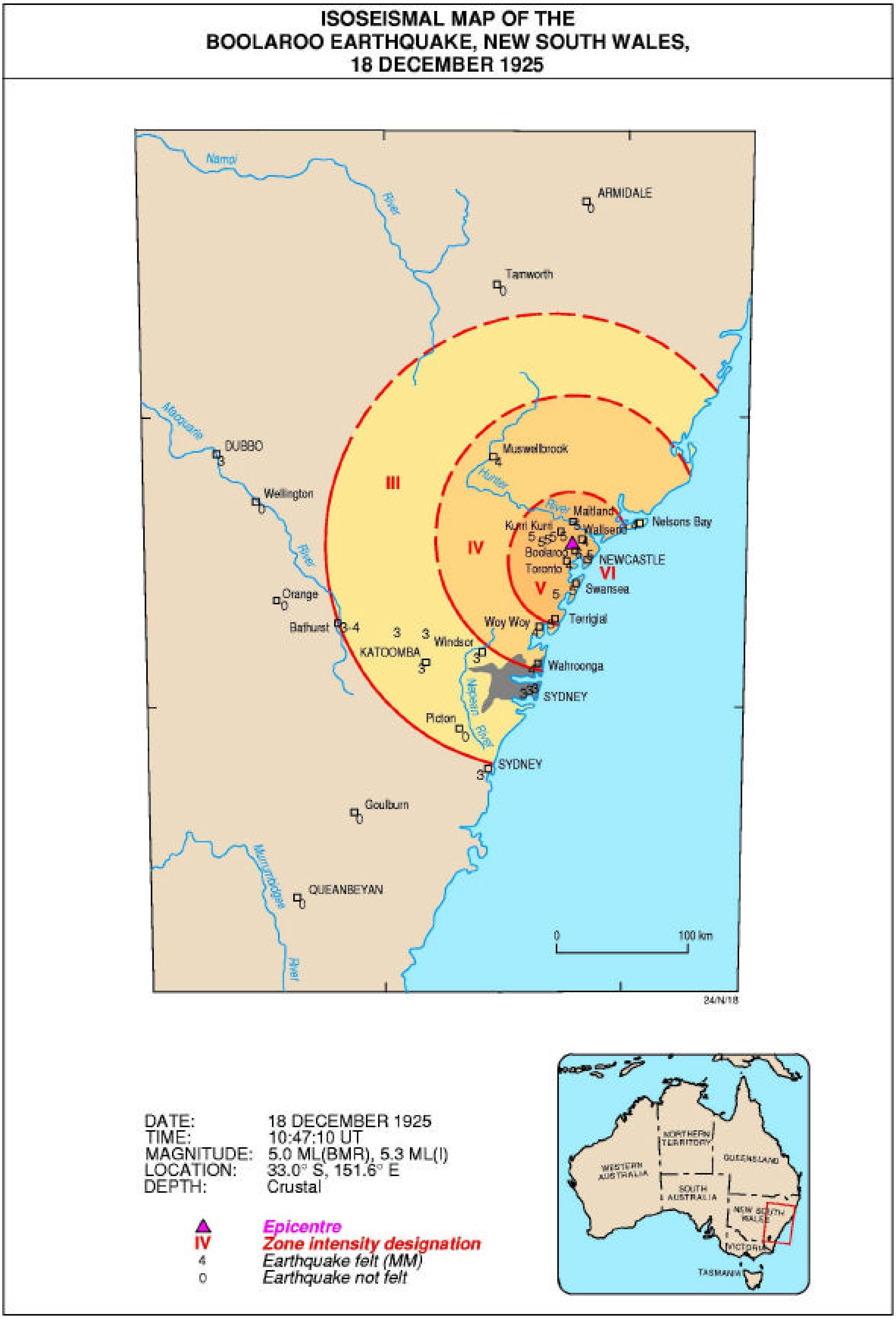


Figure B - 3: Isoseismal map for the Boolaroo earthquake, 18 December 1925

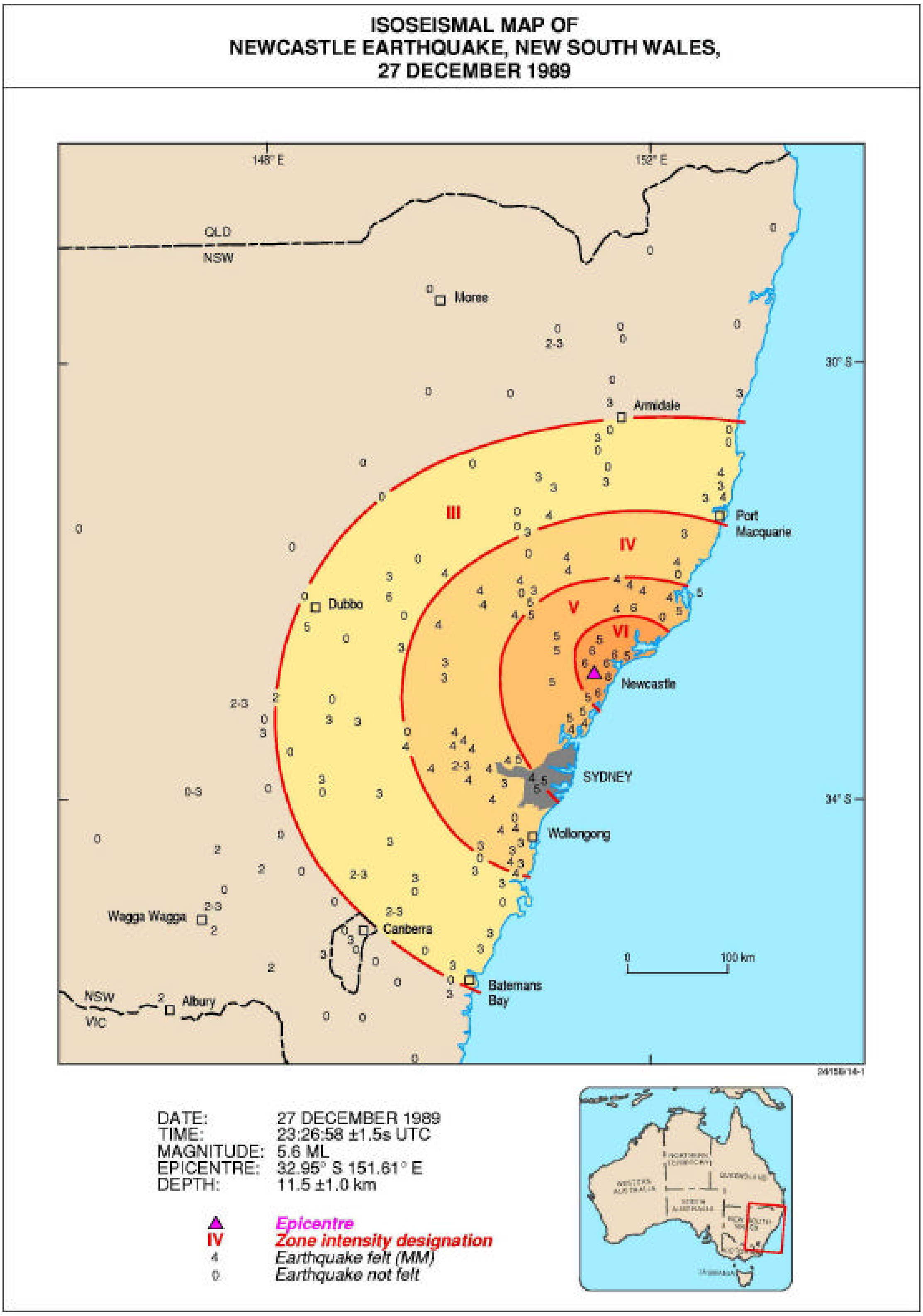


Figure B - 4: Isoseismal map for the Newcastle earthquake, 27 December 1989

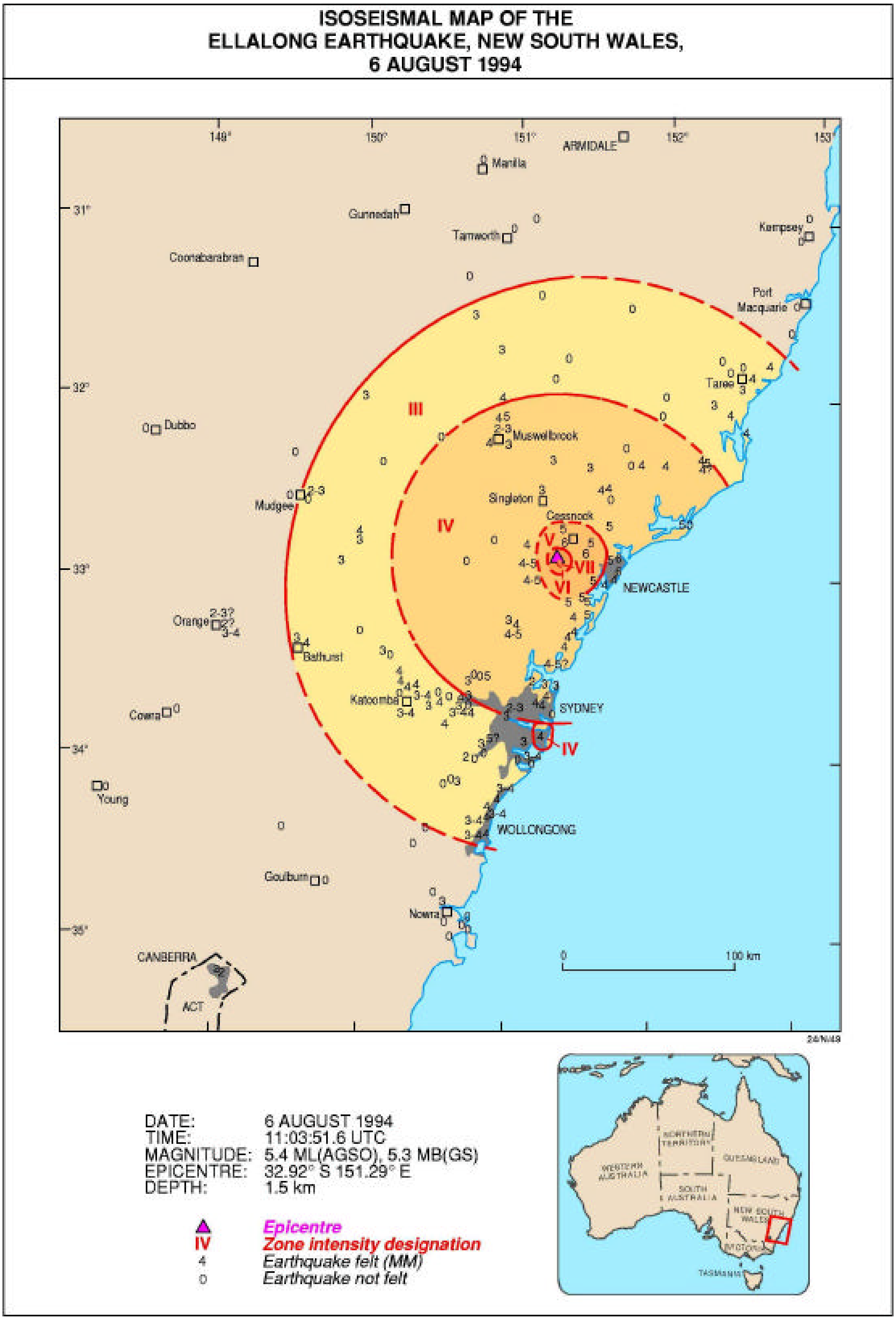


Figure B - 5: Isoseismal map for the Ellalong earthquake, 6 August 1994

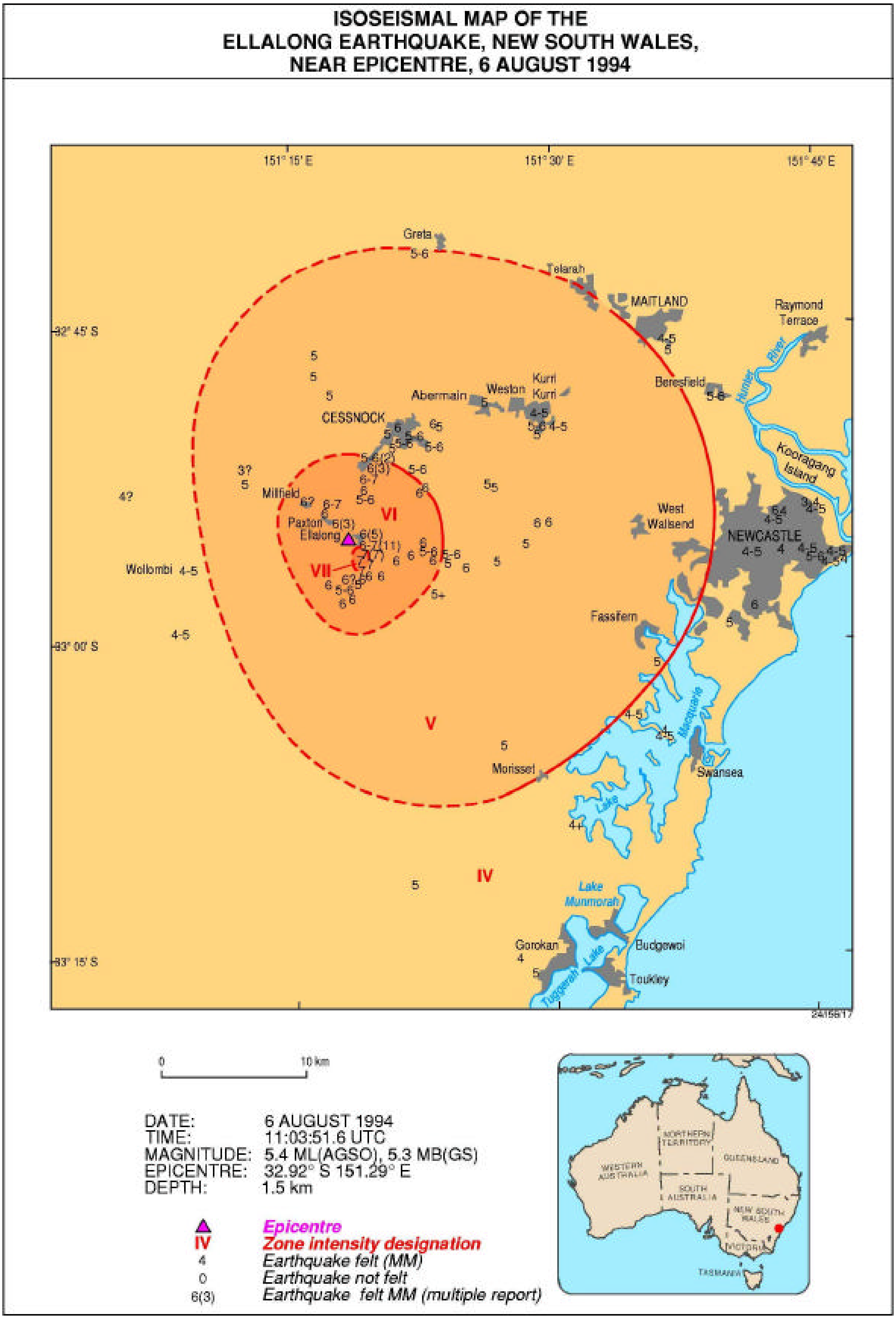


Figure B - 6: Local isoseismal map for the Ellalong earthquake, 6 August 1994

Appendix C - EARTHQUAKE HAZARD IN THE LOWER HUNTER REGION OF NSW

C.1 The Workshop

The following is a draft report on a workshop held in Sydney on 19 December 2000 attended by a group of scientists experienced in the geological and tectonic structures of the Hunter Region. Geoscience Australia has used the outcomes from the workshop to refine the analytical processes for estimating seismic hazard. This appendix is presented as a short technical note followed by informal notes from the meeting.

C.2 Part A - Regional Earthquake Hazard Models

C.2.1 The Cities Project

The Cities Project is examining risk to Australian urban communities from a range of geohazards. The Newcastle part of this project is particularly looking at risk from seismic hazards. Risk is defined in a quasi mathematical form as:

RISK = $f\{$ Hazard, Elements Exposed, Vulnerability $\}$

Risk contains both time and magnitude elements and is an expression of the cumulative or compendium probability of events occurring. This cumulative dimension is particularly important in considering massively impacting events such as earthquakes or tsunamis for which the estimate of recurrence interval is stated in hundred or thousand year periods.

C.2.1.1 Geological Structures and Seismic Hazard Workshop

One of the main tasks of the project is development of an earthquake hazard model for the Newcastle and Lake Macquarie region. The earthquake hazard model formed the basis from which ground-shaking scenarios with associated likelihood of occurrence were generated, for Newcastle and Lake Macquarie. The ground shaking scenarios, suitably modified by amplification factors that account for local ground conditions, were be used to assess earthquake risk in the Newcastle/Lake Macquarie study area.

Geoscience Australia (GA) sought the most knowledgeable experience available of tectonic structures and of possible active fault zones in the project region to refine this model. A workshop was convened as a part of the Cities Project following formal and informal discussions within the geological and seismological community.

The objective for GA was to develop a model for the occurrence of earthquakes for the study region, based on a consensus of expert opinion on the likelihood, magnitude and location of events. Wave propagation and ground shaking were not considered in this part of the process. The Risk Assessment process being used for this project required an estimate of the seismic hazard of the Study Region. The two specific outputs which GA wished to take away from the workshop were:

- A description of seismic occurrence models for the Newcastle and Lake Macquarie region, specifically focused on recurrence intervals, locations and magnitudes of events, and;
- Estimation of specific parameters for the model

An informal meeting with the several most experienced and knowledgeable geologists and seismologists available, was convened in Sydney on Tuesday 19 December 2000 to assist with this task. At the commencement of the workshop the group considered that it could reach a consensus and should aim to do so, rather than be pressed to voting on points.

C.2.1.2 Terminology used

Hazard can be defined as the probability of occurrence, within a specified period of time in a given area, of a potentially damaging natural phenomenon (earthquakes in this case).

Models are the theoretical constructs which are used to describe the tectonic structures and seismic behaviour, past and possible future, for the Lower Hunter region. Two sets of these models, accepted as providing feasible representations of the geology and tectonics of the Lower Hunter Region, were considered. Area Source models assume that probability of seismic events exists uniformly across a defined zone and Fault Source models assume that seismic activity will occur on specified faults.

C.2.2 Definition of Earthquake Source Zones

C.2.2.1 Area Source Seismic Zones

Earthquake source zones which have a random distribution of earthquake epicentres within a given geographic area are termed Area Source Seismic Zones. Earthquakes of given magnitudes have an equal probability of occurrence anywhere in each zone. The EQ magnitude/return period function is calculated for events of all magnitudes to estimate the seismic hazard faced by communities in the Study Area according from these zones. Those accepted were:

Tasman Sea Margin Zone (or TSMZ)

This zone is defined as a single, uniform hazard earthquake source zone that extends from northern Tasmania into Queensland as far north as the southern extremity of the Great Barrier Reef. The western margin of the TSMZ corresponds approximately with the 350 m AHD topographic contour west of the Great Dividing Range, and its eastern margin is located approximately along the eastern Australian continental shelf margin. The TSMZ is associated with the opening of the Tasman Sea and the separation of the New Zealand and Australian land masses. A square zone of side 300km centred on the Newcastle/Lake Macquarie study area is a subset of the Tasman Sea Margin Zone with uniform seismic probability derived from the larger zone and is termed the Newcastle Study Zone for the subject work. The boundaries of this zone are based on the assumption that no geological features can be identified which might change the probability of EQ occurrence in any part of the zone, such as the Hunter Region, from the overall TSMZ statistical averages. The TSMZ is shown in Figure 1.

Newcastle Triangle Zone

This zone has been specified on the hypothesis that the geological structures of the Lower Hunter region are well defined and have sufficiently clear tectonic inter-action to determine local seismic activity which is different from that in the wider field Tasman Sea Margin Zone. This comprises a triangular zone of approximately 3,000 km^2 defined by the geological structures of the Lower Hunter Region and is assumed to have uniform earthquake occurrence.

The triangle is bounded by the coastline, a north-west – south-east line through Port Stephens representing the edge of the New England Fold Belt and a north-west - south-east line through Wyong and Singleton (Figure 2). Seismic activity outside this triangle zone would be derived from the Tasman Sea Margin Zone. Coordinates of the Newcastle Triangle Zone are: near Nelson Bay (32^* 45’, 152^* 10’), near Wyong (33^* 15’, 151^* 30’), and near Singleton (32^* 30’, 151^* 15’). The south-west side of this triangle does not well represent a geo-tectonic feature and at this stage the Newcastle Triangle Zone is only a first approximation of a local zone of heightened seismic activity.

This zone is based on the assumption that the occurrence of EQs within it is more conditioned by the geological structures of the Hunter Region than by the average occurrence over the whole Tasman Sea Margin Zone. Although a triangular shaped zone has been adopted at this stage of the analysis, further work is proceeding on specifying the boundaries as they represent actual deep geological features with tectonic significance.

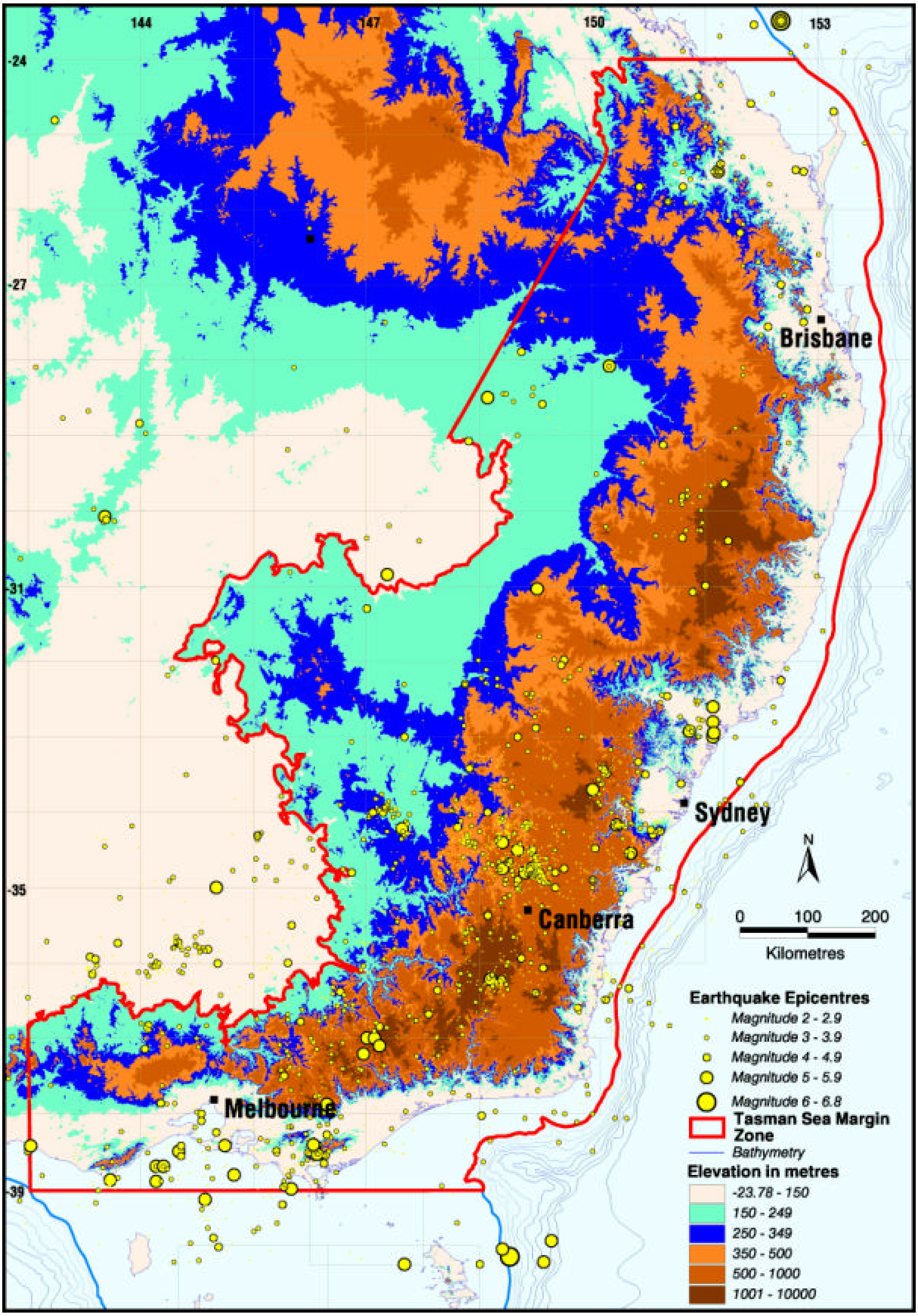
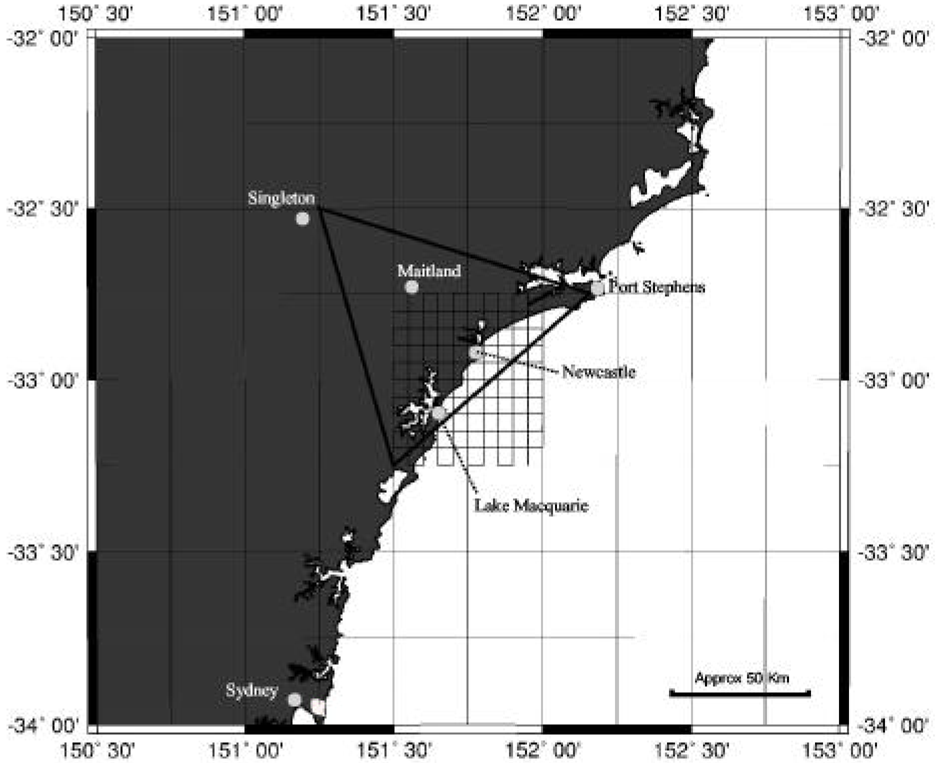
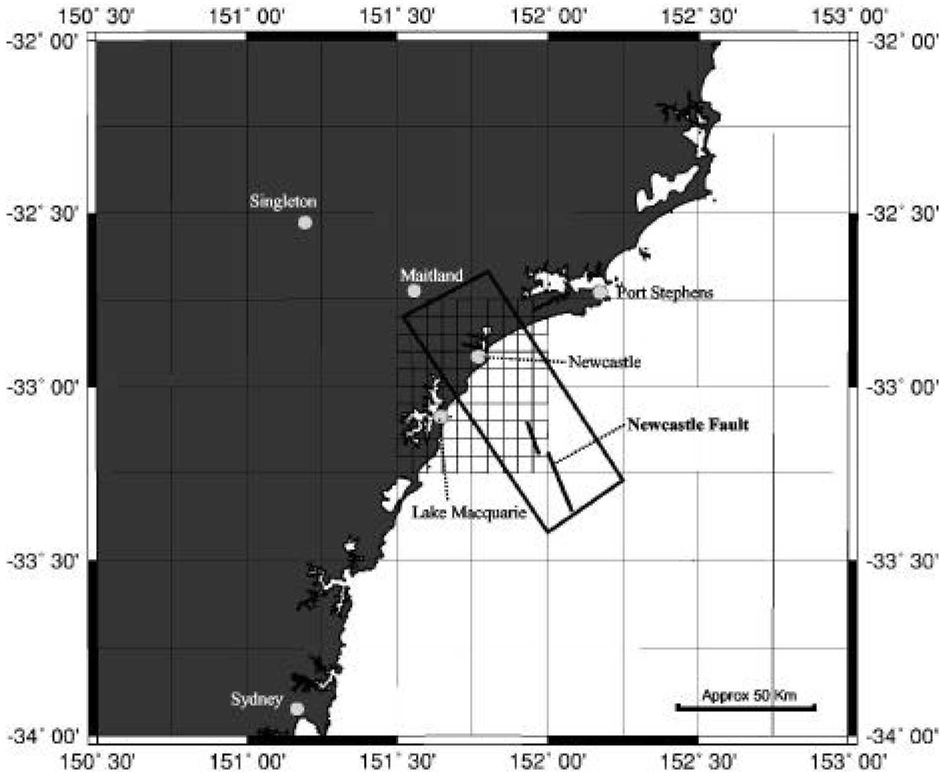


Figure 1: Tasman Sea Margin earthquake source Zone (TSMZ)



Newcastle Triangle Zone



Newcastle Onshore/Offshore Polygon Zone

Figure 2:Part 1 - Newcastle Triangle Zone, Part 2: - Newcastle Onshore/Offshore Polygon Zone. Its boundaries also correspond to the Newcastle/Hunter River Cross Fault Zone

Newcastle Onshore/Offshore Polygon Zone

This is a polygon zone defined to include the fault structures on- and off- shore in the Lower Hunter Region. The faults considered to be potentially active are the Newcastle Fault, offshore from Newcastle and reported by G Huftile in the literature, and a feature between the end of the Mooki Thrust near Maitland and the coastline near the city of Newcastle. This zone of uniform EQ hazard is a rectangle 20 to 30 km wide, aligned north-west - south-east, centred on a line approximately through Nobbys Head, bounded by a NE/SW line through Maitland and a line approximately 50 to 60 km parallel to it and off the shore (Figure 2).

C.2.2.2 Fault Source Zones

Only one fault system was accepted by the workshop. It is termed the *Newcastle/Hunter River Cross Fault Zone* and is a coupled fault system comprising: It is described in more detail in Appendix C.

The *Newcastle Fault* (offshore, but possibly also onshore) being the structure described by Huftile et al. (1999), lying 20 to 50 km south-east of Newcastle.

The *Hunter River Cross Fault* lies in the *Hunter River Transverse Zone* being a zone from the eastern extremity of the Hunter Mooki Thrust Zone near Maitland to the coast at Newcastle. This fault has uncertain location and was accepted by the workshop as being equivalent to the onshore component of the Newcastle Fault suggested above.

The *Newcastle/Hunter River Cross Fault Zone* is shown in Figure 2. The only other major fault was the Hunter Mooki Thrust which was not considered by the workshop to be an active fault structure.

C.2.3 Conclusions & Recommendations

Workshop delegates agreed to an Areal Source Zone earthquake hazard model, a Fault Zone earthquake hazard model, and an ultimate Earthquake Hazard Model that combines the areal zone and fault zone models in a probabilistic form.

C.2.3.1 Area Source Zone Model

In and near the study area, the model assigns equal (ie., 50%) weighting to the Newcastle Triangle Zone and to the Newcastle Onshore/Offshore Polygon Zone. Outside of this area, earthquakes are generated with likelihood of occurrence determined by the seismicity parameters of the Tasman Sea Margin Zone.

In practice, GA decided to use an Area Source Zone Model with 100% weighting applied to the Newcastle Triangle Zone within the Tasman Sea Margin Zone. That is, the Newcastle Onshore/Offshore Polygon Zone was not included in the Area Source Zone Model. The reason for this move is that estimates of earthquake hazard from a Newcastle Onshore/Offshore Polygon Zone are essentially the same as estimates of earthquake hazard from a Fault Source Zone Model, as we describe below. Its inclusion in both the Area Source Zone Model and the Fault Source Zone Model would have led to an overweighting on the Newcastle Onshore/Offshore Polygon Zone in comparison to other possible Lower Hunter earthquake source zones.

C.2.3.2 Fault Source Zone Model

The Newcastle/Hunter River Cross Fault Zone, a coupled fault system, was accepted as a fault model. The model assumes that earthquakes will be located on the Newcastle Fault or its on-shore extension. Earthquakes of equal magnitudes will be located with equal probability along the fault. Earthquakes can also occur in the region beyond the fault zone with a likelihood of occurrence given by the seismicity parameters of the *Tasman Sea Margin Zone*.

In practice, the Newcastle/Hunter River Cross Fault Zone has boundaries that correspond closely to the Newcastle Onshore/Offshore Polygon Zone. GA decided that the modelled ground motions in the study area resulting from earthquake occurrence on a distributed system of sub-parallel, north-west trending faults in the Newcastle/Hunter River Cross Fault Zone would be little different from modelled ground motions resulting from the random occurrence of earthquakes in the Newcastle Onshore/Offshore Polygon Zone.

C.2.4 Earthquake Hazard Model for the Lower Hunter

The probabilistic Earthquake Hazard Model for the Lower Hunter assigns weighting to the likelihood of occurrence of earthquakes as follows:

Event Magnitude	***Area Source Zone Model***	***Fault Source Zone Model***
Small earthquakes (M< 5.5)	75%	25%
Large earthquakes (M5.5 to 6.5)	25%	75%

The maximum earthquake magnitude considered possible in the study region is M6.5 plus or minus M0.5.

C.3 Part B - Notes From the Workshop

C.3.1 Hazard Models Framework

C.3.1.1 Introduction

At the commencement of the workshop the group considered that it could reach a consensus and should aim to do so, rather than be pressed to a vote on conclusions, which would raise the issue of the weighting of votes.

The following notes were prepared by GA and circulated to all participants for comment, addition and correction. They are abbreviated and intended to capture the principal statements and conclusions of all participants, but they are neither a full record of all discussion nor are they minutes of the workshop. They attempt to include all significant points made by all participants.

C.3.1.2 Seismic Incidence Science

Geoscience Australia presented the principles of seismic incidence science covering: the Guttenberg/Richter curve with the “a & b” parameters and the characteristic “bump” at maximum magnitude; the occurrence of ground shaking at a location, affected by decay and attenuation of the energy wave as it travels from its source; and the site factors at a location which can amplify the amplitude of shaking and bring frequency into proximity to that of the surface soil layer and structures on the surface. The probability analysis for seismic response at a location is obtained by integrating all possible seismic events received at that location. In summary, the seismic experience at a location is comprised of:

* the location, frequency and magnitude of rock mass rupture events,
* attenuation as energy travels from these events to the specified location of concern, and
* site amplification within surface layers at the location.

A very big uncertainty for GA’s cities project is information on probable locations of earthquake events within the region, being the three spatial coordinates of a seismic rupture event, the direction and the nature of the rock mass movement of this event. There are two types of this uncertainty, randomness in nature, and human knowledge of activity on existing faults.

C.3.1.3 Decision Making Process

The fault logic tree template which GA will adopt was discussed.

C.3.2 Regional Earthquake Catalogue

It was noted that the GA catalogue contains, for the Lower Hunter Region, seventy five (75) EQs of magnitude >2.0ML.

Depths range from 0 to 21 km with error of +- 5 km.

The Newcastle EQ1989 was at depth 11 km and its location has been ascribed accuracy of +- 5 km in all x, y ,z coordinates.

The Ellalong EQ1994 was at depth 2 km (it may have been mining related though this hypothesis is rejected by GA).

The Newcastle EQ1989 occurred over a fault face of about 5 km square. The participants agreed that it resulted from a reverse thrust mechanism.

The catalogue is complete offshore.

Instrumentation has been normalised so that all events >3.2M are included for the last 20 years, >4.0M for the last 100 years.

Events have not been stratified by depth.

Mine activity, blasts and collapses have been removed from the catalogue.

C.3.3 Tectonic Framework

Participants briefly outlined the tectonic structure of the Lower Hunter:

The Hunter Thrust has an end about 10 km west of the coast and then roughly follows the Hunter River inland in a WNW direction.

The Sydney Basin in this region is underlain by the Lachlan Fold Belt at a depth of about 6 km.

The Hunter River Transverse (Cross Fault) Zone (HRTZ) is an indicator of old structure in continental formation, with a NW orientation.

If EQs are occurring at depths much greater than 6 km (as is indicated) this may indicate re-activation of old stress fields and faults in the older HRTZ.

A discussion followed on the location of possible activity and age of structures involved:

The stress field in the Sydney Basin is variable with strong NW but some NS measurements. Work by Dr J Enver of CSIRO is a reference. There is a strong NE trending signal close to Newcastle.

There may be old blocks which have rotated with the stress field unrelieved, leading to an array of observed stress orientations.

What is the relevance of the question of depth? There are modern day stresses and there is re-activation of structures. Whether the EQ events are in the Sydney Basin or deeper there are two fracture planes, whether these are Sydney Basin or deeper in the Lachlan is an unknown.

A M5.5 EQ would be expected to rupture on 25-35 km^2 of fault and the aftershock, which was measured, would probably be on the edge of the main fault. This could put the depth as deep as 14km.

If the events are deep in the Lachlan then we are looking at Lachlan seismic events which occur as far south as Goulbourn and Canberra. This would influence the EQ catalogue used to estimate return periods.

The on-shore off-shore differences were noted. Geology offshore is not necessarily the same as geology onshore eg. Currarong Oregon is different and it is poorly known in the Sydney-Newcastle area. There is evidence of faulting offshore. Events in this medium may not be related to Lachlan based events.

The relationship between surface geology, tectonic structures and zones of varying seismic activity were considered. Field research over recent years has shown no sign to indicate the Hunter Thrust is active.

The seismic activity polygons developed by Gibson and others, based on the Gibson EQ catalogue and used in other studies in the Sydney Basin were discussed. The Gibson work produced a zone around Newcastle which included most of the observed EQ Events.

It was noted that caution is needed when laying seismic activity polygons over the surface geology. The size of events and whether mine shocks were included was an issue. Is it possible to plot energy released rather than just events? Are aftershocks from larger events removed?

If there is a re-activation of old rift faults, the currently observed surface features and zone boundaries may be less relevant.

C.3.4 Source Models

Geoscience Australia staff then described the three seismic source model types which GA was proposing: zone models, area source models, and fault models. The three parameters in these models are ‘a’ the y intercept of frequency, ‘b’ the slope of occurrence against magnitude and ‘M_{MAX}’ the maximum magnitude. M_{MAX} cannot be calculated from the earthquake catalogue but must come from the geology and palaeontology of a zone. All EQs occur on faults; large EQs occur on faults with an area large enough.

The sampling and analysis problem of dealing with errors in small numbers was questioned because the scientific record in Australia is very short. [This point did not raise sufficient debate during the workshop, considering its significance in the work of EQ forecasting.]

C.3.4.1 Zone Models

A new tri-polygon model which includes the majority of EQ events on the continental plate has previously been proposed by GA. One of the polygons includes most of eastern Australia, from north Queensland to Tasmania.

This tri-polygon model, including most of eastern Australia in large zone, was rejected by the workshop as irrelevant – the stress patterns at the north end are quite different from at the south end. A revised zone was proposed, termed the Tasman Sea Margin Zone (TSMZ) which includes the majority of seismic events in eastern Australia, extending from Fraser Island in SE Queensland to Melbourne. This was agreed to be a very significant tectonic structure in the continental plate [inclusion of north-eastern Tasmania was uncertain in the workshop, and it was excluded later by GA because of tectonic differences].

The continental shelf is 40-60 km offshore at Newcastle with a depth change from 200m on the shelf down to 2000 to 5000m over the edge. It is a passive margin but deeper than world average passive margins.

A discussion ensued on very large earthquakes, the scale of fault movement and energy needed to generate them and the likely maximum EQ Event in the Lower Hunter Region. Later discussion put this as a maximum M6.5 +- 0.5 Event. It was noted that bigger EQs were typically at 15km depth. It was noted that different geo-structures exist at different depths.

Geoscience Australia noted that the catalogue enabled EQs down to M3.0 to be analysed in this TSMZ ‘though it excluded the two large M6 events near Gladstone in Queensland. John Schneider commented that only parameter ‘a’ was taken from the zone analysis and that maximum magnitude would come from the geological context. However more large EQ events decrease the error in “b” and hence have an effect on the hinge point of the curve.

Tasman Sea Margin Zone (TSMZ)

This model assumes uniform EQ hazard on the coastal zone extending from north-east Tasmania to south-east Queensland. This model is statistically reduced through analysis of the catalogue to a square zone of 100,000 km2 of uniform seismic probability centred on the Newcastle/Lake Macquarie study area. This is termed the Newcastle Study Zone and is a subset of the Tasman Sea Margin Model.

C.3.4.2 Area Source Models

The Gibson Mooki Polygon which was discussed earlier under Tectonic Structures was reviewed and adjusted by an appraisal of geological structures.

A large triangle was drawn with a SW/NE side along the coast from near Terrigal to Birubi Point (Anna Bay), a NW/SE side from Birubi Point to just north of Singleton, and an uncertain NW/SE side from Singleton to Terrigal. This was termed the “Newcastle Triangle Zone”. The north and east sides were considered to have geological significance; the south-west side had uncertain significance and/or location. It was agreed that this triangle represented a zone of stress build up squeezed in the Sydney Basin. The corners of this triangle were at 32:50S/151:50E, 33:20S/151:30E, 32:10S/150:50E drawn very, very approximately.

The seabed between the coast and a line parallel to the coast and about 100km offshore (edge of continental shelf) may be of New England Fold Belt origins. The offshore continental shelf also has geological significance in consideration of tectonic structures and seismic events.

Newcastle Triangle Zone

This comprises the Newcastle Triangle Polygon. Seismic activity outside this zone would be represented by the Tasman Sea Margin Zone model. The Newcastle Triangle Polygon Model assumes uniform EQ hazard for a smaller triangular zone bounded by the coastline, a north-west – south-east line through Port Stephens and a north-west - south-east line through Wyong and Singleton (Figure 1).

C.3.5 Fault Sources

C.3.5.1 Newcastle Fault

Recent research was presented.

The Offshore Newcastle fault is west dipping, shows at least 30m of uplift and a minimum area of 1000 km2 , with incomplete mapping so the area is bigger than this.

- The estimated dip is 39°+-3°.

If Newcastle EQ 1989 was typical it would take 30,000 such events to generate this fault; if these had occurred over 3 million years this gives a return period of 100 years.

The surface shows as a monocline with no surface rupture. World experience is that EQs with magnitude M6.0 to M6.5 will break the surface so it is hypothesised that the Newcastle Fault has experienced no events of magnitude greater than M6.0 over the last one million years.

The next stage of investigation would be drilling and careful logging to determine materials, age, source etc in the top of the offshore Quaternary. The PROD device at Sydney University may be appropriate and can drill to depths of 250m. “Swath” mapping and side-scan sonar would also be good investigation tools. Such research is needed to substantiate hypotheses of seismic activity on this fault.

A discussion followed on relationship between the Newcastle Fault and the nominated EQ1989 epicentre at Boolaroo.

The Newcastle fault can fit the epicentre well; the strike is well defined from several lines.

The Newcastle Fault could extend inshore but would not necessarily be seen closer inshore.

As the surface layers are soft they would not rupture but be deformed by plastic strain; does this affect the maximum magnitude?

If the fault moved in one event on the mapped section (30 km length at 40° dip to a depth of 15 km) then a M7.2 event would have occurred; this would rupture the surface.

The maximum possible magnitude on this fault may be > M6.0< M7.0 and this would not rupture the whole length in one event.

The average rate of movement could be 30 metres over about 5 million years.

C.3.5.2 Hunter-Mooki Thrust and Hunter Transverse Zone

As stated earlier field research over recent years has shown no evidence which indicates that the Hunter Thrust (HMT) is active. What is the meaning if the Hunter-Mooki Thrust is not active and the Newcastle Fault is?

The Hunter-Mooki Thrust has an easterly end near Maitland. There may be a link between the Newcastle Fault offshore and the HMT ie. a continuity of structure and fracture. At this point it was proposed that the current term for the HR Transverse Zone should be used; this is Hunter River Cross Fault (HRCF).

Geoscience Australia has shown that the Ellalong EQ 1994 could not have occurred on the onshore extension of the Newcastle Fault. This is relevant in justifying the adoption of the dual model.

Geoscience Australia noted that the seismic budget for the zone seemed to exceed the supply available from the Newcastle Fault capacity. Does this mean that return periods will be less than calculated earlier or that another source of seismic budget exists, such as in the HR Cross Fault Zone?

One estimate showed that if 50 metres of fault slip occurred over 5 million years this would indicate a M7.0 event approximately every 200,000 years, or a M5.5 event every 2,000 to 3,000 years. One researcher favoured a series of M5.0 to M5.5 events.

C.3.6 Conclusions

Comments were then made on Earthquake hazard models for the Hunter Region. Zones which were not considered significant and which were rejected for more detailed analysis were the NSW Microzone Model after Gibson and the east Australian polygon model after GA. A poll was taken on Hunter Region earthquake models and considerable consensus achieved. No participants disagreed with the following table of possible models.

The maximum possible magnitude for an earthquake in the Lower Hunter Region was considered with full agreement to be M6.5 +- 0.5.

Agreed weights for seismicity models

	Random model	**Fault model**
Earthquakes M<5.5	75%	25%
Earthquakes M5.5 to M6.5	25%	75%

Agreed models	Comments	Active or accepted Y/N	% weight of total
Random earthquake models			
Newcastle onshore triangle (Blue Triangle)	Equal weight 50% with Newcastle onshore/offshore model	Y	Combined 50/50
Newcastle offshore/onshore polygon (Red Polygon)	Equal weight 50% with Newcastle onshore triangle model	Y	
Tasman Sea Margin Zone	Preferred to Large Quadrilateral As uniform model - 100%, or as background seismicity	Y	100% or background
Gibson Mooki microzone model	Not accepted.	N	Nil
Large east Australian rectangle (the GA model)	Not accepted; replaced by Tasman Sea Margin Zone	N	Nil
Fault models			
6 Newcastle Fault, offshore and onshore	Onshore occurrence uncertain. Modelling coupled with Hunter River Cross Fault	Y	Coupled fault structures
7 Hunter River Cross Fault	Location uncertain Modelling coupled with Newcastle Fault	Y	
8 Hunter-Mooki Thrust	Not supported	N	

C.4 Part C - Workshop Participants

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Appendix D - GEOLOGY AND TECTONIC FRAMEWORK

D.1 Introduction

The geology of the Newcastle and Lake Macquarie municipalities described in this appendix, forms the framework for ground shaking assessment modelling. As alluvial sediments are the major geological amplifier of seismic energy, the Quaternary geology is the primary focus of this paper. The underlying Permian basement and associated structural elements are also discussed to provide geological context.

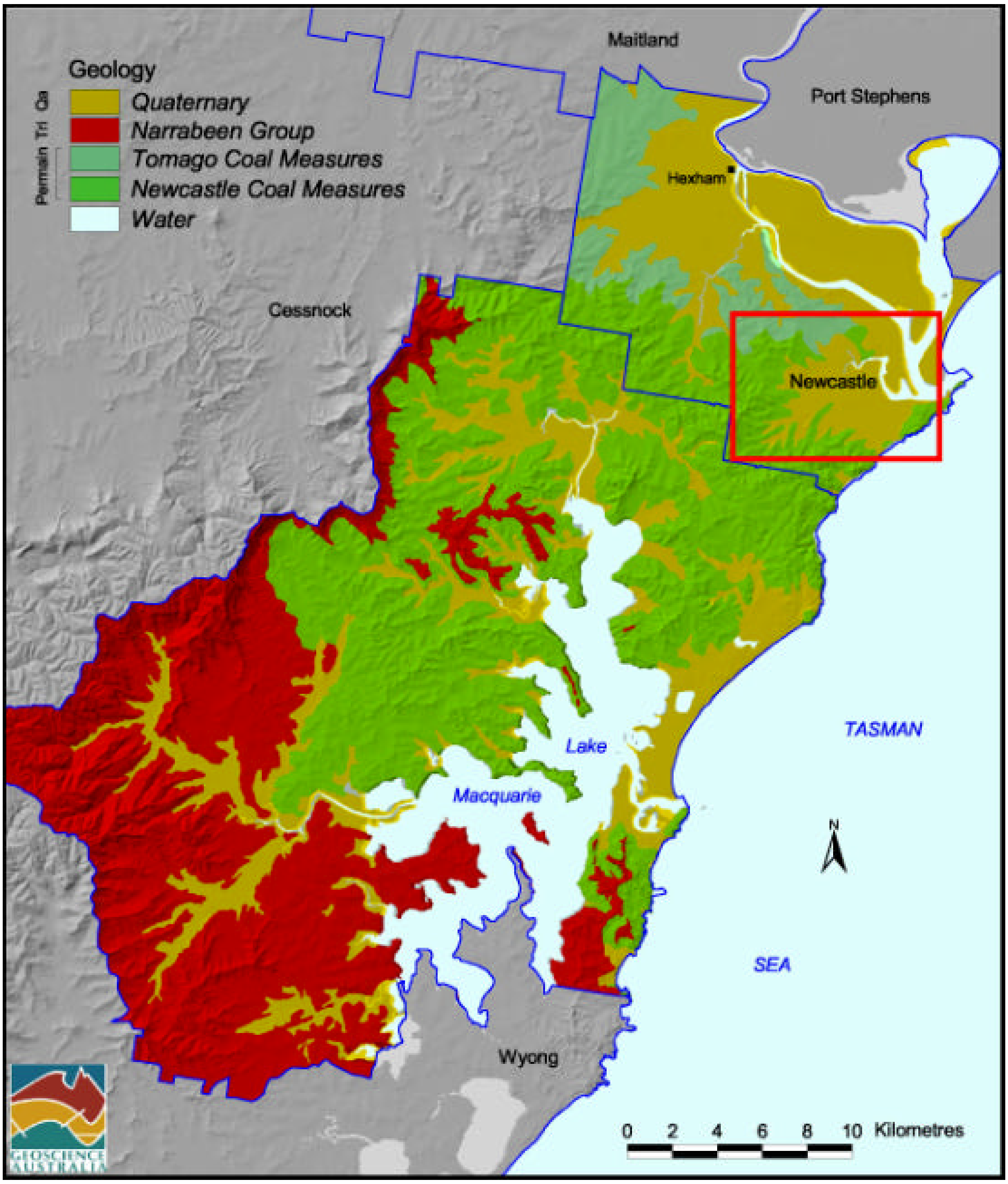


Figure D - 1: Geology of the Newcastle and Lake Macquarie regions. The Quaternary sediments within the red box outlined above are referred to as the Newcastle Basin.

Detailed facies and depositional interpretations based on a detailed subsurface dataset are presented for the Quaternary succession in the area directly to the south of the Newcastle municipality, hereafter referred to as the Newcastle Basin ('study area' in Figure D - 1). In the area to the north of Newcastle City and around Lake Macquarie, interpretations are based primarily on the work of others (Roy et al. 1995) and surface geophysical data, and thus these interpretations are broader in scope.

D.1.1 Regional Geology

D.1.1.1 Tectonics

This Section briefly outlines the tectonic setting of the study area, as a basic understanding of this tectonic context is critical when considering the underlying structures that may be responsible for earthquakes in the region.

The Newcastle region is situated in the north-eastern portion of the Sydney Basin (Figure D - 2). The Sydney Basin is the southern component of the composite Sydney-Gunnedah-Bowen Basin, a Permo-Triassic sedimentary basin extending from near Batemans Bay in the south to Collinsville in the north (Bembrick et al., 1980).

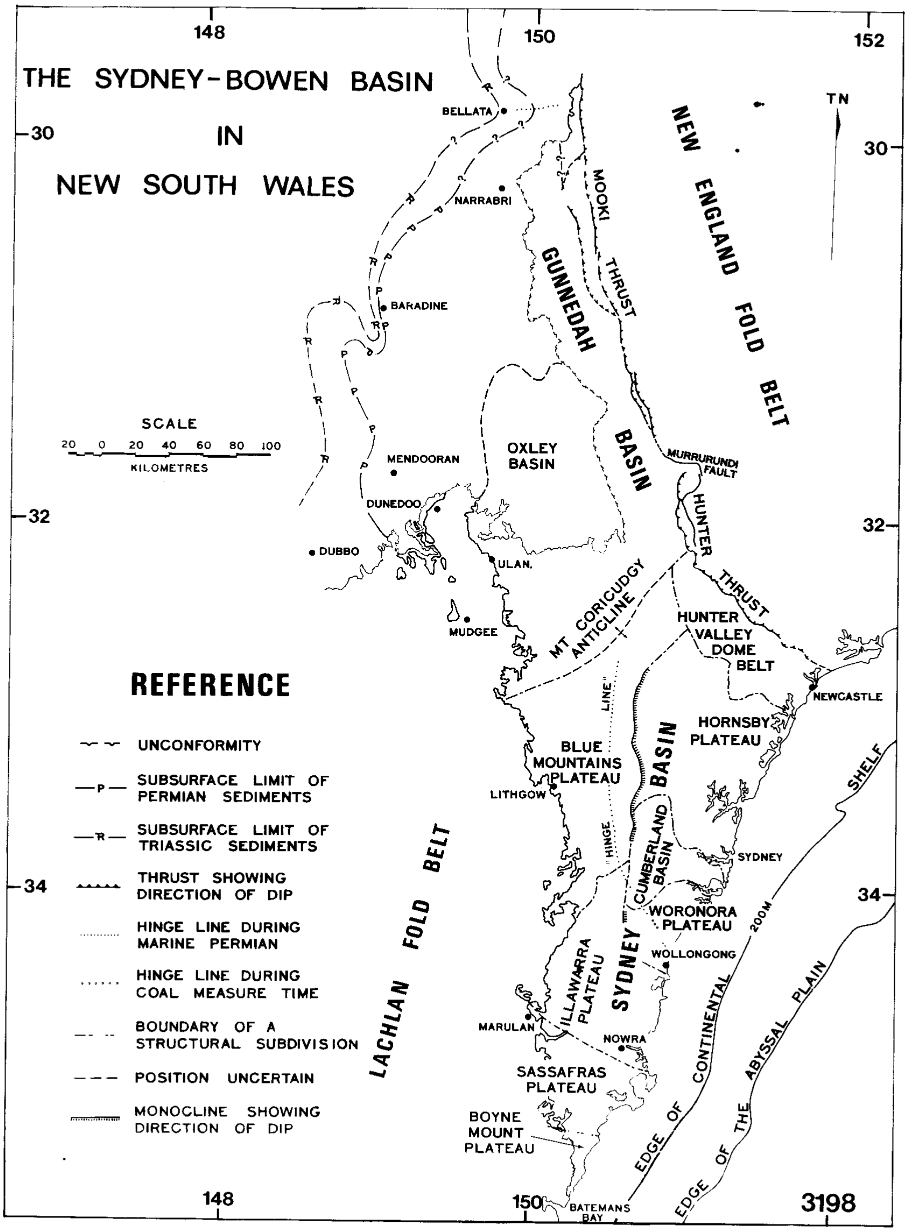


Figure D - 2: Tectonic elements of the Sydney-Bowen Basin in New South Wales (Bembrick et al., 1980)

The Sydney Basin is separated from the New England fold-belt in the north-east by the Hunter-Mooki Thrust system. The basin unconformably overlies the Lachlan foldbelt, to the south-west. It is essentially continuous with the Gunnedah Basin to the north, but a boundary between the two is drawn along the Mount Coricudgy Anticline. Sydney Basin sediments appear to extend out under the continental shelf in the region between 32º and 35ºS and may be exposed in canyon systems (Kamerling, 1966; Mayne et al., 1978).

On a regional scale, two morpho-tectonic divisions have been described within the Newcastle region (Bembrick et al., 1973; Bembrick et al., 1980). The northern element is the Hunter Valley Dome Belt, and the southern element is the Hornsby Plateau. The Hunter Valley Dome Belt is an area of Permian sedimentary and volcanic rocks, generally of low relief, characterised by low amplitude folds with short axial traces, and north-west – south-east trending faults. The municipality of Newcastle and the northern half of Lake Macquarie are located within the Hunter Valley Dome Belt. The southern half of Lake Macquarie is situated on the Triassic sedimentary rocks of the Hornsby Plateau, which is of relatively higher relief, and is characterised by large scale low amplitude folds and only minor faults. The plateau forms the southern boundary of the Hunter Valley and is marked by an escarpment of Triassic age rocks (Lohe and Dean-Jones, 1995).

D.2 Structural Geology

D.2.1 Offshore Structural Geology

The major offshore structural elements are a series of coast parallel folds, which comprise a coastline-marginal anticline, the Offshore Syncline and the Offshore Uplift, and the coast perpendicular extension of the Newcastle Syncline (Crouse and McGuire, 1993).

In recent years seismic surveys have delineated a monocline in near surface sediments which trends NW-SE with the south-west side up (Figure D - 3). This monocline is interpreted to be the result of movement on a shallowly south-west dipping reverse fault (Figure D - 4). The fault terminates approximately 20km south-east of Newcastle (Figure D - 5), and is assumed to have formed relatively recently due to the Cainozoic age of the pre-growth and growth strata (Huftile et al., 1999).

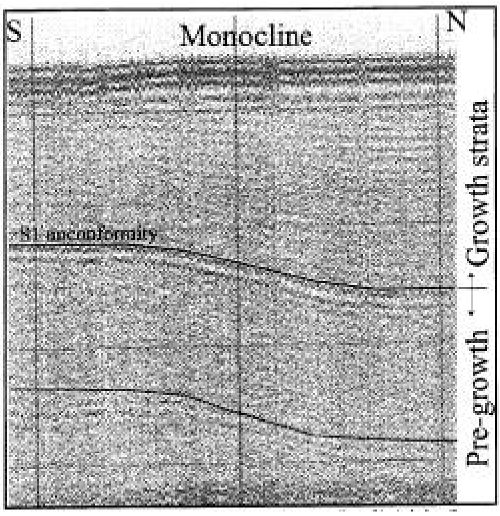


Figure D - 3: Seismic survey showing monocline in sediments offshore from Newcastle (Boyd et al., 1988)

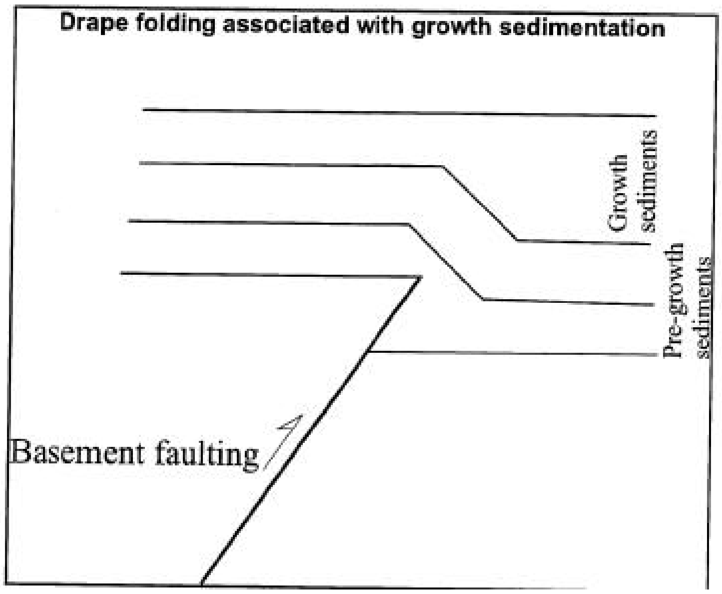


Figure D - 4: Schematic showing the fault interpreted to have formed the monocline in the sediments offshore from Newcastle (Boyd et al., 1988)

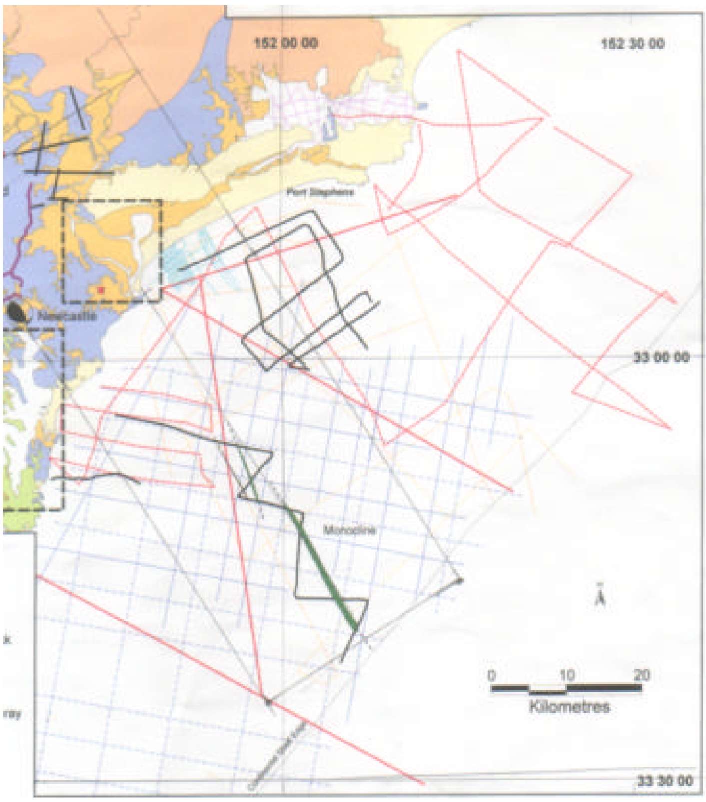
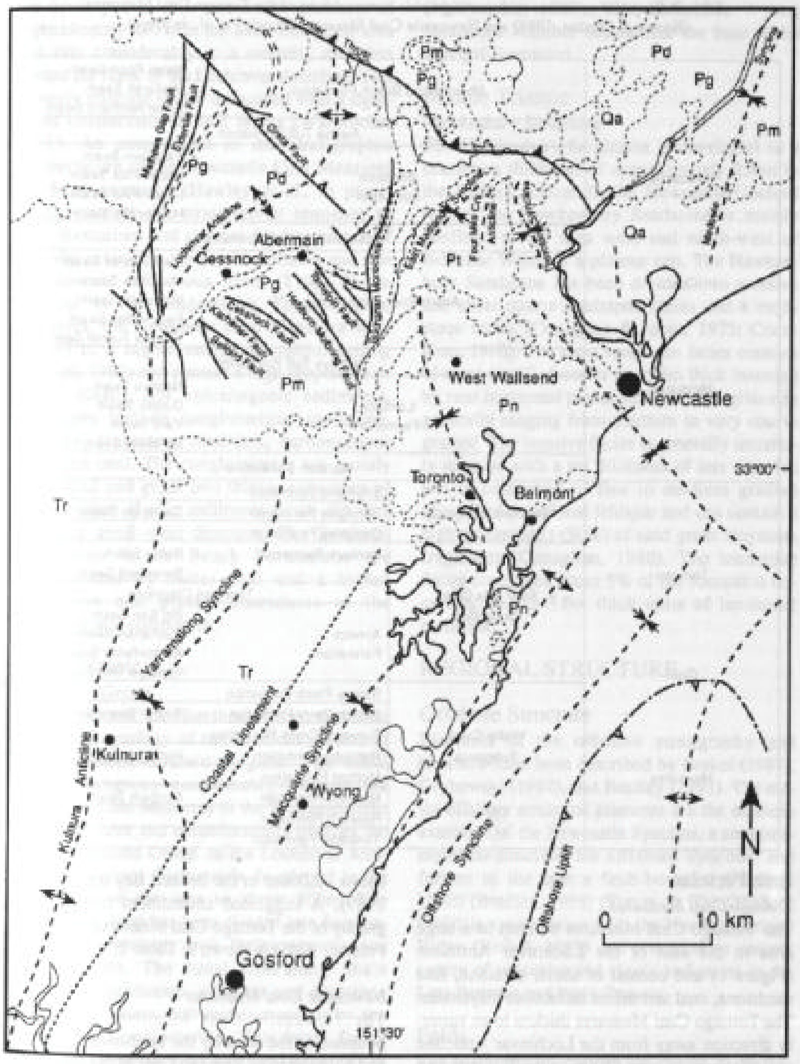


Figure D - 5: Position on the Newcastle fault offshore from the study area. The green lines running NW-SE delineate the position of the fault

D.2.2 Onshore Structure

D.2.2.1 Folds

The Newcastle-Gosford region is characterised by a series of north-east to north-west trending open folds with curvilinear traces. These folds are broad open structures plunging shallowly to the south. From west to east the main fold structures are the Lochinvar-Kulnura Anticline, Yarramalong Syncline, and Macquarie Syncline (Figure D - 6).



Regional structural elements of the Newcastle Coalfield. Pd Dalwood Group; Pg Greta Coal Measures; Pm Maitland Group; Pt Tomago Coal Measures; Pn Newcastle Coal Measures; Tr Triassic; Qa Quarternary alluvium.

Figure D - 6: Regional structural elements of the Newcastle-Gosford area (Lohe and Dean-Jones, 1995)

As a lower order feature, there are a number of small east-west cross folds that post date the meridional folds. One major monoclinal feature, the Buchanan Monocline occurs in the northern central part of the region (Figure D - 6).

D.2.2.2 Faults

Normal Faults

Normal faults are the most obvious and dominant brittle deformation style in the region. Normal fault planes generally dip between 55-75 degrees and have a curved (listric) cross-sectional profile that flattens out at depth

(Lohe and Dean-Jones, 1995). North-west to north-north-west trending normal faults are the dominant style in the Newcastle region. They typically have a vertical displacement of less than 6m (Crapp and Nolan, 1975).

Thrust and Reverse Faults

The major thrust fault system in the area is the Hunter-Mooki Thrust, which consists of a series of generally north-west trending ramps dipping north-east at approximately 14 degrees (Figure D - 6). Displacements associated with the Hunter-Mooki Thrust have propagated well into the Sydney Basin affecting both Permian and Triassic strata, but no recent activity has been recorded on the fault system (Lower Hunter Geological Structures Working Group, 2000).

It is thought that an onshore extension of the offshore Newcastle fault may exist. This structure, termed the Hunter River Cross Fault continues inland across the northern part of the Sydney Basin. It lies south of the Hunter-Mooki Thrust and has been suggested to extend east-south-east through older rocks to the Narromine area (Glen and Walshe, 1999).

High angle reverse thrusts also occur in the region in association with the dominant north-west trending normal faults and represents compressional reactivation of these faults (Williams, 1979).

Strike-slip faults

Strike-slip displacements are probably relatively common in the region but are difficult to positively identify because stratiform markers are not offset (Lohe and Dean-Jones, 1995).

D.2.2.3 Basement Geology

The stratigraphy of the Sydney Basin is shown in Figure D - 7. Within the study area the sedimentary rocks of the Late Permian Tomago Coal Measures (TCM) and Newcastle Coal Measures (NCM) form the basement for the Quaternary basin fill.

The TCM underlie the majority of the Quaternary basin fill to the north of Newcastle City, with the greatest proportion of outcrop occurring to the west of Hexham. These predominantly fine-grained sedimentary rocks consist of shale, siltstone, fine sandstone, coal, and minor tuffaceous claystones. The TCM thicken eastward away from the Lochinvar Anticline, to a thickness of over 1200 m in the Williamtown area (Lohe and Dean-Jones, 1995). Sedimentary structures suggest deposition took place on tidal mud flats under marine to brackish conditions (Diessel, 1980).

The NCM outcrop to the south and west of Newcastle City. The unit underlies the southern portion of the Newcastle area Quaternary basin fill and the Quaternary sediments preserved around the northern end of Lake Macquarie. In contrast to the older TCM, the NCM contain a greater proportion of coarse sedimentary rocks, including conglomerate and sandstone. Siltstone, claystone, laminites, carbonaceous shale, and coal are also major constituents. The NCM are developed to their maximum thickness of approximately 450m in the Lake Macquarie area, and thin considerably in a westerly direction toward the flank of the Lochinvar Anticline (Lohe and Dean-Jones, 1995). The lower part of the NCM was deposited in a beach or shoreface environment (Moelle and Dean-Jones, 1995), but the majority of the unit was deposited by deltaic and fluvial processes on an alluvial plain (Diessel, 1980).

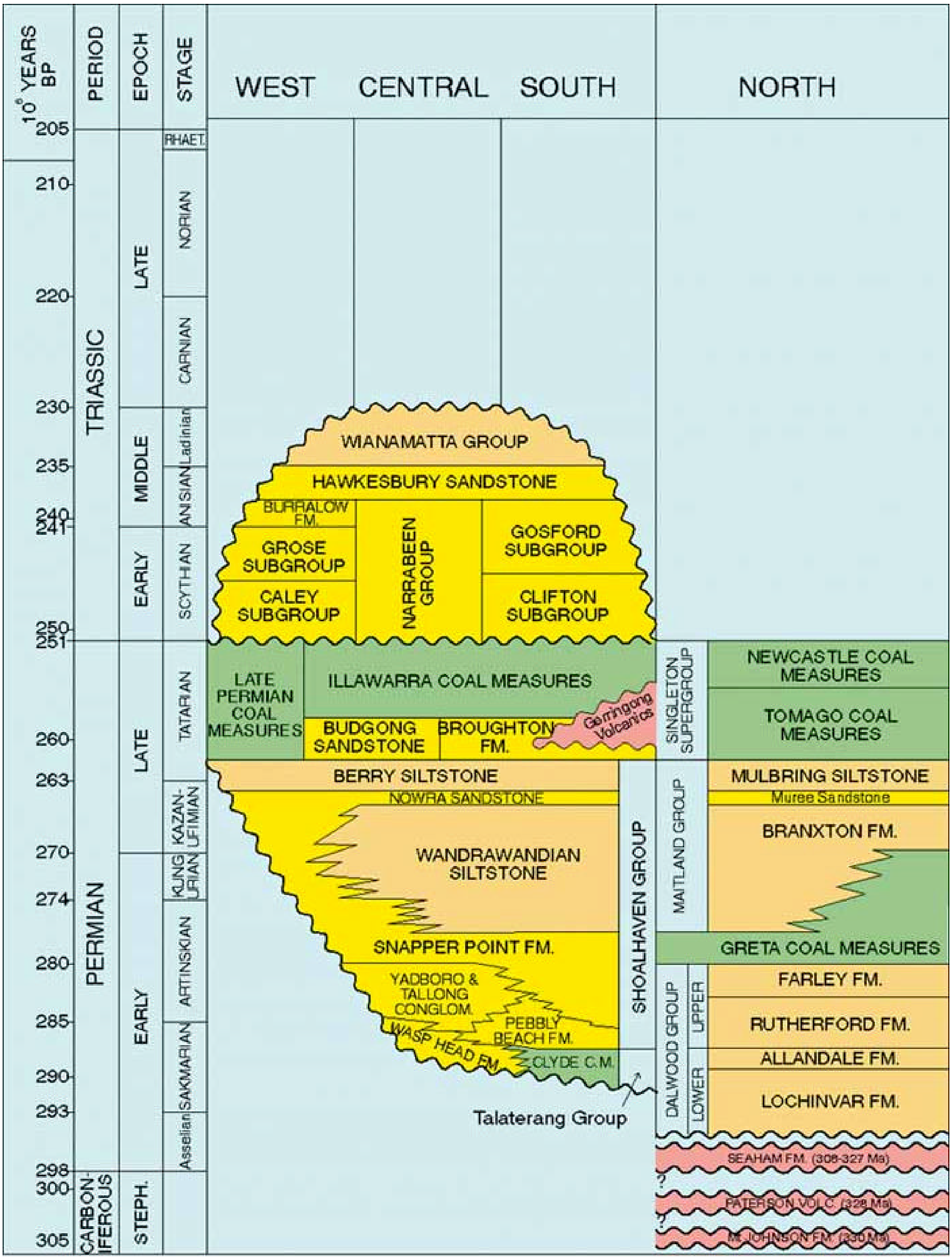


Figure D - 7: Stratigraphy of the Sydney Basin[25]

[25] *NSW Department of Mineral Resources, www.minerals.nsw.gov.au/petrol/offstrat.htm*

D.3 Quaternary Geology

D.3.1 Previous Work

The Quaternary sediments of the Newcastle and Lake Macquarie region have been studied for over a century, with papers describing the geology of the lower Hunter Delta published in the 19th century and early 20th century (David and Etheridge, 1890; David and Guthrie, 1904). More detailed studies of the Central Coast region were presented over the last 50 years {(Thom, 1965){(Roy, 1980){(Roy and Crawford, 1980){(Thom et al., 1981){(Thom and Murray-Wallace, 1988).

In recent years, a comprehensive geological analysis of the Hunter Delta described the lithofacies in the area to the north of Newcastle city, and outlined the depositional history for the region in the Holocene (Roy et al. 1995). This study supplements that work, in that the main focus is a detailed description of the area to the south of Newcastle.

A small number of studies have been undertaken on the Quaternary geology of Lake Macquarie (Roy and Peat, 1973). Conclusions regarding facies or depositional history presented in this study for the Lake Macquarie region are based primarily on this previous work, with minor input from subsurface data collected to the east if Lake Macquarie.

D.3.2 New Data and Methodology

The detailed geological interpretations presented in this study for the Newcastle and eastern Lake Macquarie area are based primarily on approximately 100 lithological logs (Figure D - 8) derived from a cone penetration test (CPT) data-set acquired by the Engineering Department at the University of Newcastle. In the CPT, a conical penetrometer tip is pushed slowly into the ground and monitored. The device contains electrical transducers to measure both tip (Qc) and side (Fs) resistances as the instrument is advanced. A friction ratio is calculated by relating the sleeve friction to the tip resistance ($^{Fs}/_{Qc}$). Coarse grained sediments such as sands and gravels tend to resist penetration at the tip, whereas finer grained sediments such as clays and silts resist penetration along the sleeve, therefore there is a direct relationship between the friction ratio and lithology. The higher the friction ratio the finer the sediment grain size.

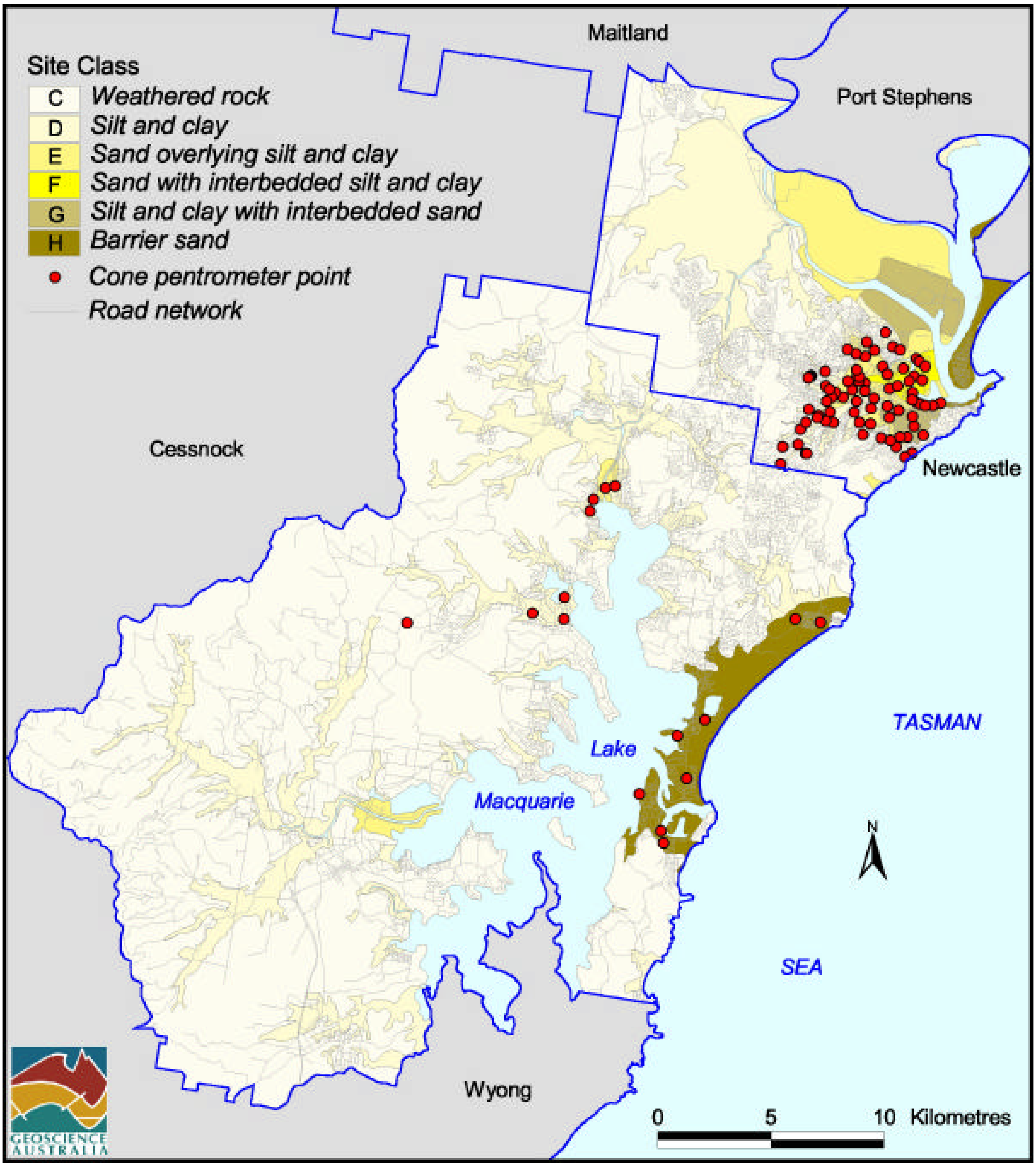


Figure D - 8: Locations of cone penetration tests undertaken by the University of Newcastle Engineering Department

Beyond the Newcastle basin the only data-set with moderate spatial coverage is a series of natural period measurements obtained through a microtremor investigation. This dataset was used to make minor, broad interpretations, but the inherent assumptions involved in the microtremor analysis prevent more than the most cursory analysis. A detailed description of the methodology involved in the microtremor study is presented in Appendix E.

D.3.3 Newcastle Basin Quaternary Succession

The sediments of the Newcastle Basin are discussed here in some detail as this is the first documented analysis for this section of the Quaternary alluvium in the Newcastle district, based on a series of highly detail sedimentary logs obtained through a cone penetration test. The Quaternary geology to the north of Newcastle city is not discussed in this study as it is addressed in detail by Roy et al. (1995).

Five sedimentary facies are identified in the Newcastle Basin on the basis of CPT log analysis. Sedimentary facies are aerially confined parts of an assigned stratigraphic unit that show characteristics clearly distinct from those of other parts of the unit.

D.3.3.1 Sedimentary Facies

Estuarine silts and clays

Silt and clay of this facies characteristically forms the lowermost unit across the majority of the Newcastle Basin. In addition to being the most widespread of the facies it is also the thickest, with a maximum thickness of approximately 28m in hole Wik-01. In some localities a clear fining upward succession is preserved, from sandy silt to clay (Figure D - 9); elsewhere the silt and clay is interlayered and intermixed.

This facies is commonly overlain by tidal delta sands, and occasionally by other facies. In some localities in the western part of the basin this facies contains estuarine delta or colluvial lobe sands.

The fine grained nature of this facies indicates it was deposited in a low energy environment. The Newcastle basin lies directly adjacent to the junction of the Hunter River and the ocean, therefore these silts and clays appear to comprise fine terrigenous material that has been carried into a near-shore system by the Hunter River and floodwaters. The most likely depositional environments are estuarine or lagoonal systems. This interpretation is consistent with previous work (Roy et al. 1995) which displays estuarine basin mud as the most geographically widespread facies towards the mouth of the Hunter River.

The characterisation of this facies as estuarine muds, is also supported by the interpretation of the overlying sand body as a tidal delta. Wave dominated estuarine systems typically comprise a wedge of littoral sand prograding landward into muddy estuarine sediments (Reinson, 1992). The Newcastle Basin is an excellent example of this estuarine morphology.

The fining upward succession preserved in a number of CPT holes is interpreted to be a function of the rise in global sea levels associated with the termination of the last glaciation approximately 20 thousand years ago. The global sea level rise resulted in a post-glacial marine transgression, which inundated coastal valleys (Roy and Thom, 1981). The progressively finer sediments were deposited in the progressively deeper water as the lower energy conditions in deep water are favourable for the deposition of fine sediment.

Tidal delta sands

The sand of this facies characteristically forms one of the upper horizons in the sediment column across the eastern half of the basin. The sand unit is distinctly wedge shaped, thinning from a maximum thickness of 8-9m in Car-01 (Figure D - 10) and Ham-04 towards the outlet of the Hunter River, to a sharp or gradational boundary with the estuarine and tidal delta silts and clays towards the middle of the Newcastle Basin. From the CPT data, the sand appears to be homogenous in grain size to the extent that it does not fine into silt or coarsen into gravel.

The upper and lower boundaries of the sand unit are generally sharp. In the majority of localities this facies overlies the estuarine silts and clays, and it commonly underlies floodplain silts and clays or is preserved to the surface.

The homogenous nature and sharp boundaries of this facies indicates that it was not deposited due to a gradual change in the nature or intensity of a depositional process which was already occurring in the basin. The wedge-like cross-sectional shape of the unit indicates deposition must have taken place through the incursion of the sand unit from the east. This indicates that the sand body was not introduced as part of a deltaic system associated with the Hunter River, as this would have deposited a wedge which thickens to the north. The most likely candidate for deltaic deposition from the east is a tidal delta, which is forming through the back-stepping of sand from the coastal barrier system as a result of tidal action and storm surges. This interpretation is consistent with the work of Roy et al. (1995), who displays extensive deposition of sand by tidal deltas in this part of the Newcastle Basin.

Where the lateral boundary with silts and clays is gradational, this is interpreted to be a function of mixing with estuarine silts and clays at the delta front.

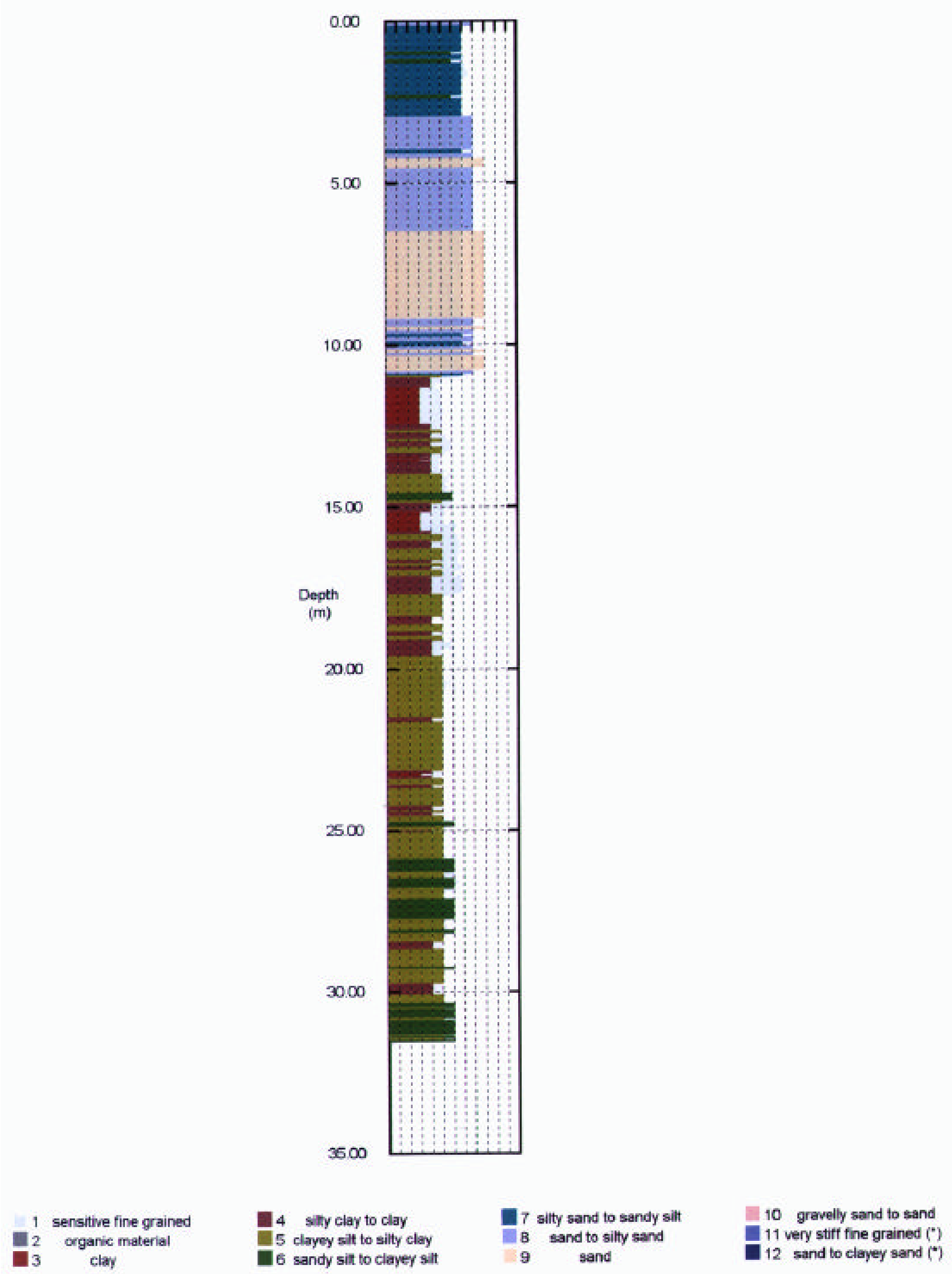


Figure D - 9: The CPT log from Ham-a3 showing a fining upward succession from silt to clay in the lower section

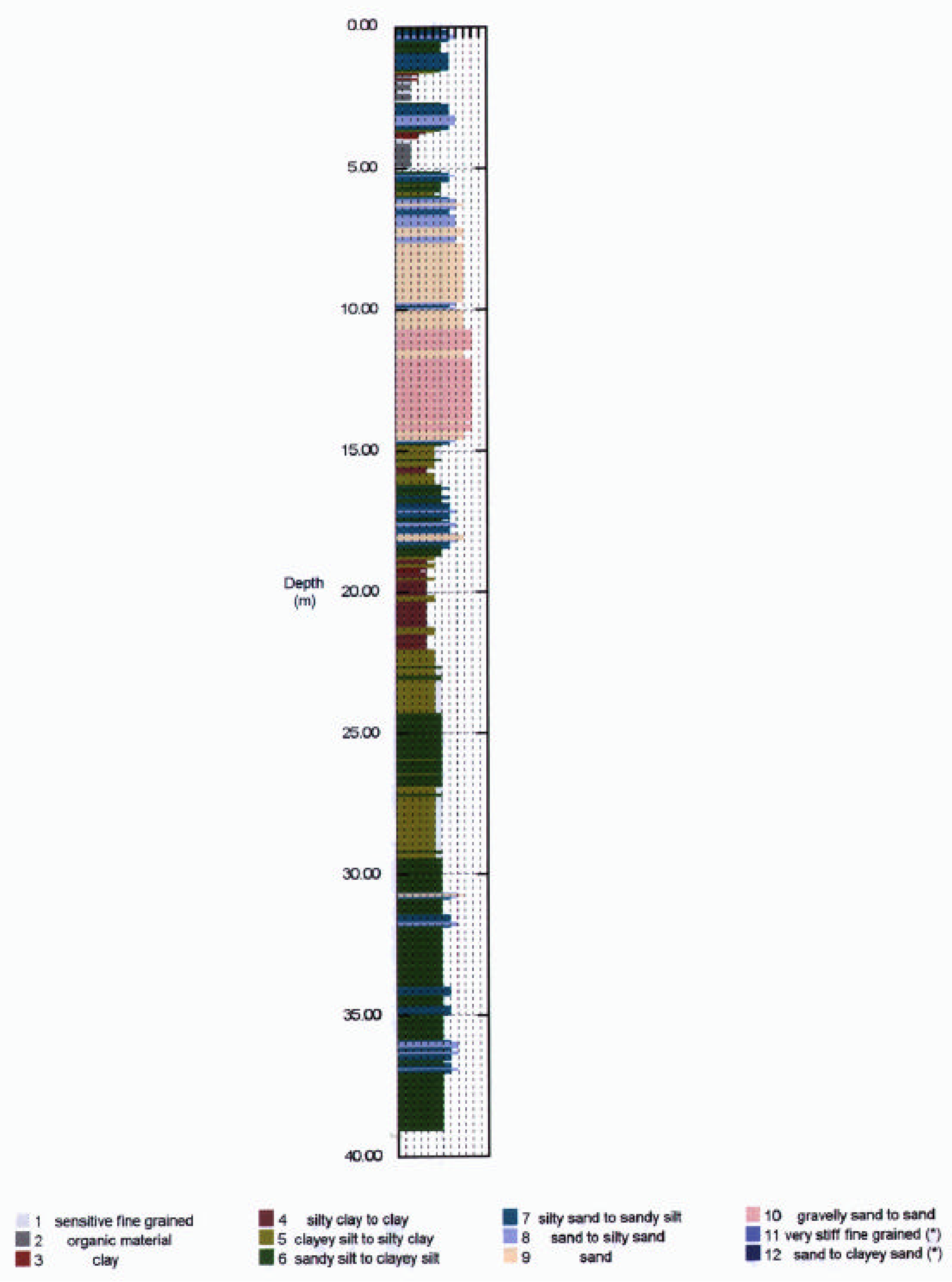


Figure D - 10: The CPT log from Car-01 showing a thick sand body overlying silts and clays

Estuarine delta or colluvial lobe sands

A number of thin lens-shaped sand units are preserved within the estuarine silts and clays around the western, southern, and northern edges of the Newcastle Basin (Figure D - 11). The maximum thickness for this facies is preserved in Brd-03, which contains two units, both of which are approximately 2m thick. They appear to preserve a lobate geometry, and like the tidal delta sands these sand units tend to have sharp boundaries.

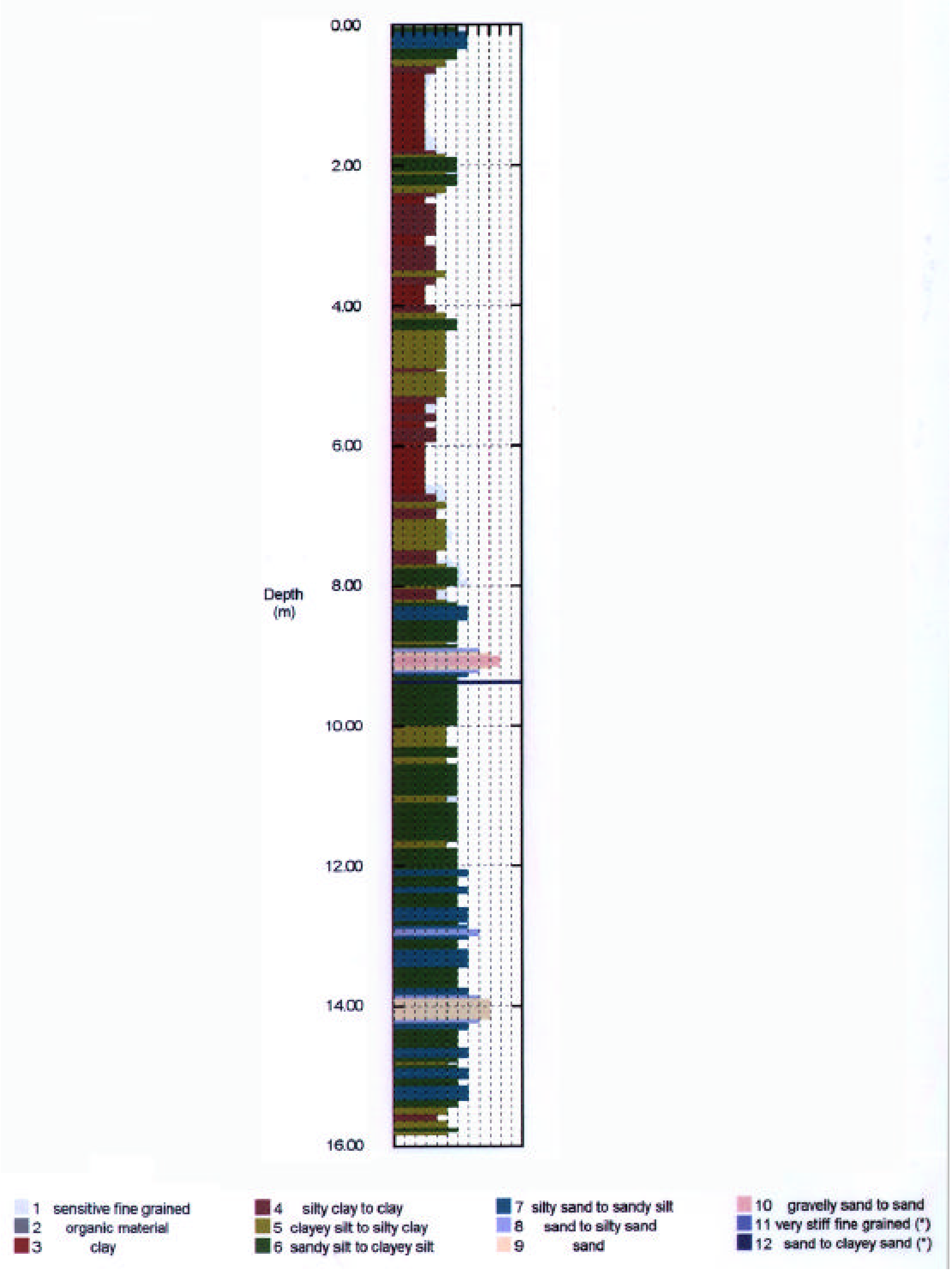


Figure D - 11: The CPT log from Adm-01 showing thin sand horizons within slits and clays

The relatively sparse distribution of this facies, both spatially and stratigraphically, makes interpretation difficult. Minor fluvial deltas exist around the Newcastle basin where tributaries of the Hunter River enter the basin (Roy et al. 1995). These thin lenses of sand may have been deposited through this process but an alternative hypothesis is that they are the preserved remains of colluvial lobes, which entered the basin as gravity flows.

This facies is not considered to have been deposited as crevasse splays for two reasons. Firstly the lobes of sand appear to have been sourced from the edges of the basin away from the Hunter River channel, and secondly they are deposited within estuarine muds, as opposed to floodplain muds which commonly preserve crevasse splays.

Floodplain silts and clays

In a number of localities across the eastern portion of the Newcastle Basin, silts and clays are preserved overlying the tidal delta sand facies (Figure D - 12). The silts and clays tend to be interlayered and intermixed, with no clear trends in grain size. Preserved within this facies, at a small number of localities, are thin lens-shaped units of organic clay. Away from the tidal delta sands, it can be assumed that these silts and clays overlie the estuarine silts and clays, but with only CPT data it is impossible to distinguish between the two.

There is no direct evidence to suggest that these muds were deposited on a floodplain as opposed to within an estuarine system, but they differ from the estuarine silts and clays outlined above, in a number of aspects. Firstly these overlie the tidal delta sands, secondly they are the only facies to preserve organic clays, and finally they do not preserve any thin sand units. Therefore this facies is described as floodplain silts and clays, primarily to distinguish it from the stratigraphically lower muds.

Interpreting this facies as being deposited on a floodplain is somewhat supported by the work of Douglas (1995) who states that floodplain alluvium forms a superficial veneer on top of estuarine muds and extends from upstream of the delta region to about 4km downstream of Hexham. These silts and clays may therefore represent the southernmost extension of those floodplain muds.

Floodplain organic clays

As noted above, thin lens-shaped units of organic clay are preserved within the floodplain silts and clays (Figure D - 13). The maximum thickness is slightly less than 2m in Kot-02. The boundaries appear to be gradational for the most part, with clays increasing in organic content up section.

The fact that this facies is preserved entirely within the floodplain silts and clays indicates that it was also deposited on a floodplain. The depositional environment is envisioned to be one in which, following a flooding event, the floodplain was infilled to the point that a swamp was formed. This swamp added a large proportion of organic material to terrigenous muds, which resulted in the deposition of organic clay.

D.3.4 Lake Macquarie Quaternary Succession

Due lack of geological data in the western Lake Macquarie area, only the broadest assumptions are made in regards to the geology of this region.

The relatively few CPT holes pushed into the Quaternary sediment to the west of Lake Macquarie indicate that they are comprised of a relatively thin succession of silts and clays. Additionally, the geographic morphology of the alluvial units preserved around the north, west and south edges of the lake are very similar to the shape of the Newcastle Basin towards its extreme western end (Figure D - 1). The period at which the sediment naturally vibrates due to ambient seismic energy around these parts of the lake, as recorded through a microtremor study, are also similar to those for the western end of Newcastle Basin. These similarities, and the absence of a major fluvial system which would facilitate the formation of a major estuary, indicate that the alluvium around Lake Macquarie, except to the east, is primarily of floodplain origin, either from the Hunter River to the north or the smaller fluvial systems which enter Lake Macquarie from the west. The sediments are thus likely to be silts and clays, with minor input of sands through the erosion for the lake foreshore (Roy and Peat, 1973).

A small number of geotechnical boreholes have been drilled through the Quaternary alluvium to the east of Lake Macquarie, around the Swansea area (Douglas, 1995). These boreholes penetrated through an average of 30m of sand. The small number of CPT holes pushed into this region, and approximately 10km to the north adjacent to the coast, also intersected intermediate thicknesses of predominantly sand. The sediments in this area are not represented by any of the facies documented above for the Newcastle Basin, because they are closest to the tidal delta sands in lithology, but the two sand units differ in a number of aspects. Firstly they differ in thickness, as this sand unit is at least three times thicker than the tidal delta sands. They also in geometry as the tidal delta sands are lobate, whereas this sand body appears to be elongate, running parallel with the coast. Finally the tidal delta sands are wedge shaped in cross section, and this sand unit appear consistently thick over at least five kilometres.

High microtremor values are recorded in the Swansea area, extending up the coast along the elongate sedimentary body that separates Lake Macquarie from the ocean, indicating the presence of this sand unit throughout. The thick sandy nature of the sediments and the elongate geographic morphology indicates that this section of sediment is represented by a barrier sand system. This interpretation is consistent with previous work which identifies barrier sand bodies along the central coast of New South Wales (Roy et al., 1995).

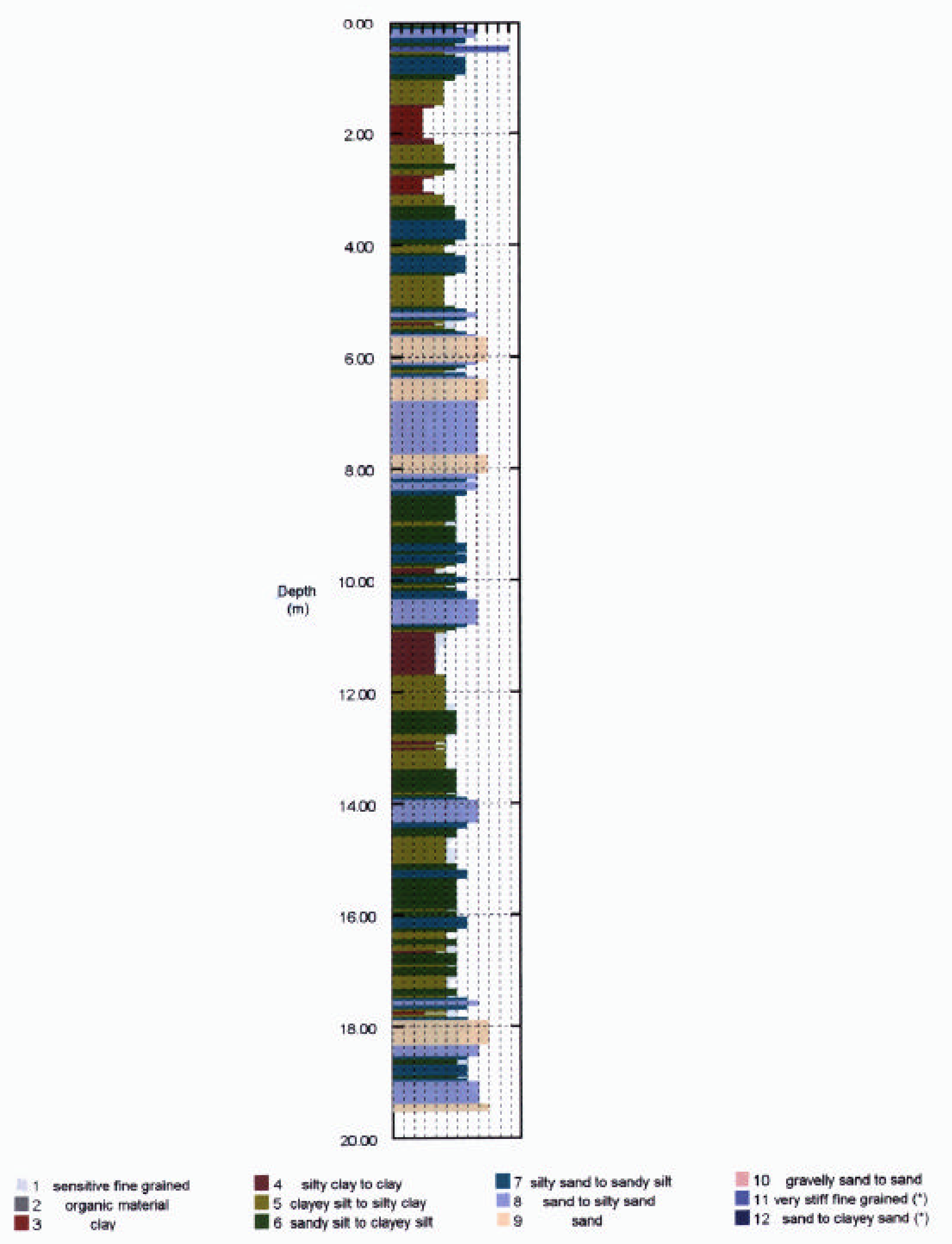


Figure D - 12: The CPT log from Nlt-08 showing silts and clays overlying a thick sand body

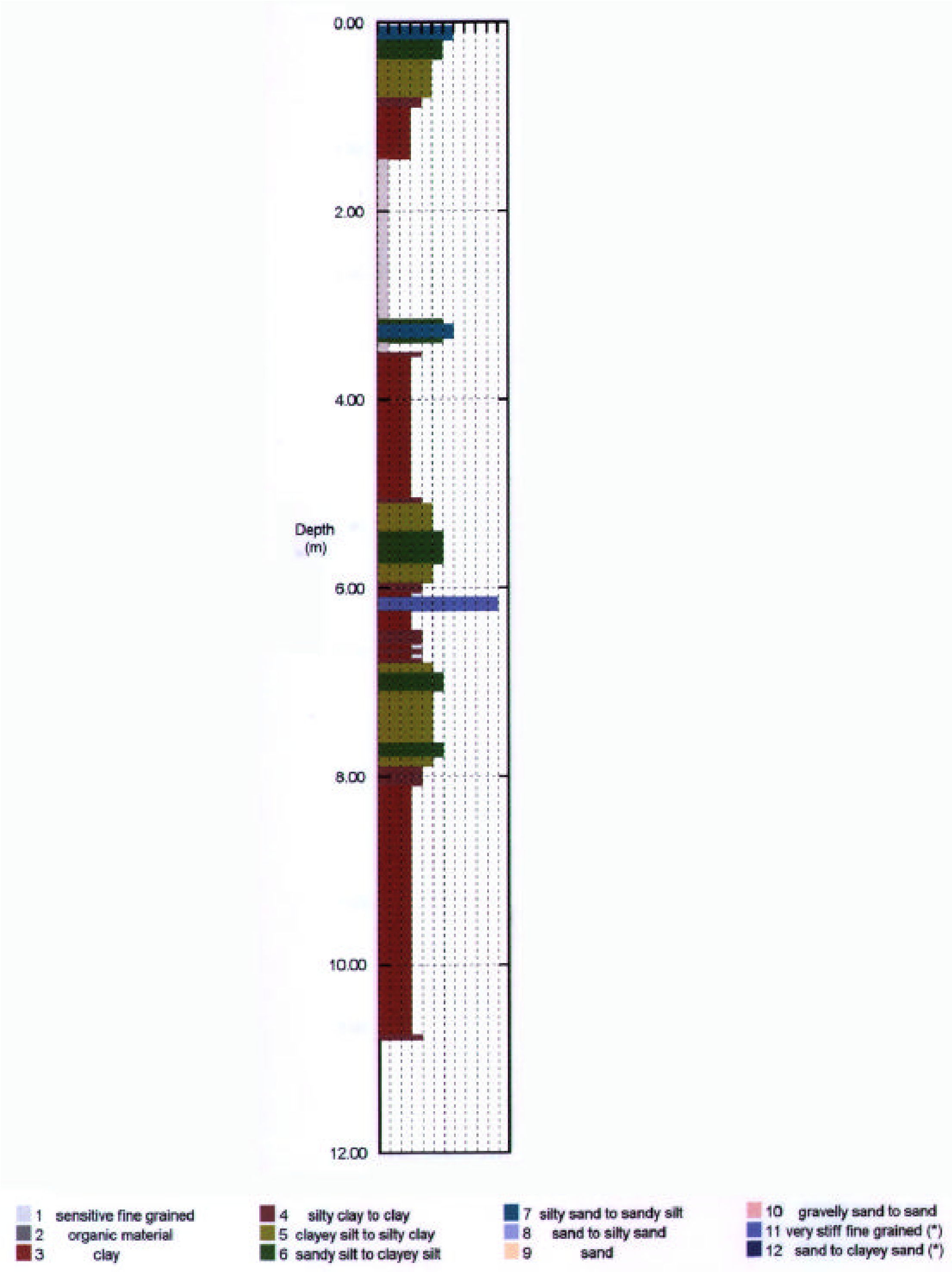


Figure D - 13: The CPT log from Kot-02 showing a thin horizon of organic clay

D.3.5 Depositional History

This depositional history is based primarily on the sedimentary facies identified by CPT in the Newcastle Basin. Application to the Lake Macquarie area is less reliable, because of the sparsity of the data, noted above. The Newcastle Basin and Lake Macquarie were probably formed due to the incising of fluvial systems, the Hunter River in the case of Newcastle Basin, through the Permian and Triassic sedimentary rocks in the area at the onset of the last glaciation, about 30ka. Following the termination of glaciation, a marine transgression infilled the palaeovalleys with estuarine silts and clays. During sea level highstand barrier systems formed along the mouths of the palaeovalleys, then tidal deltas formed through the backwashing of barrier sands by tidal and storm surge processes. Eventually the estuarine environments were buried by floodplain silts and clays, which occasionally developed into swamps and facilitated the deposition of organic clays.

D.4 Characterisation of Site Classes Based on Local Geology

The local geology of Newcastle and Lake Macquarie, as outlined above, was used to construct a series of site classes for the regolith of the region. These site classes represent regions that are considered to have a similar response when exposed to an earthquake.

D.4.1 Weathered Rock

All regions of the study area that do not preserve sediments overlying the bedrock were categorised as site class C. The bedrock within this class, which also underlies the Quaternary sediments, was assumed to have a 10 - 15 m thick weathering profile. This assumed thickness of weathering was based on the expert opinion of staff from the NSW Department of Public Works and Services, who referred to weathering profiles of a similar thickness in nearby parts of the state (NSW Department of Public Works and Services, 1998).

D.4.2 Quaternary Sediments

The semi- to unconsolidated Quaternary sediments overlying the bedrock are the primary geological amplifier of earthquake energy and therefore these are the major focus in defining site classes.

The lithology and structure of the sedimentary succession in the vicinity of Newcastle city and eastern Lake Macquarie was outlined in detail by a series of cone penetrometer (CPT) logs which were assembled and analysed by the Engineering Department at the University of Newcastle. Due to the spatial distribution of this detailed data set, and a lack of subsurface geological data for the remainder of the study area, site classes were defined for the Newcastle Basin and eastern Lake Macquarie and then extrapolated across the study area.

The CPT logs in the Newcastle region revealed a sedimentary succession dominated by silt and clay, overlain in the deeper part of the basin by a thick sand unit, with rare, thin lenses of organic clay and sand. These predominantly comprise estuarine silts and clays, overlain in places by tidal delta sands, with minor input from estuarine delta or colluvial sands. Four site classes were therefore characterised for the Newcastle region and are shown as site classes D - G in Figure D - 14. Site class D comprises estuarine silts and clays overlying weathered rock, possibly with some input from floodplain silts and clays. Site Class E comprises estuarine silts and clays overlain by a relatively thin bed of tidal delta sand. Site Class F comprises estuarine silts and clays, with an estuarine delta or colluvial sand interbed, overlain by a relatively thick bed of tidal delta sand. Site class G comprises estuarine silts and clays overlain by either tidal delta, estuarine delta or colluvial sand, which in turn is overlain by floodplain silts and clays. A sixth site class, H, was defined to characterise the thick barrier sand body to the east of Lake Macquarie and to the north of Newcastle city.

D.4.3 Extrapolation of Site Classes to Broader Newcastle and Lake Macquarie Region

An extensive microtremor survey was carried out across the broader Newcastle and Lake Macquarie regions to supplement the limited subsurface geological data outside the Newcastle basin area. Microtremor data is used to measure of the natural period of vibration for subsurface sediments. A detailed description of microtremor theory and sampling methodology is outlined in Appendix E. A combination of microtremor and CPT data as well as inferences regarding depositional processes was used to characterise the isolated alluvial deposits to the north, west and south of Lake Macquarie. The natural periods of these deposits, as measured through the microtremor survey, were exclusively low, which indicates that the deposits are shallow but does not allow for further classification.

Each of the CPT holes pushed into the isolated deposits north of Lake Macquarie penetrated approximately 15m of sediment, comprising predominantly silts and clays. Thus, the majority of these CPT holes were pushed into regolith corresponding to Site Class D. The exception in terms of the CPT holes in this area is Bol-1, which preserves a significant proportion of sand, and thus the area surrounding this hole was characterised as Site Class E. Bol-1 is located directly adjacent to Cockle Creek, therefore the most likely explanation for the presence of sand within this hole is that it was introduced into the system as fluvial outwash forming an estuarine delta sand body. There is only one other significant fluvial system entering Lake Macquarie, that being Dora Creek which flows from the west. The section of the alluvial deposit that underlies the downstream terminus of Dora Creek, was classified as Site Class E due to its similarity with the region around Bol-1, and the probability that this fluvial system is also introducing some sand into the lake. With the exception of these two areas, the isolated alluvial deposits were interpreted to represent Site Class D, due to the predominance of silts and clays in the CPT points to the north of Lake Macquarie, and the lack of fluvial influence throughout the region.

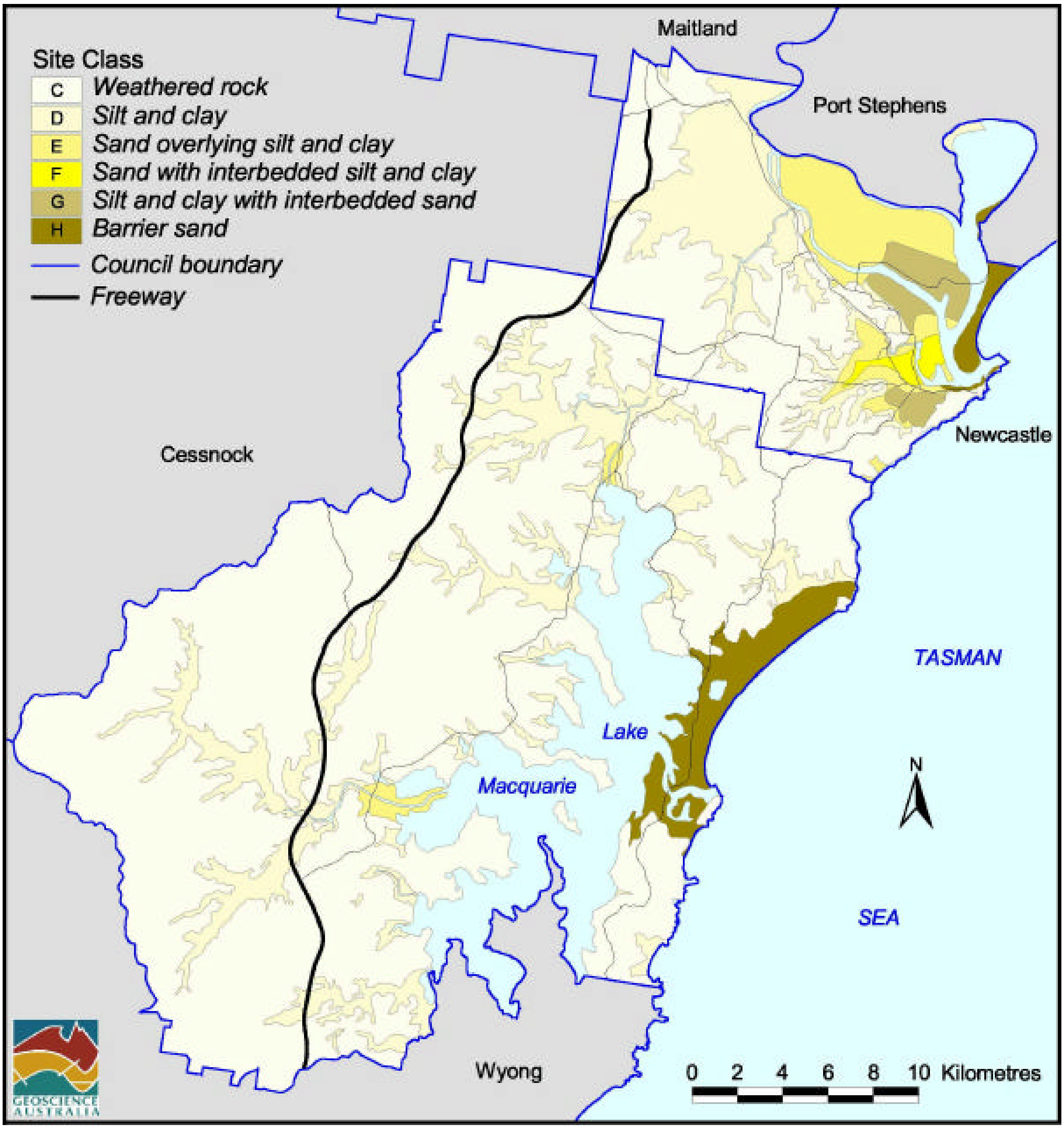


Figure D - 14: Regolith site classification of the Newcastle and Lake Macquarie region

Appendix E - MICROTREMOR SURVEY

Microtremor data provides an invaluable tool for estimating the natural period of vibration for soils. Microtremor data is especially useful in regions where there is little or no detailed geological or geotechnical data available. Whilst microtremor data by itself does not allow for confident estimations of the amount of ground shaking amplification likely to be experienced in a region, it can provide valuable insight into which periods of motion are most likely to be amplified. In addition to this, microtremor data is quickly and easily obtained, and is perhaps the least expensive form of data available that can provide insight into the amplification of ground shaking.

E.1 Methodology

Within the course of this project, Geoscience Australia (GA) seismologists used portable, digital seismographs to record microtremors at about 450 sites in Newcastle and Lake Macquarie in 2000 (Figure E - 1). Sensors were a triaxial, passive type with a natural period of 1 s and used a sampling rate of 100 Hz. The sites had a nominal 250 m spacing within the Newcastle CBD, and 500 m spacing for the remainder of the survey region, and were located primarily on sediments. Two recordings, each of 200 s duration, were made at each site.

The single site, H/V, or 'Nakamura' method was used in order to obtain measurements of natural period from microtremor data. In this method the horizontal, spectral, ground shaking is divided by the vertical, spectral, ground shaking to produce H/V spectral ratio plots. A resonant peak may be observed in the spectral ratio plot for a site, and that peak is interpreted to occur at the fundamental period of vibration of the sediment column. A large body of theoretical and empirical research from the past decade has analysed the H/V method and compared its prediction of the fundamental ground period with, for example, assessments made from earthquake recordings (Nakamura, 1989; Lachet and Bard, 1994; Field and Jacob, 1995; Nakamura, 2000). The results generally indicate that the method is robust in revealing the natural period of sediment vibration excited by vertically propagating seismic shear waves.

The recordings were divided into time series of 40 s duration each with 10 s overlap. Each of these smaller time series was Fourier transformed via a FFT algorithm, and then smoothed. The smoothed horizontal spectrum was then divided by the smoothed vertical spectrum for each of the time series, to produce a set of spectral ratios. These spectral ratios were then averaged, and standard deviations were calculated, in order to produce spectral ratio plots. The FFT computer programs written by Cvetan Sinadinovski and other programs written by Vic Dent and Long Cao, all of GA, were used to process the data. Denis Hackney processed and analysed the microtremor data.

E.2 Natural Period Results

A comparison of contours of natural period with the site classes for the Newcastle region demonstrates that there is a good correlation between these two models (Figure E - 2). The general shape of the contours matches the shape of the site classes very well everywhere but in the region towards the north of Newcastle. In this region there is a distinct difference between the two models. This discrepancy between geological model and natural period could be due to a number of factors. However, given the close proximity of bedrock, the most likely reason appears to be basin-edge effects.

Figure E - 2 also demonstrates that there is a good correlation between the thickness of sediment and the calculated natural period, with an increase in thickness being associated with an increase in natural period. If the thickness of the alluvium, H, is well constrained, then the equation:

$$Vs = 4H/T,$$

can be used to determine the shear wave velocity, Vs, from the natural period T. This method does assume that the alluvium beneath the microtremor point is acting as a single homogenous unit. Nevertheless, this method could be used to gain valuable insight into subsurface velocities where there is no available information from boreholes etc.

Whilst microtremor data was not used to create the main site class models used in this report, it has demonstrated it's effectiveness at detecting changes in the amplification properties of soils. The method has also been used within this study as an invaluable aid in the mapping of site classes away from regions where the geology is well constrained. In addition to this, the main reasons for the detailed study of amplification factors presented in Chapter 4 was to understand and quantify any amplification of ground shaking in the Newcastle and Lake Macquarie region, and to help explain the damage caused by the 1989 Newcastle earthquake. Whilst detailed geotechnical data was available for this study, unfortunately this is not the norm. Given the inexpensiveness and ease of acquisition of microtremor data, it is imperative that more work be carried out to understand the full potential of this data for ground shaking amplification studies.

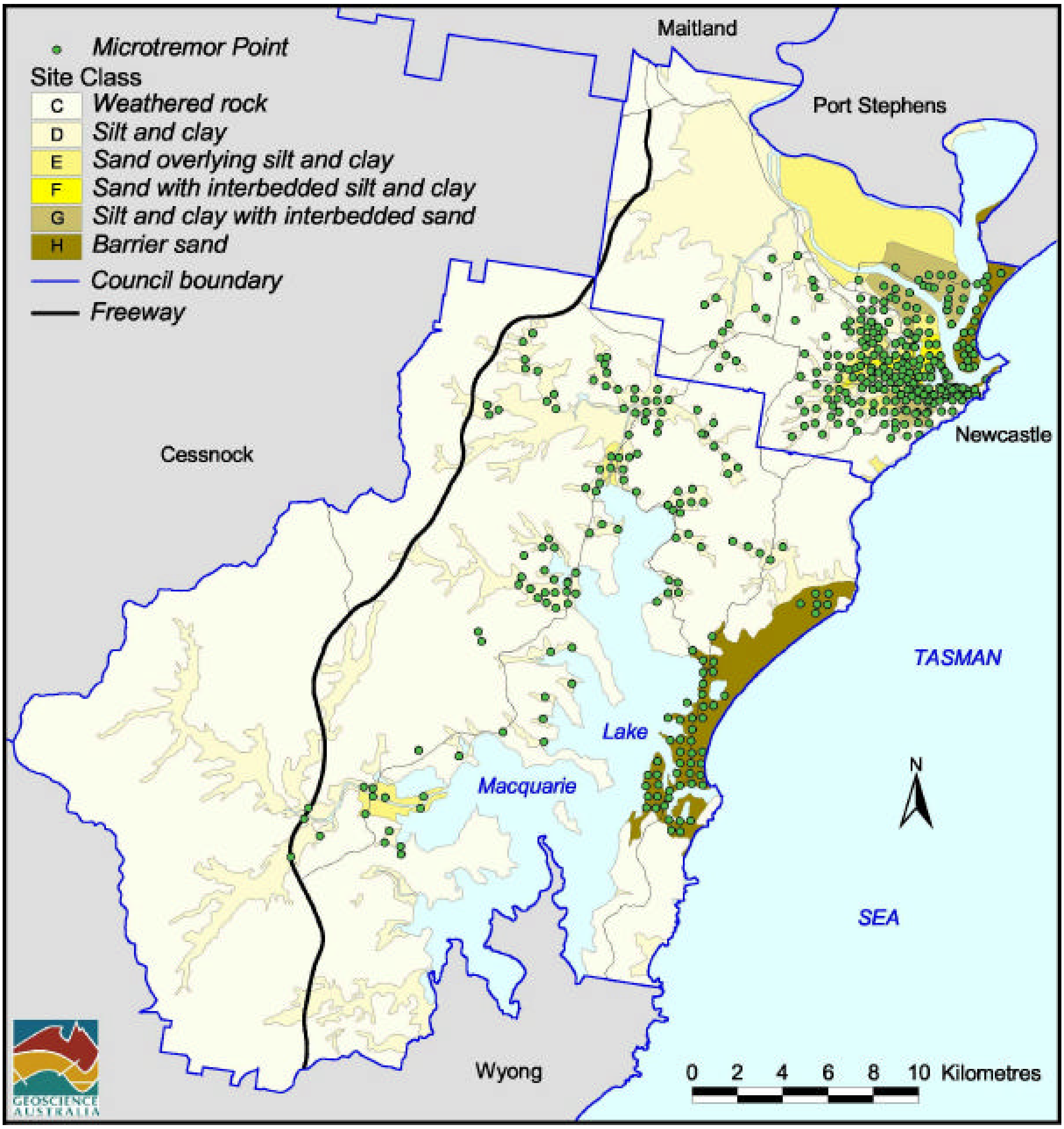


Figure E - 1: Location of Newcastle and Lake Macquarie microtremor readings

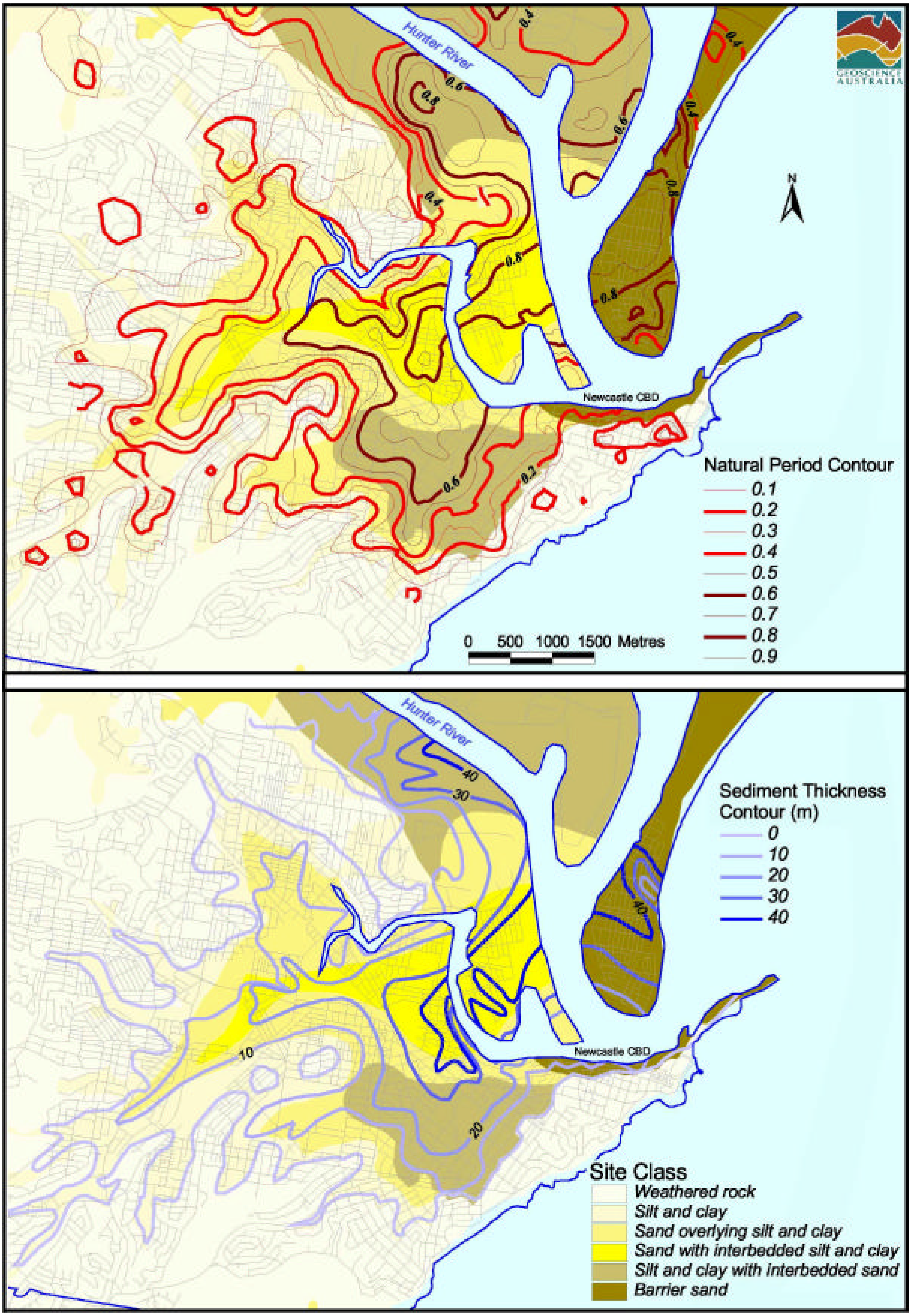


Figure E - 2: Comparison of natural period contours, Newcastle site classes and sediment thickness

Appendix F - Geotechnical Properties Of Newcastle and Lake Macquarie Regolith Site Classes

The following Sections describe how the velocities and densities used in Chapter 4 were obtained.

F.1 Shear Wave Velocity

The University of Newcastle has undertaken a significant program of seismic cone penetration testing (SCPT) throughout the Newcastle municipality. Each SCPT provides a measure of shear wave velocity for each 1.5 m interval down the cone penetrometer hole. The locations of the SCPTs used are shown in Figure F - 1. In order to develop a characteristic shear wave velocity profile for each site class, the SCPTs in each site class were grouped together. For any given depth all of the available velocities at that depth were averaged to produce a mean shear wave velocity profile. This mean profile was then used as the characteristic velocity profile for that site class. The velocity data for site classes D through H are shown in Figure F - 2 - Figure F - 6

Unfortunately little information was available about the velocities of both the unweathered and weathered basement within the region. Consequently, velocities were extracted from a NSW Department of Public Works and Services publication (NSW Department of Public Works and Services, 1998). These velocities were P wave, velocities, so a Poisson's ratio of 0.3 was used to obtain the shear wave velocities used in Chapter 4.

F.2 Densities

The density values used within this work were taken primarily from published values, and discussions with geological experts in the region. Table F - 1 describes all of the density values used within this work, as well as the source of each density.

Table F - 1: Density values and their sources for the Newcastle Lake Macquarie region

Material / Class	Density (gcm^{-3})	Source
Sand (Class E/J, F/K and G/L)	1.78	Published densities on Page 2-18 of (Kulhawy and Mayne, 1990)
Clay (Class E/J and F/K)	1.82	
Silt (Class E/J and F/K)	1.98	
Clay (Class D/I)	1.3	
Silt (Class D/I)	1.56	
Weathered Bedrock (All Classes)	2.14	Expert opinions from staff of NSW Department of Mineral Resources and Coffey Geosciences
Unweathered Bedrock	2.39	

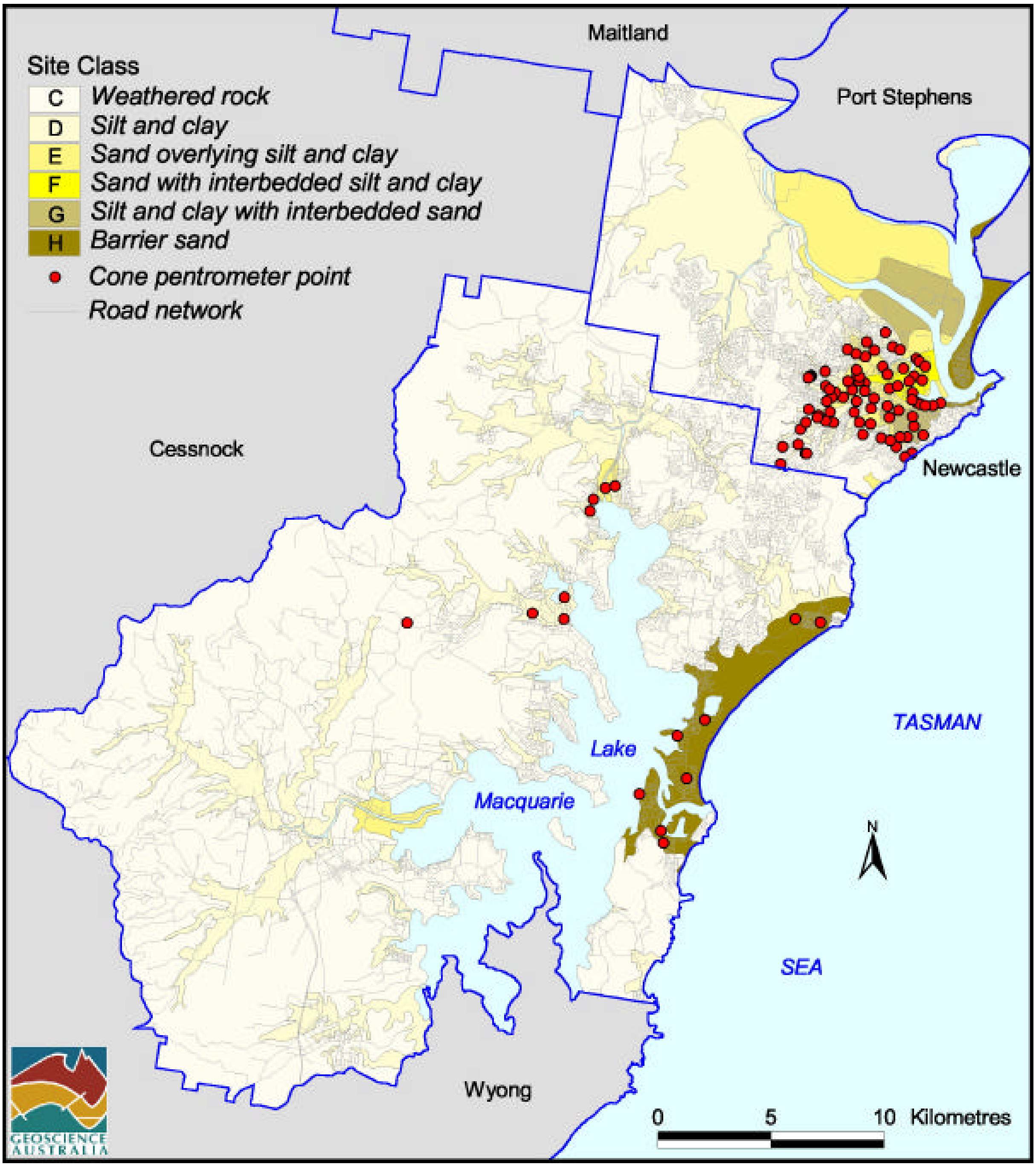


Figure F - 1: Location of SCPT holes used to determine the velocities used within this study

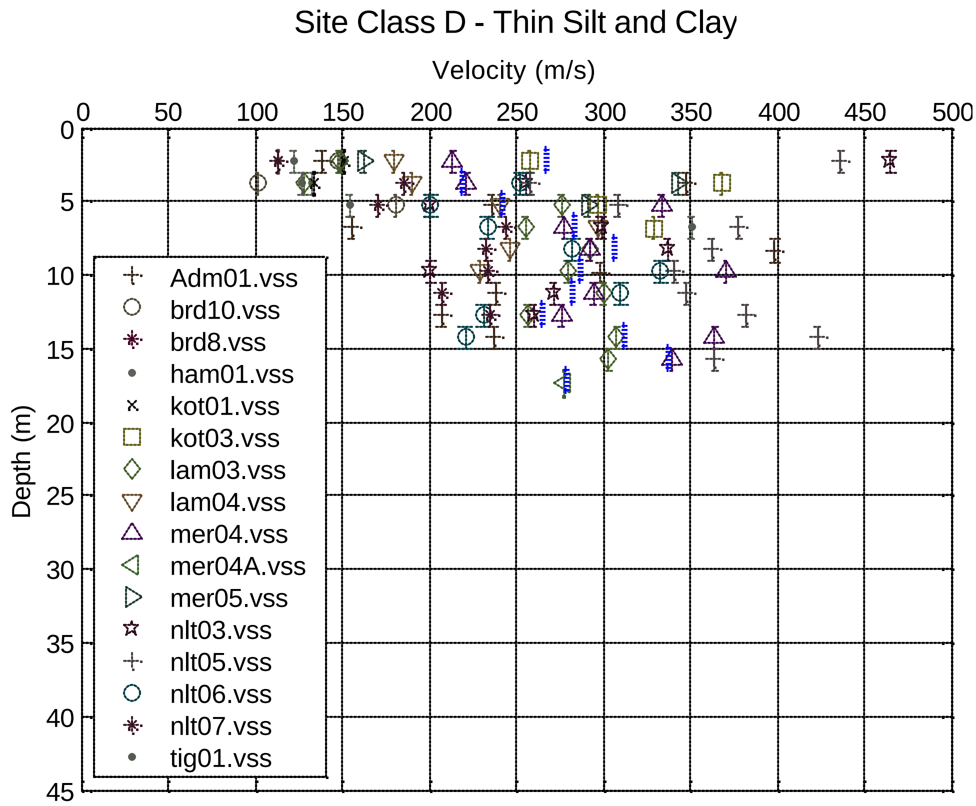


Figure F - 2: Shear wave velocity data for regolith site class D. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

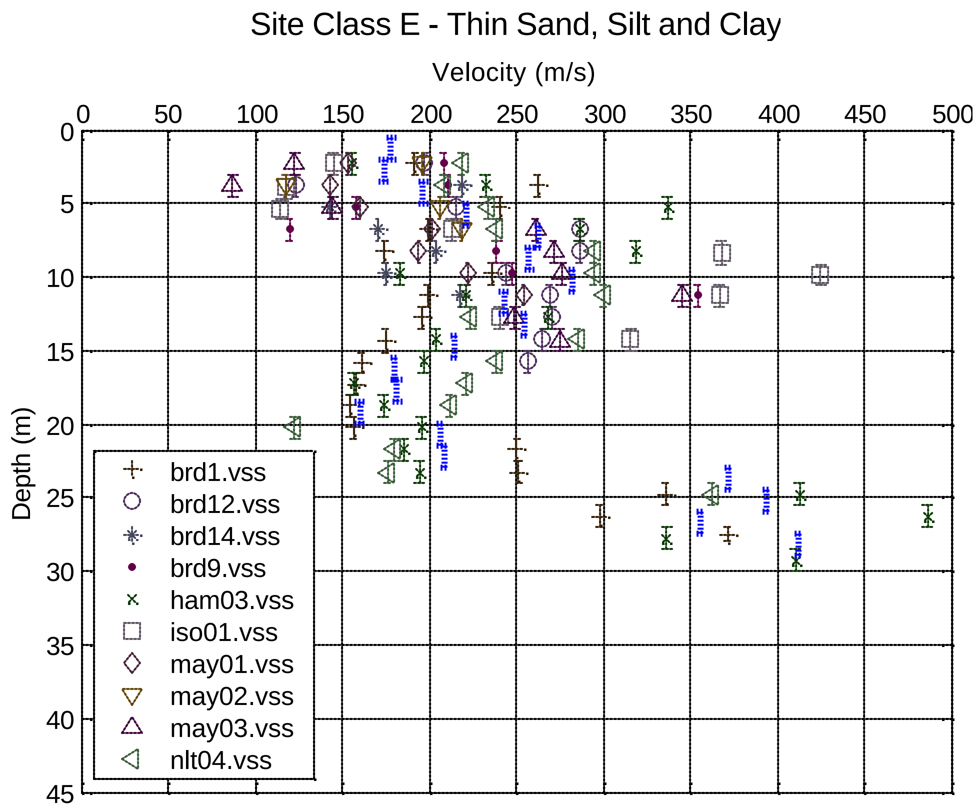


Figure F - 3: Shear wave velocity data for regolith site class E. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

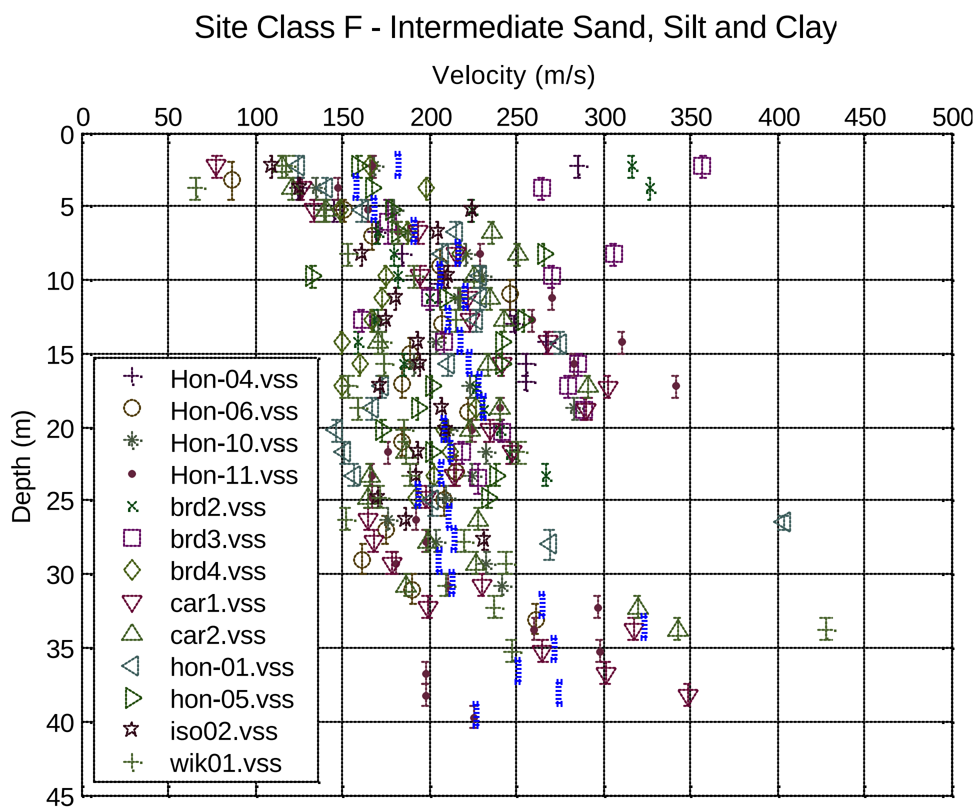


Figure F - 4: Shear wave velocity data for regolith site class F. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

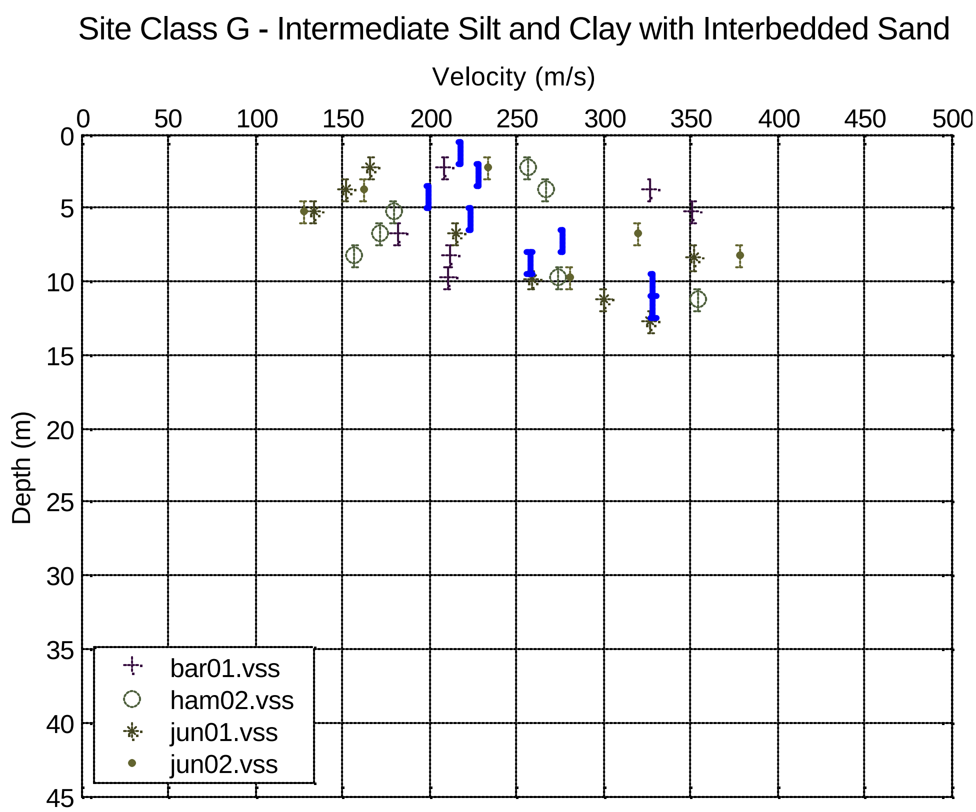


Figure F - 5: Shear wave velocity data for regolith site class G. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

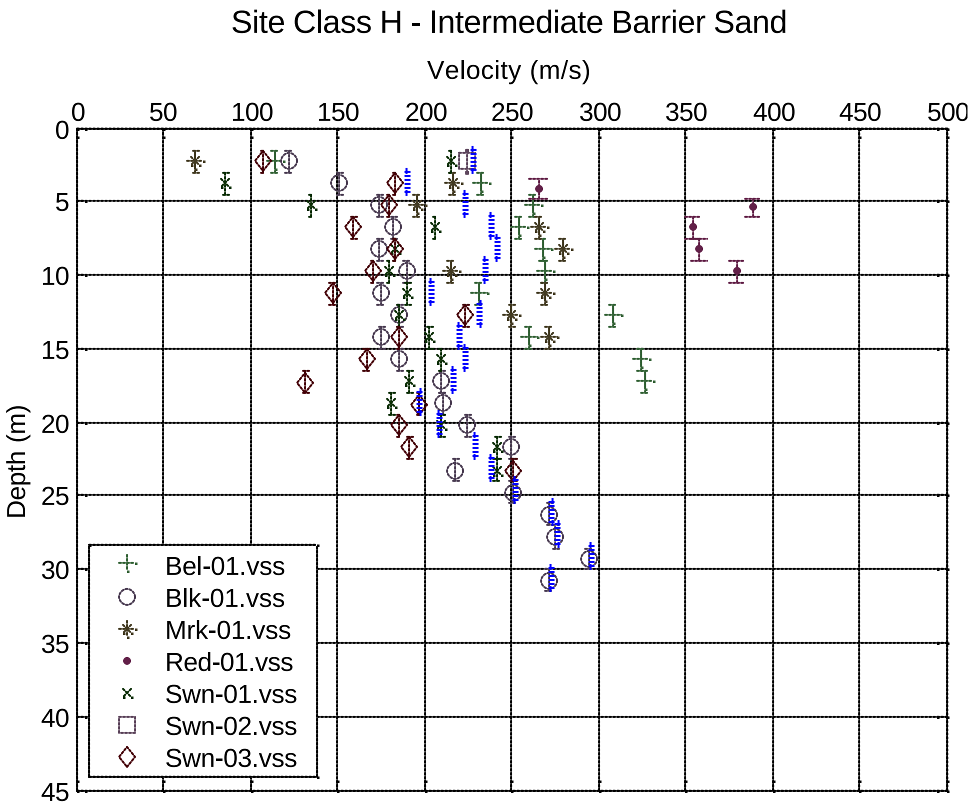


Figure F - 6: Shear wave velocity data for regolith site class H. Note that the thick blue line is the mean shear wave velocity for a given depth, and is used as the characteristic velocity model for the site class

Appendix G - BUILDING INVENTORY

Building inventory for the Newcastle and Lake Macquarie regions was not readily available for the risk assessment process. Hence, a field survey was conducted by the Cities Project to determine a sample representation of the building stock. The building survey involved a three week effort by an approximate full-time equivalent of 5 people. The survey was conducted on foot, bike and in cars by collecting data on palmtop computers, with spatial location recorded with a Differential GPS unit (Stehle and Pownall, 2001).

Approximately a 1 in 10 nominal survey rate was employed for inner Newcastle. This rate was 1 in 20 for outer Newcastle and even coarser for Lake Macquarie (see Figure G - 1). The 1 in 10 survey rate was implemented by surveying buildings with addresses ending with the numeral "5". The 1 in 20 survey rate was similarly implemented by surveying buildings ending with "05", "25", "45", "65" and "85". The survey rates, number of buildings surveyed and total building numbers for each suburb are listed in Table G - 1. Overall, approximately 6300 sites were surveyed.

The sampling regime was roughly checked by comparing the statistically inferred number of buildings per suburb, as determined from the survey, to statistics generated from 1996 census data and cadastral lot information. Neither source is expected to be totally accurate sine 1996 data only roughly reflects the present built environment, and the cadastral lots are not necessarily built upon. The building numbers, as shown in Table G - 2, for each suburb, indicate a reasonable level of agreement.

For all the suburbs inside the study region a multiplying factor was derived from dividing the total number of buildings surveyed in the field for each suburb by the total number of existing buildings for each suburb. In hindsight, all commercial, industrial, and special buildings such as fire stations, police stations should have been ignored to give a more accurate multiplying factor as the real total building count is for residential dwelling only. Such an adjustment is only a minor one however it does fine tune the risk assessment process.

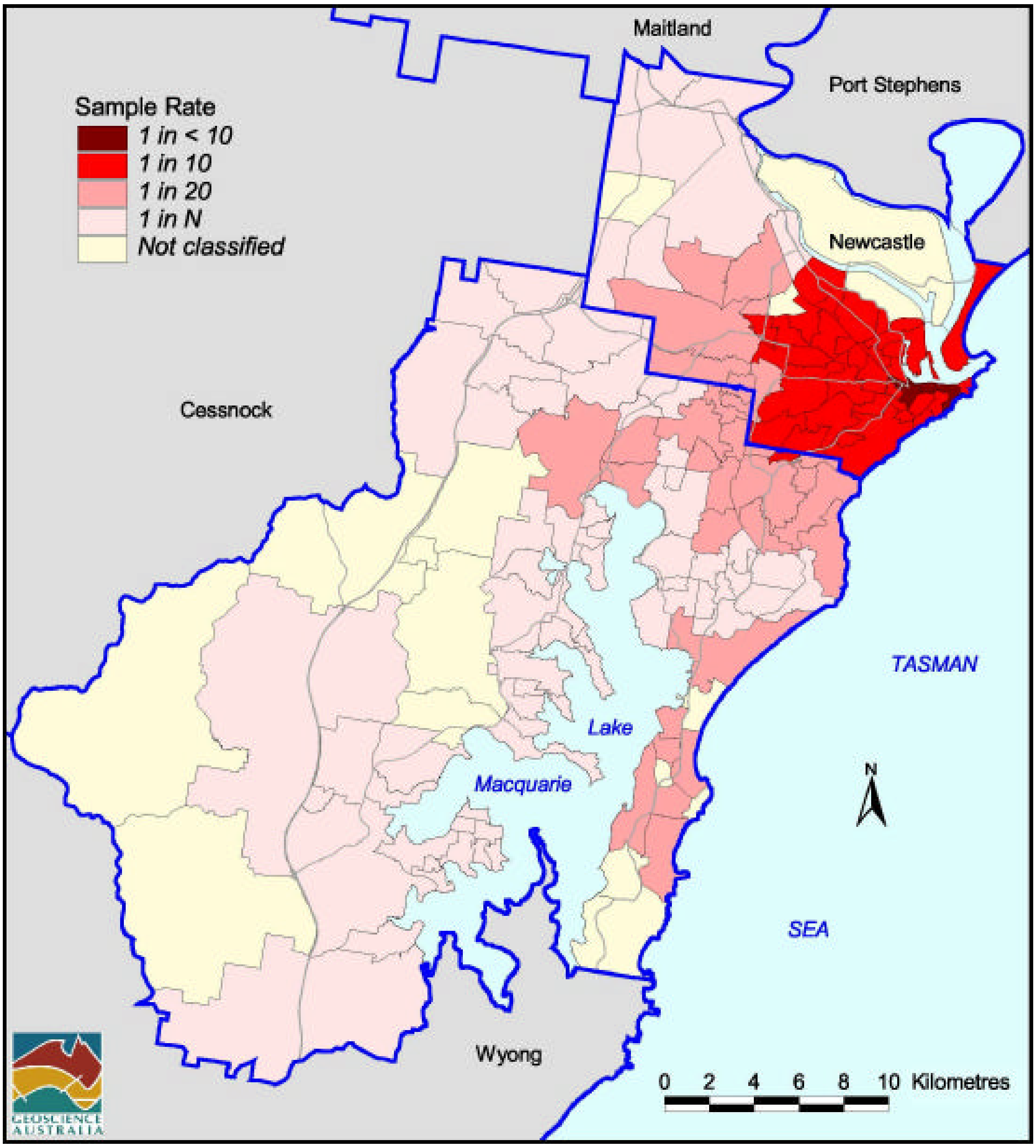


Figure G - 1: Survey rates across the study region

Table G - 1 : Survey rates and building counts by suburb

SUBURB	No. of surveyed sites	Survey rate / Multiple	Total Building Count	Cadastre Count
ADAMSTOWN	210	9.6	2015	2004
ADAMSTOWN HEIGHTS	194	10.4	2011	1989
ARCADIA VALE	3	220	660	676
ARGENTON	3	188.3	565	584
BALCOLYN	3	130	390	391
BALMORAL	3	89	267	286
BAR BEACH	30	10.1	302	296
BARNSLEY	3	339.3	1018	1077
BELMONT	8	275.6	2205	2212
BELMONT NORTH	21	96.4	2025	2035
BELMONT SOUTH	5	83.2	416	430
BENNETTS GREEN	3	1	3	41
BERESFIELD	7	187	1309	1364
BIRMINGHAM GARDENS	43	18.5	796	797
BLACK HILL	3	16.7	50	14
BLACKALLS PARK	3	351	1053	1130
BLACKSMITHS	42	17.7	744	768
BOLTON POINT	3	244.7	734	716
BONNELLS BAY	5	300.6	1503	1609
BOOLAROO	28	22.9	640	652
BOORAGUL	4	127.5	510	504
BRIGHTWATERS	3	128.3	385	367
BROADMEADOW	80	8.8	705	967
BUTTABA	3	112.7	338	515
CARDIFF	70	37.2	2602	2533
CARDIFF HEIGHTS	37	11.8	438	429
CARDIFF SOUTH	57	17.9	1021	1103
CAREY BAY	3	91.7	275	273
CARRINGTON	66	13.3	880	655
CAVES BEACH	60	25.8	1550	1564
CHARLESTOWN	259	17.9	4642	4508
COAL POINT	3	234	702	610

SUBURB	No. of surveyed sites	Survey rate / Multiple	Total Building Count	Cadastre Count
COOKS HILL	110	8.4	920	659
COORANBONG	4	127.5	510	951
CROUDACE BAY	3	60.7	182	183
DORA CREEK	4	197.3	789	782
DUDLEY	50	19.2	961	950
EDGEWORTH	7	417.6	2923	2914
ELEEBANA	5	397	1985	1899
ELERMORE VALE	70	20.9	1460	1428
ERARING	3	6.7	20	1
ESTELVILLE	3	52.3	157	349
FASSIFERN	3	65	195	208
FENNELL BAY	3	205.3	616	594
FISHING POINT	3	161.7	485	492
FLETCHER	3	34.3	103	391
FLORAVILLE	3	129	387	387
GARDEN SUBURB	37	13	481	551
GATESHEAD	86	14.5	1250	1255
GEORGETOWN	85	9.6	820	828
GLENDALE	3	367.7	1103	1125
HAMILTON	172	10.4	1790	1200
HAMILTON EAST	46	9	412	403
HAMILTON NORTH	56	7.4	416	394
HAMILTON SOUTH	151	6.7	1006	1074
HEXHAM	3	26.3	79	175
HIGHFIELDS	15	22.4	336	338
HILLSBOROUGH	14	17.3	242	244
HOLMESVILLE	5	104	520	425
ISLINGTON	108	8.3	898	800
JESMOND	72	9.6	694	672
JEWELLS	3	281.7	845	833
KAHIBAH	47	17.6	826	800
KILABEN BAY	3	138.3	415	385
KILLINGWORTH	3	73.7	221	475

SUBURB	No. of surveyed sites	Survey rate / Multiple	Total Building Count	Cadastre Count
KOTARA	172	9.1	1563	1554
KOTARA SOUTH	20	22.5	450	473
LAKELANDS	3	159.3	478	477
LAMBTON	205	9.7	1998	2029
MACQUARIE HILLS	5	162.4	812	833
MARKS POINT	30	16.8	504	559
MARMONG POINT	3	59.3	178	162
MARYLAND	127	16.4	2080	2318
MARYVILLE	68	8.9	603	613
MAYFIELD	384	10.6	4075	4005
MAYFIELD EAST	67	9.4	628	653
MAYFIELD WEST	91	8	730	778
MEREWETHER	365	9.8	3590	3533
MEREWETHER HEIGHTS	45	11.2	503	511
MINMI	4	57	228	245
MIRRABOOKA	3	102.7	308	313
MORISSET	7	90	630	676
MORISSET PARK	3	44.7	134	114
MOUNT HUTTON	45	17.6	790	848
NEW LAMBTON	383	10	3822	3809
NEW LAMBTON HEIGHTS	56	16.4	920	883
NEWCASTLE	179	1.1	200	539
NEWCASTLE EAST	36	2.5	90	249
NEWCASTLE WEST	89	1.3	120	283
NORTH LAMBTON	113	11.6	1310	1322
PELICAN	16	20	320	382
RANKIN PARK	45	21.2	956	938
RATHMINES	3	298.3	895	905
REDHEAD	5	184.8	924	1199
SANDGATE	3	50	150	160
SEAHAMPTON	3	33.3	100	182
SHORTLAND	57	24.4	1389	1366
SILVERWATER	2	67.5	135	117

SUBURB	No. of surveyed sites	Survey rate / Multiple	Total Building Count	Cadastre Count
SPEERS POINT	48	25	1202	1203
STOCKTON	196	8.2	1612	1645
SUNSHINE	2	121	242	241
SWANSEA	73	26.1	1908	1895
TARRO	5	120.4	602	584
TERALBA	23	21.7	500	505
THE HILL	35	13.4	470	392
THE JUNCTION	45	8.4	380	363
TIGHES HILL	85	9.4	795	785
TINGIRA HEIGHTS	3	246.7	740	733
TORONTO	9	266.7	2400	2341
VALENTINE	5	364.8	1824	2044
WALLSEND	251	18.2	4570	4461
WANGI WANGI	8	165	1320	1326
WARABROOK	53	9.1	483	585
WARATAH	151	10.7	1615	1585
WARATAH WEST	107	10	1070	1058
WARNERS BAY	6	439.8	2639	2535
WEST WALLSEND	7	109.7	768	743
WHITEBRIDGE	61	14.8	900	862
WICKHAM	61	4.1	250	410
WINDALE	5	213.6	1068	1057
WINDERMERE PARK	3	101	303	298
WOODRISING	3	177	531	523
WYEE	3	166.7	500	726
WYEE POINT	3	115	345	960
YARRAWONGA PARK	3	67	201	205
TOTAL	6339		117652	

Table G - 2 : Building counts by postcode and suburb

POSTCODE	SUBURB	CENSUS	Cadastre	Building Count	Difference
2264	BALCOLYN	3700	5114	5040	74
	BONNELLS BAY				
	BRIGHTWATERS				
	DORA CREEK				
	ERARING				
	MIRRABOOKA				
	MORISSET				
	MORISSET PARK				
	SILVERWATER				
	SUNSHINE				
	WINDERMERE PARK				
	YARRAWONGA PARK				
2265	COORANBONG	1511	951	510	441
2267	WANGI WANGI	1029	1326	1320	6
2278	BARNSLEY	////	1552	1541	11
	KILLINGWORTH				
2280	BELMONT	8333	8253	8388	-135
	BELMONT NORTH				
	CROUDACE BAY				
	FLORAVILLE				
	JEWELLS				
	MARKS POINT				
	VALENTINE				
2281	BLACKSMITHS	4517	4609	4522	87
	CAVES BEACH				
	PELICAN				
	SWANSEA				
2282	ELEEBANA	4714	4911	5102	-191
	LAKELANDS				
	WARNERS BAY				
2283	ARCADIA VALE				
	BALMORAL				
	BLACKALLS PARK				

POSTCODE	SUBURB	CENSUS	Cadastre	Building Count	Difference
	BOLTON POINT				
	BUTTABA				
	CAREY BAY				
	COAL POINT	7665	9131	8620	511
	FASSIFERN				
	FENNELL BAY				
	FISHING POINT				
	KILABEN BAY				
	RATHMINES				
	TORONTO				
2284	ARGENTON				
	BOOLAROO				
	BOORAGUL				
	MARMONG POINT	3978	4133	4126	7
	SPEERS POINT				
	TERALBA				
	WOODRISING				
2285	CARDIFF				
	CARDIFF HEIGHTS				
	CARDIFF SOUTH	8305	8937	8899	38
	EDGEWORTH				
	GLENDALE				
	MACQUARIE HILLS				
2286	ESTELVILLE				
	HOLMESVILLE	1254	1699	1545	154
	SEAHAMPTON				
	WEST WALLSEND				
2287	BIRMINGHAM GARDENS				
	ELERMORE VALE				
	FLETCHER				
	MARYLAND	9488	10578	10193	385
	MINMI				
	RANKIN PARK				
	WALLSEND				
2289	ADAMSTOWN				

POSTCODE	SUBURB	CENSUS	Cadastre	Building Count	Difference
	ADAMSTOWN HEIGHTS				
	GARDEN SUBURB				
	HIGHFIELDS	6829	6909	6856	53
	KOTARA				
	KOTARA SOUTH				
2290	BENNETTS GREEN				
	CHARLESTOWN				
	DUDLEY				
	GATESHEAD				
	HILLSBOROUGH				
	KAHIBAH	11665	11440	11278	162
	MOUNT HUTTON				
	REDHEAD				
	TINGIRA HEIGHTS				
	WHITEBRIDGE				
2291	MEREWETHER				
	MEREWETHER HEIGHTS	5563	4407	4473	-66
	THE JUNCTION				
2292	BROADMEADOW	687	967	705	-262
2293	MARYVILLE	816	1023	853	170
	WICKHAM				
2294	CARRINGTON	693	655	880	-225
2295	STOCKTON	1840	1645	1612	33
2296	ISLINGTON	622	800	898	-98
2297	TIGHES HILL	674	785	795	-10
2298	GEORGETOWN				
	WARATAH	3737	3471	3505	-34
	WARATAH WEST				
2299	JESMOND				
	LAMBTON	4109	4023	4002	21
	NORTH LAMBTON				
2300	BAR BEACH				
	COOKS HILL				
	NEWCASTLE	3835	2135	1982	153

POSTCODE	SUBURB	CENSUS	Cadastre	Building Count	Difference
	NEWCASTLE EAST				
	THE HILL				
2302	NEWCASTLE WEST	21	283	120	163
2303	HAMILTON	4308	3071	3624	-553
	HAMILTON EAST				
	HAMILTON NORTH				
	HAMILTON SOUTH				
2304	MAYFIELD	5871	6181	6066	115
	MAYFIELD EAST				
	MAYFIELD WEST				
	SANDGATE				
	WARABROOK				
2305	NEW LAMBTON	4720	4692	4742	-50
	NEW LAMBTON HEIGHTS				
2306	WINDALE	834	1057	1068	-11
2307	SHORTLAND	1369	1366	1389	-23
2322	BERESFIELD	4700	2137	2040	97
	BLACK HILL				
	HEXHAM				
	TARRO				
2259	WYEE		1686	845	841
	WYEE POINT				

The sampling rate determines the level of uncertainty in the inventory data. Hence, the risk assessment results are expected to be less uncertain for the Newcastle region. However, due to the random nature of the spread of building stock within a community, the uncertainty can not be well defined by statistical means.

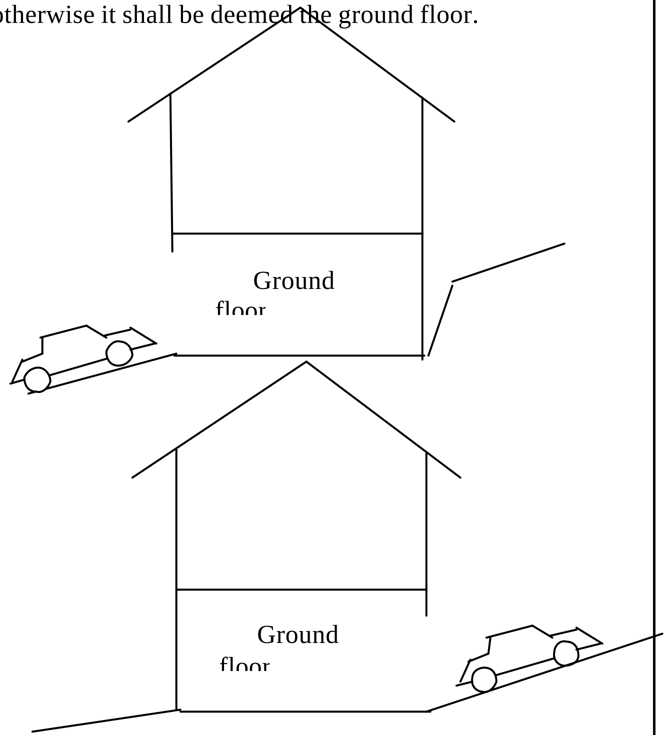
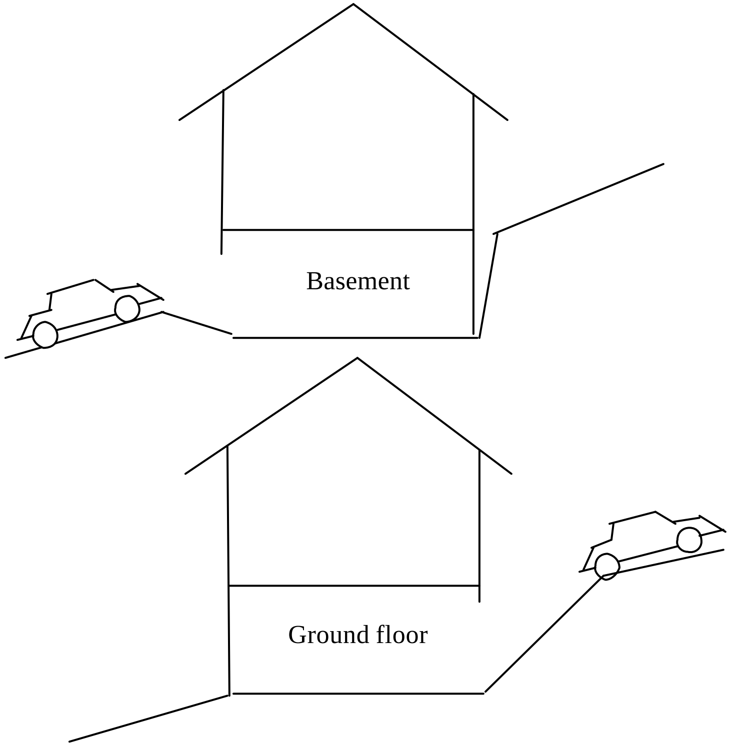
An attempt was made to survey all large buildings and special buildings such as fire stations, ambulance stations during the survey. The building data collected includes location, age, construction types, dimensions, usage, vulnerable features, irregularities and the nature of adjacent buildings on the same site. The data items and instructions given to surveyors are listed in detail in Table G - 3 to Table G - 12.

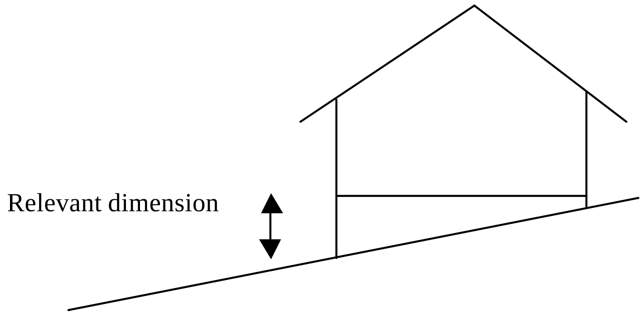
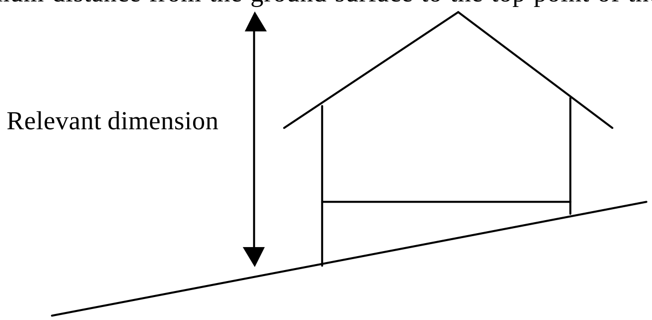
Table G - 3 : Address

Field	Data (ENTER = enter text, CHOOSE = choose from list)	Relevance
Repeat site	Tick indicates YES, otherwise NO You must be absolutely sure that the building is 100% the same as the last one surveyed (including other features). Fill in the first table only.	To reduce the boredom of the surveyor
Construction site	Tick indicates YES, otherwise NO. Some sites will be subject to construction. Fill in the first table only.	Construction sites are more highly prone to wind damage.
Photos taken	ENTER number Take a photo of the building, trying to get the foundations, roof, front wall and one side wall in the picture. Take a second photo only if absolutely necessary. A picture of the streetscape must be taken for every address which ends with the numerals "05".	Photos taken so that data can be easily checked later without necessarily going back out into the field. Photos of streetscapes will allow qualitative judgement of the aesthetic importance of the structure.
Today's date	ENTER number (today's date is default) Today's date is defaulted so just tick the box.	Date recorded since buildings may be demolished, or changed in some way in the future. Date is also useful for bookkeeping purposes.
Address number	CHOOSE from "OTHER,UNKNOWN,5,15,25,35,45,55,65,75,85,95,105,115,125,135, 145,155,165,175,185,195,205" In case of "OTHER", ENTER the number, or if the building occupies more than one address enter a range: ie. "3-11" Survey every building with an address which ends with the numeral	Address allows spatial location in the risk analysis (checked also by coordinates). Sufficient numbers of properties are to be surveyed to give the sample statistical certainty as discussed previously.

	"5" (or buildings with a range of addresses which includes an address ending in "5" within the range. ie. "3-11"). If buildings are large and are occupied by single entities, the address of the building may be specified as a single address number instead of a range: ie. You may have addresses 95, 101,113,117,121,125 in that sequence. In this case, survey the buildings which immediately follow where an address ending in "5" should be. In this case you would survey buildings 95, 113 (follows where 105 should be), 117 (follows where 115 should be) and 125. Also survey all other buildings which are: EDUCATION, MEDICAL or SAFETY types of any size. Important (can contain more than 100 people or service more than 10,000 people per day). Potentially hazardous to large amounts of people. Ie. storage of toxic chemicals/explosive material.	All important and large buildings are important in terms of risk assessment since the community is reliant on them.
Street	CHOOSE from list, OTHER, UNKNOWN A list of streets should be uploaded for the area you are surveying. If the street name does not exist in the list then choose "OTHER" and type the street name in the comment field.	Address allows spatial location in the risk analysis (checked also by coordinates).
Suburb	CHOOSE from list, OTHER, UNKNOWN A list of suburbs should be uploaded for the area you are surveying. If the suburb name does not exist in the list then choose "OTHER" and type the street name in the comment field.	Address allows spatial location in the risk analysis (checked also by coordinates).
Age	CHOOSE from up to 1900, 1901 up to 1930, 1931 up to 1950, 1951up to 1960, 1961 up to 1970, 1971 up to 1980, 1981 up to 1990, 1991 up to 2000, UNKNOWN Make your best guess.	Building categories in risk assessment may be typified by age.
Living units	CHOOSE from 0,1,2,3,4,6,8,10,15,20,30,50,100+, UNKNOWN The number of family living units. Look at letterbox.	Important for estimating the numbers of lives at risk.

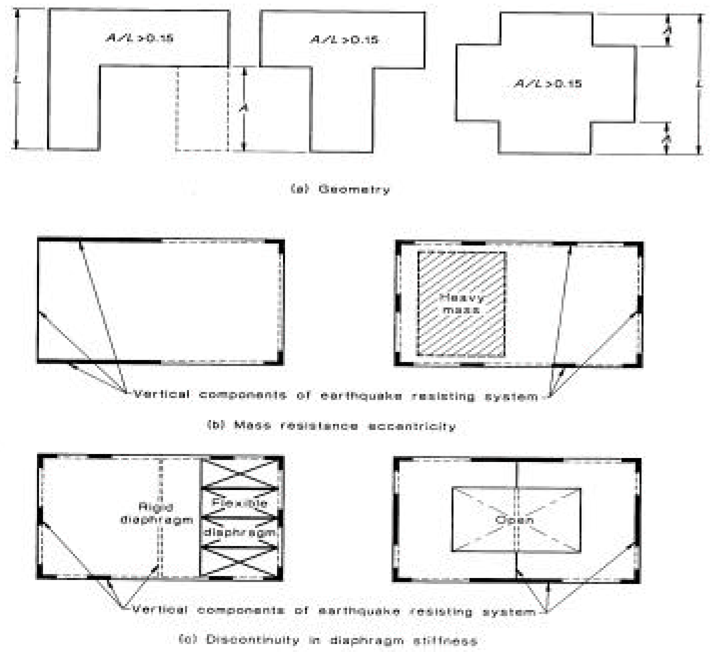
Table G - 4 : Size

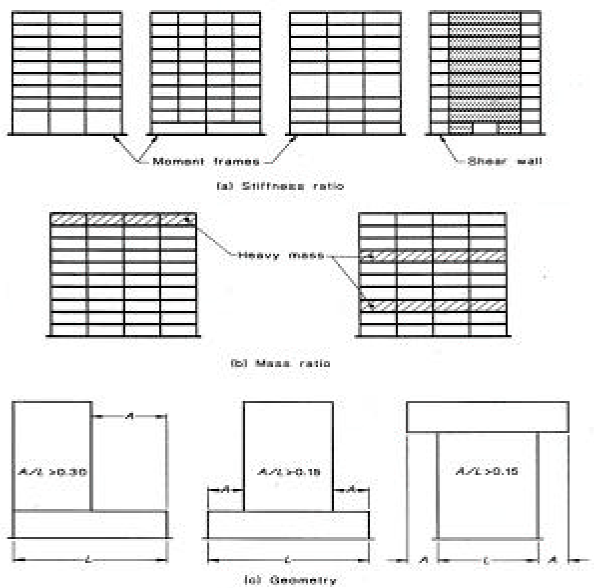
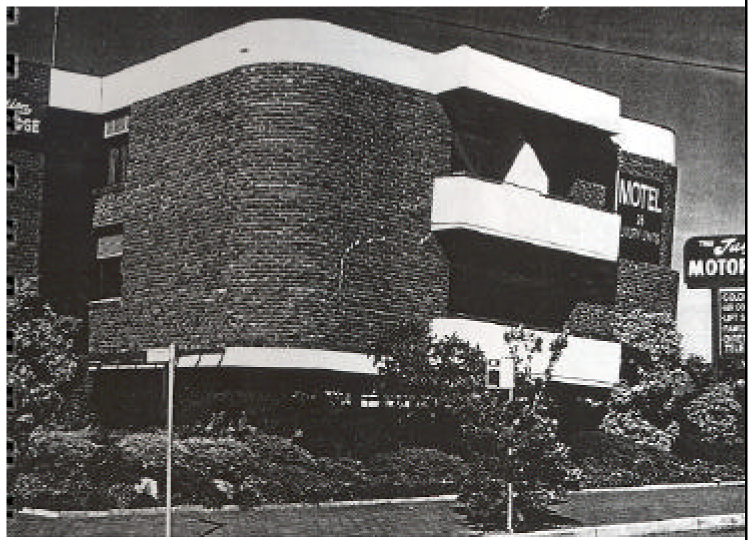
Field	Data (ENTER = enter text, CHOOSE = choose from list)	Relevance
Basements	CHOOSE from 0,1,2,3,4,6,8,10+, UNKNOWN Multi-storey buildings are more likely to have one or more basements – enter the building if publicly accessible and observe the number of basements indicated by the lift.	Important mainly for flood risk assessment.
Storeys	CHOOSE from 0,1,2,3,4,6,8,10,20,40,60,100+, UNKNOWN The number of storeys includes the ground floor. A storey which has its floor level below the ground's natural surface for at least two side faces of the building shall be deemed a basement, otherwise it shall be deemed the ground floor. Ie.  	Average storey heights can be estimated which may be of importance for flood risk assessment. 

Ground floor height (m)	CHOOSE from 0,0.3,0.6,1.0,1.5,2,2.5, UNKNOWN Maximum distance from the ground surface to the level of the ground floor. Ie. 	Important in terms of flood risks. Also important in earthquakes, where this dimension will describe the slenderness of the foundations and may imply the foundation type where it can't be seen due to a facade.
Roof height (m)	CHOOSE from 0,2,2.5,3,4,5,6,8,10,12,15,20,30,50,100+, UNKNOWN Maximum distance from the ground surface to the top point of the roof. Ie. 	Important in terms of most hazards. For floods, the roof could be the last resort for residents. For wind, height implies wind loading. For earthquakes, height implies structure stiffness and consequently expected seismic performance.

Floor plan width (m)	CHOOSE from 3,5,8,10,12,15,20,30,50,100+, UNKNOWN Estimating by pacing out the distance.	Important for estimating the wind or earthquake load attracted to the structure and for also estimating the structural stiffness. Floor plan area can be determined which can be used to imply the value of the building.
Floor plan depth (m)	CHOOSE from 3,5,8,10,12,15,20,30,50,100+, UNKNOWN Estimate by looking at the side wall and comparing to the estimate of floor plan width.	As above.
Distance to nearest neighbouring building	CHOOSE from 0,0.1,0.3,0.5,1,2,4,10,20+, UNKNOWN If nearest neighbouring building is abutting then distance is zero. A neighbouring building may be one on the same property if there is more than one building on the property.	Important in terms of the potential for pounding in earthquakes between adjacent structures. Also important in terms of the shielding of wind. Also important regarding fire spread.

Table G - 5 : Construction

Field	Data (ENTER = enter text, CHOOSE = choose from list)	Relevance
Plan regularity	CHOOSE from REGULAR, IRREGULAR, UNKNOWN REGULAR floor plans are approximately of rectangular, triangular or circular shape, with stiffness and mass evenly distributed. Most houses will fall in this category. IRREGULAR floor plans may be assessed by considering the examples given here (adopted from AS1170.4): 	Mainly important in terms of earthquake response. Irregular structures have seismic demand concentrations.

Vertical regularity SOFT STOREY	CHOOSE from REGULAR, IRREGULAR, SOFT STOREY, UNKNOWN REGULAR vertical plans are approximately of rectangular or triangular shape, with stiffness and mass evenly distributed. Most houses will fall in this category. IRREGULAR vertical plans and SOFT STOREYS may be assessed by considering the examples given here (adopted from AS1170.4): (A SOFT STOREY is the first example shown) 	Mainly important in terms of earthquake response. Irregular and soft storey structures have seismic demand concentrations. Example:  *Figure G - 2: The importance of soft storeys. The ground floor consisted mainly of slender reinforced concrete columns. Seismic damage was concentrated in this soft storey, resulting in demolition of the building (Melchers, 1990)*
Foundations	CHOOSE from SLAB ON GROUND, BRICK WALL, BRICK PIER, CONCRETE WALL, CONCRETE PIER, TIMBER WALL, TIMBER PIER, METAL STRUTS, OTHER, UNKNOWN Note only what you see.	Important in terms of seismic response. Some foundation types (such as slender unbraced piers) are particularly prone to behave like a soft-storey.

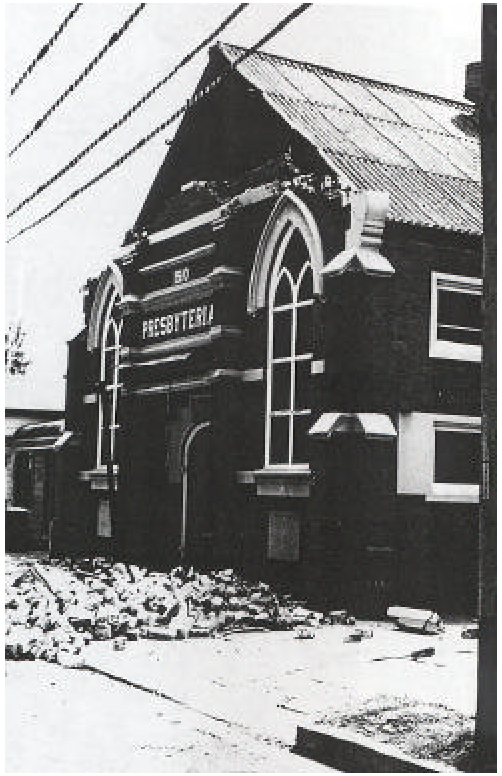
Walls	CHOOSE from BRICK, TIMBER, MASONRY, STONE, FIBRO, METAL, PRE-CAST CONCRETE, REINFORCED CONCRETE, MASONITE, GLASS, R/C FRAME WITH BRICK/MASONRY INFILL, OTHER, UNKNOWN Note only what you see.	Building categories in risk assessment may be typified by walls. Earthquake performance is often characterised by the stiffness, strength, displacement capacity and ductility of walls. Example:  *Figure G - 3: Importance of wall type: Brick walls are susceptible to racking damage from earthquakes due to brittle material properties (Melchers, 1990)*
Roof	CHOOSE from TILE, CONCRETE, METAL, SLATE, FIBRO, TIMBER, OTHER, UNKNOWN Note only what you see.	Important in terms of the determination of a structure's fundamental period which is of most importance for seismic performance. Different material types may also be more prone to wind and hail damage.

Table G - 6 : Other features - 1

Field	Data (ENTER = enter text, CHOOSE = choose from list)	Relevance
Windows	CHOOSE from LARGE, MEDIUM, SMALL, NONE, OPEN, UNKNOWN LARGE is defined as windows which occupy more than 40% of the area of the most heavily windowed face. MEDIUM is defined as windows which occupy between 15% and 40% of the area of the most heavily windowed face. SMALL is defined as windows which occupy less than 15% of the area of the most heavily windowed face. NONE is defined as windows which occupy less than 2% of the area of the most heavily windowed face. OPEN is defined as when there are voids in the building.	Similar importance as soffit linings in terms of wind. Entry of wind and rain into the building can lead to excessive damage. May also be important in terms of hail damage.
Window protectors	Tick indicates YES, it does exist, otherwise, NO, it does not exist.	 *Figure G - 4: Window protectors greatly reduce the vulnerability of buildings to wind damage. Ref(Boughton, 1999)*

Verandah/awnings	CHOOSE from CANTILEVER, PROPPED, SUSPENDED Only significant verandahs and awnings which are not part of the roof structure should be noted. If no choice is made, then assumed to not exist.	Cantilever verandahs perform poorly when subject to high winds. Propped and suspended verandahs may perform slightly better. Shop awnings suspended by attachment to brick parapets have performed poorly when subject to earthquake loading (Melchers, 1990).
Brick chimneys	CHOOSE the chimney height from 0.3,0.6,1,1.5,2,2.5,3,5,10,20,30+ If no choice is made, then assumed to not exist.	Element highly vulnerable to earthquake loading.  *Figure G - 5: Importance of chimneys. Chimneys are highly vulnerable to earthquakes (Melchers, 1990)*
Brick parapets	CHOOSE the parapet height from 0.3,0.6,1,1.5,2,2.5,3,5,10,20,30+ If no choice is made, then assumed to not exist.	Element highly vulnerable to earthquake loading.

Brick fences	CHOOSE the fence height from 0.3,0.6,1,1.5,2,2.5,3,5,10,20,30+ If no choice is made, then assumed to not exist.	Element highly vulnerable to earthquake loading.

Gable roof with brick ends	Tick indicates YES, it does exist, otherwise, NO, it does not exist.	Gable roofs with brick end walls are more prone to earthquake damage. Example:  *Figure G - 6: The importance of gable roofs. The gable end of this roof, constructed from bricks failed out-of-plane under seismic loading (Melchers, 1990)*

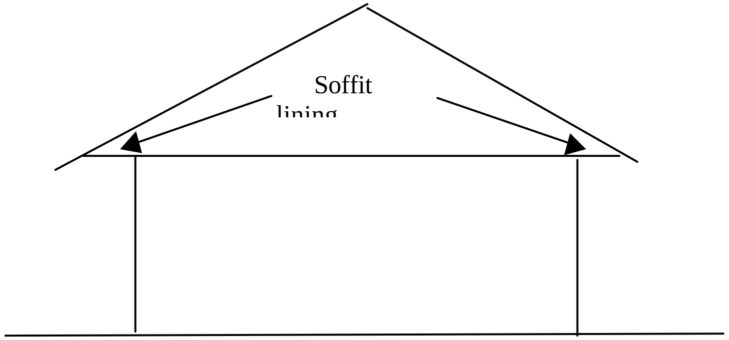
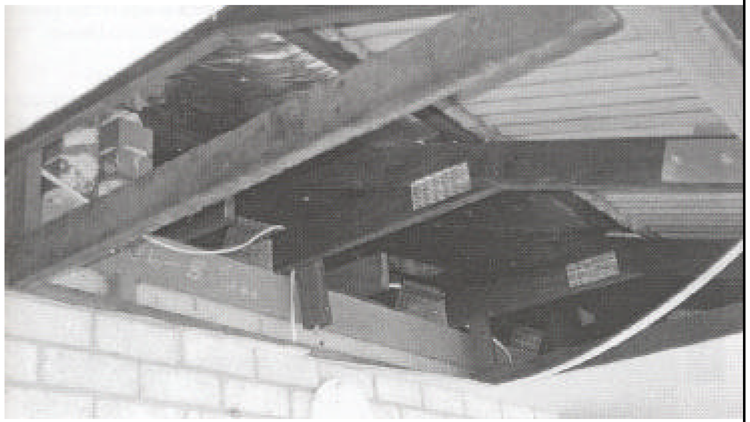
Soffit	Tick indicates YES, it does exist, otherwise, NO, it does not exist. The location of the soffit lining is indicated here:  	Important in terms of wind. Many instances have been observed of wind blowing through the soffit lining which leads to internal pressurisation of the building (and possible blow off of roof) and ingress of water which can incur severe damage to contents. Example:  *Figure G - 7: The importance of soffit lining. Failure of soffit lining allows the entry of wind and rain, leading to extensive internal and roof damage. Ref(Reardon et al., 1999)*
Water tank	Tick indicates YES, it does exist, otherwise, NO, it does not exist.	Readily available supply of water to fight fire, hence reducing risk from fire hazards.
Ventilators	Tick indicates YES, it does exist, otherwise, NO, it does not exist.	Existence of ventilators increases the risk to wind damage, since water can be blown in.

Table G - 7 : Other features - 2

Parking structure – type	CHOOSE from IN BASEMENT, IN GROUND FLOOR, ATTACHED GARAGE, DETACHED GARAGE, CARPORT	 *Figure G - 8: Importance of garages. The wind damage caused to this garage will cost a significant amount of money to repair. Ref(Reardon et al., 1999)*
Parking structure – car spaces	CHOOSE from 1,2,3,4,6,8,10,20,50,100,200,500,1000+, UNKNOWN The number of car spaces.	The number of car spaces allows the quantity of elements at risk to be quantified. Parking structures also reduce the vulnerability of cars to hail damage.
Parking structure - material	CHOOSE from SAME AS PRIMARY BUILDING, BRICK, TIMBER, MASONRY, STONE, FIBRO, METAL, PRE-CAST CONCRETE, REINFORCED CONCRETE, MASONITE, GLASS, R/C FRAME WITH BRICK/MASONRY INFILL, OTHER, UNKNOWN The material which is supporting the roof, should it be walls, columns, or struts, is the material which should be noted.	Different materials perform differently in terms of stiffness, strength, displacement capacity and ductility.
Other structure – 1 – number	CHOOSE from 1,2,3,4,6,8,10,20,50,100,200,500,1000+, UNKNOWN The number of other structures. Do not include garden sheds and cubbies.	Other structures at the address may have significant levels of risk.

Other structure – 1 - relative size	CHOOSE from SAME, HALF, QUARTER, MUCH SMALLER, UNKNOWN The size relative to the primary building. The primary building should be the largest building at the address.	The number of car spaces allows the quantity of elements at risk to be quantified. Parking structures also reduce the vulnerability of cars to hail damage.
Other structure – 1 – material	CHOOSE from SAME AS PRIMARY BUILDING, BRICK, TIMBER, MASONRY, STONE, FIBRO, METAL, PRE-CAST CONCRETE, REINFORCED CONCRETE, MASONITE, GLASS, R/C FRAME WITH BRICK/MASONRY INFILL, OTHER, UNKNOWN The material which is supporting the roof, should it be walls, columns, or struts, is the material which should be noted.	Different materials perform differently in terms of stiffness, strength, displacement capacity and ductility.
Other structure – 2 – number	CHOOSE from 1,2,3,4,6,8,10,20,50,100,200,500,1000+, UNKNOWN The number of other structures. Do not include garden sheds and cubbies.	Other structures at the address may have significant levels of risk. There may be more than one other significant class of other structures. The survey form does not allow more than two classes of other structures.
Other structure – 2 - relative size	CHOOSE from SAME, HALF, QUARTER, MUCH SMALLER, UNKNOWN The size relative to the primary building. The primary building should be the largest building at the address.	The number of car spaces allows the quantity of elements at risk to be quantified. Parking structures also reduce the vulnerability of cars to hail damage.
Other structure – 2 – material	CHOOSE from SAME AS PRIMARY BUILDING, BRICK, TIMBER, MASONRY, STONE, FIBRO, METAL, PRE-CAST CONCRETE, REINFORCED CONCRETE, MASONITE, GLASS, R/C FRAME WITH BRICK/MASONRY INFILL, OTHER, UNKNOWN The material which is supporting the roof, should it be walls, columns, or struts, is the material which should be noted.	Different materials perform differently in terms of stiffness, strength, displacement capacity and ductility.

Table G - 8 : Confidence (sheet 12) - compulsory

Field	Data (ENTER = enter text, CHOOSE = choose from list)	Relevance
Confidence in data*	CHOOSE from HIGH, MEDIUM, LOW This is the confidence you have in your data.	Allows the uncertainty in the data to be quantified. Also highlights problems to the survey supervisor.
Comments	ENTER text Put in any comments you like. Maybe a comment about streetscape, particular unusualities not covered by the survey, etc.	Allows comments to be made which can not be expressed by any other field. Useful for development of the survey form.

Table G - 9: Building Use - compulsory

Field	Data (ENTER = enter text, CHOOSE = choose from list)	Relevance
Industry	See the supplementary feature attribute table, UNKNOWN	Building use implies importance to the community in risk assessment. Building types may also be typified by building use.
Category	See the supplementary feature attribute table, UNKNOWN	Building use implies importance to the community in risk assessment. Building types may also be typified by building use.
Type	See the supplementary feature attribute table, UNKNOWN	Building use implies importance to the community in risk assessment. Building categories in risk assessment may be typified by building use.

Table G - 10: Supplementary feature attribute table

Industry	Category	Type
ACCOMMODATION	HOUSE, UNITS, FLATS, HOTEL, MOTEL, RESORT, HOSTEL, CARAVAN PARK	SINGLE, ATTACHED, MULTIPLE, DUPLEX
BUSINESS	FOOD, WHITEGOODS, AUTOMOBILES, ELECTRONICS, CLOTHING, SERVICE, MULTIPLE	OFFICE, SHOP, MALL, SUPERMARKET, SERVICE STATION
COMMUNITY	ART, SPORT, RELIGION, HISTORY, SCIENCE, GENERAL	GALLERY, HALL, LIBRARY, MONUMENT, MUSEUM, TOILET, WORSHIP PLACE, CLUB, GRANDSTAND, STADIUM, CENTRE
EDUCATION	PRE-SCHOOL, CHILDCARE, SCHOOL, UNIVERSITY, COLLEGE, CONVENT	CLASSROOM, HALL, LIBRARY, CAMPUS, CENTRE, OFFICE, THEATRE
GOVERNMENT	LOCAL, STATE, FEDERAL	OFFICE, SHOP
MANUFACTURING	FOOD, WHITEGOODS, AUTOMOBILES, ELECTRONICS, CLOTHING	FACTORY, PLANT, MILL
MEDICAL	DENTIST, DOCTOR, SPECIALIST, NURSE, VET	HOSPITAL, SURGERY, CENTRE, HOME, CLINIC, HOSPICE

SAFETY	AMBULANCE, DEFENCE, FIRE, POLICE, SES	STATION, HEAD QUARTERS
STORAGE	FOOD, FUEL, CHEMICALS	DEPOT, WAREHOUSE
TRANSPORT	BUS, RAIL, SHIP, AIR	STATION, TERMINAL
UTILITY	ELECTRICITY, GAS, SEWERAGE, TELECOMMUNICATIONS, WATER	STATION, TOWER, EXCHANGE, RESERVOIR, PLANT

Table G - 11: Attributes – informative only. No input required

Field	Data (ENTER = enter text, CHOOSE = choose from list)	Relevance
All	All This is a list of all the data that has been input. No input is allowed here, however, the data may be checked.	Just for checking purposes.

Table G - 12: Geography – informative only. No input required

Field	Data (ENTER = enter text, CHOOSE = choose from list)	Relevance
GPS longitude	AUTOMATIC from GPS No input required here. Feeds your location in automatically from the differentiated GPS.	Allows data to be directly plotted on a map, and is also useful for crosschecking street addresses.
GPS latitude	AUTOMATIC from GPS No input required here. Feeds your location in automatically from the differentiated GPS.	Allows data to be directly plotted on a map, and is also useful for crosschecking street addresses.

Floor area can be used to estimate the value of property, hence the floor area represented by a surveyed point has been estimated by Equation 4.

Equation 4: Floor area calculation

$$\text{Floor area} = \text{width} \times \text{depth} \times \text{no. of storeys} \times \text{survey rate for the site} \times \text{a regularity factor}$$
$$\times \begin{pmatrix} 1 + (\text{no. of secondary buildings} \times \text{fraction of size relative to the primary building}) \\ + (\text{no. of tertiary buildings} \times \text{fraction of size relative to the primary building}) \end{pmatrix}$$

where,

$$\text{the regularity factor} = \begin{cases} 0.9 \text{ for a regular plan building} \\ 0.7 \text{ for an irregular plan building} \end{cases}$$

The spatial distribution of surveyed buildings according to external wall material is shown in Figure G - 9 to Figure G - 11. The distribution of vulnerable building details such as brick chimneys, brick parapets, brick gable end roofs and structural irregularity is shown in Figure G - 12 - Figure G - 18. The size of the building floor area represented by each survey point is shown in Figure G - 19 - Figure G - 21 with size denoted by colour.

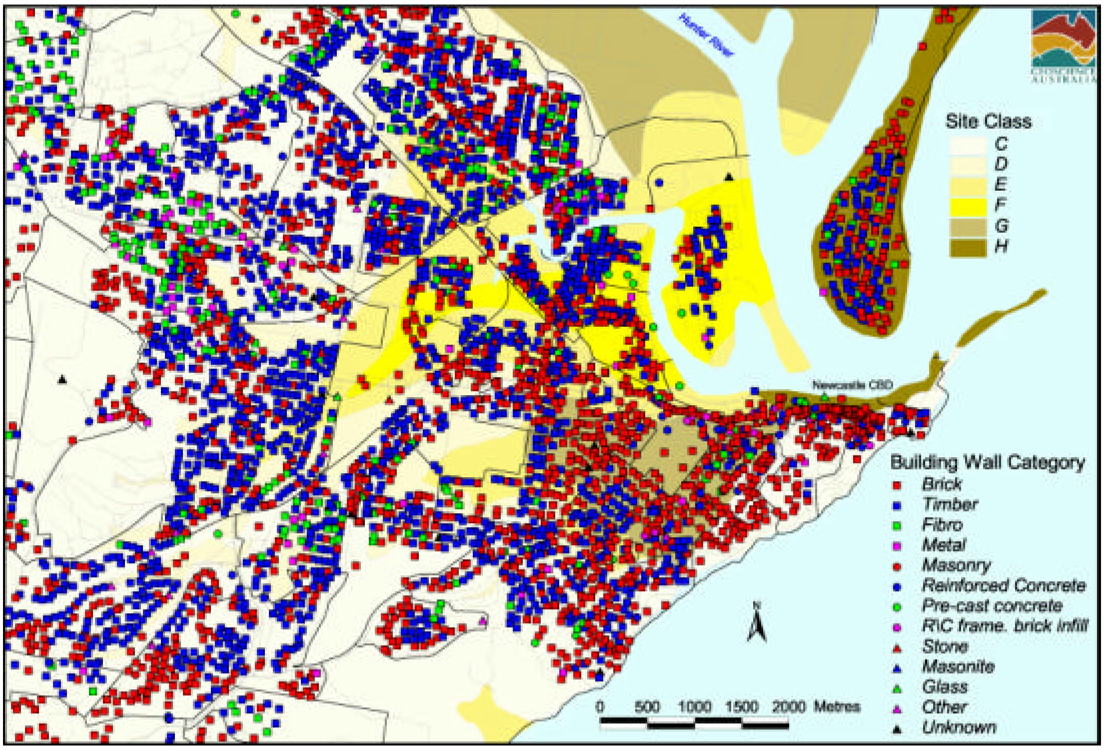


Figure G - 9: Distribution of buildings in the Newcastle area according to external wall type

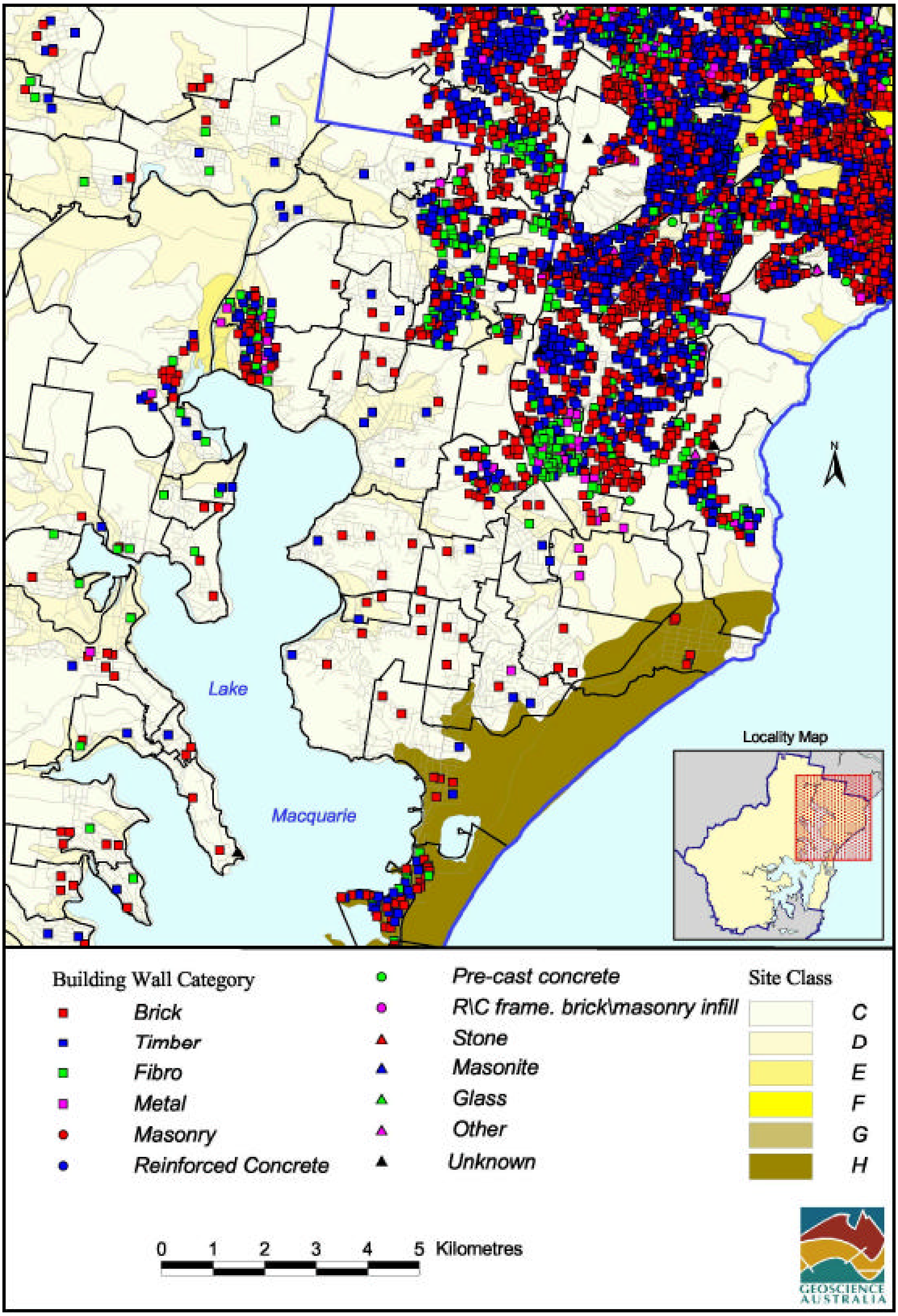


Figure G - 10: Distribution of buildings in the northern Lake Macquarie area according to external wall

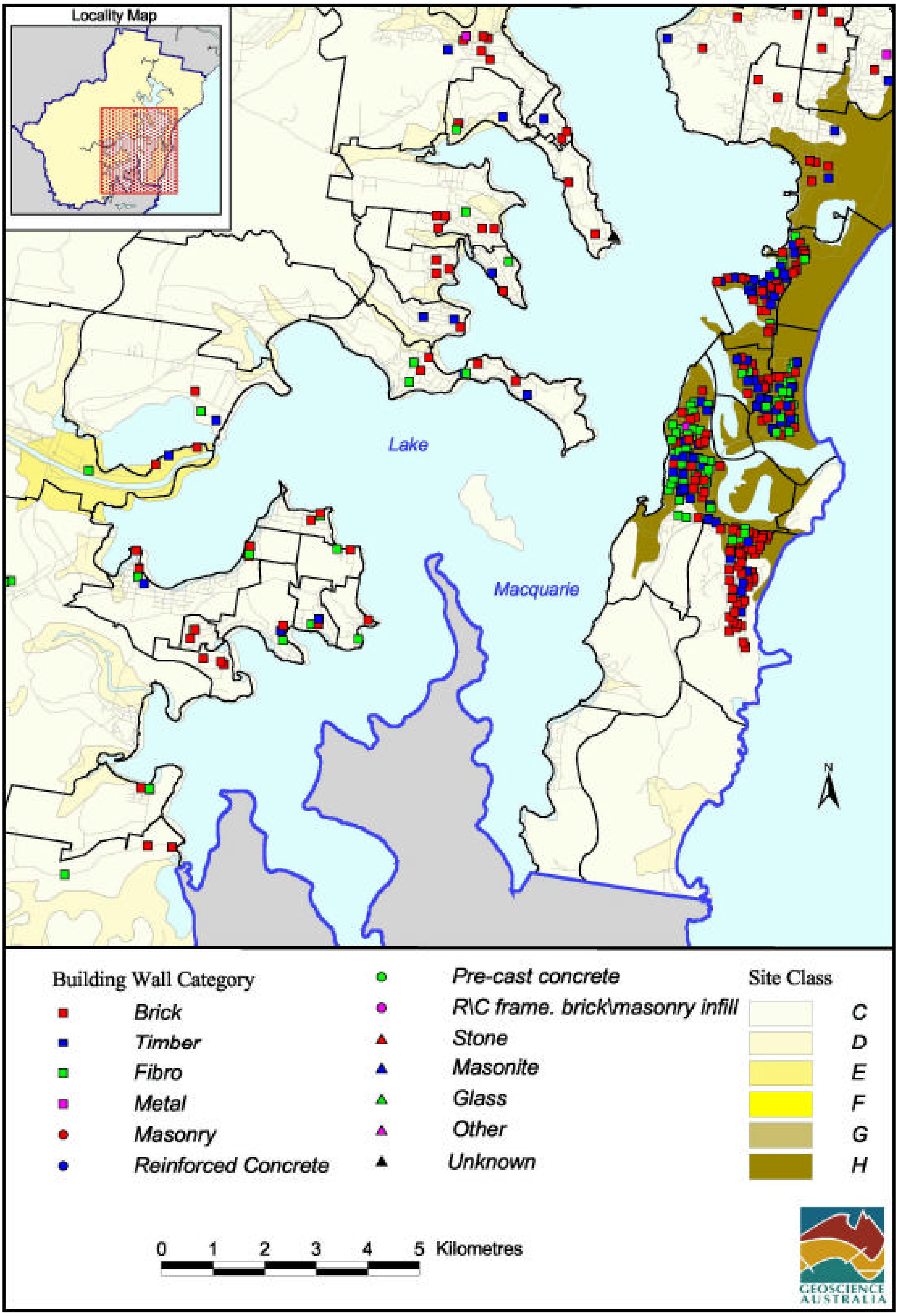


Figure G - 11: Distribution of buildings in the southern Lake Macquarie area according to external wall

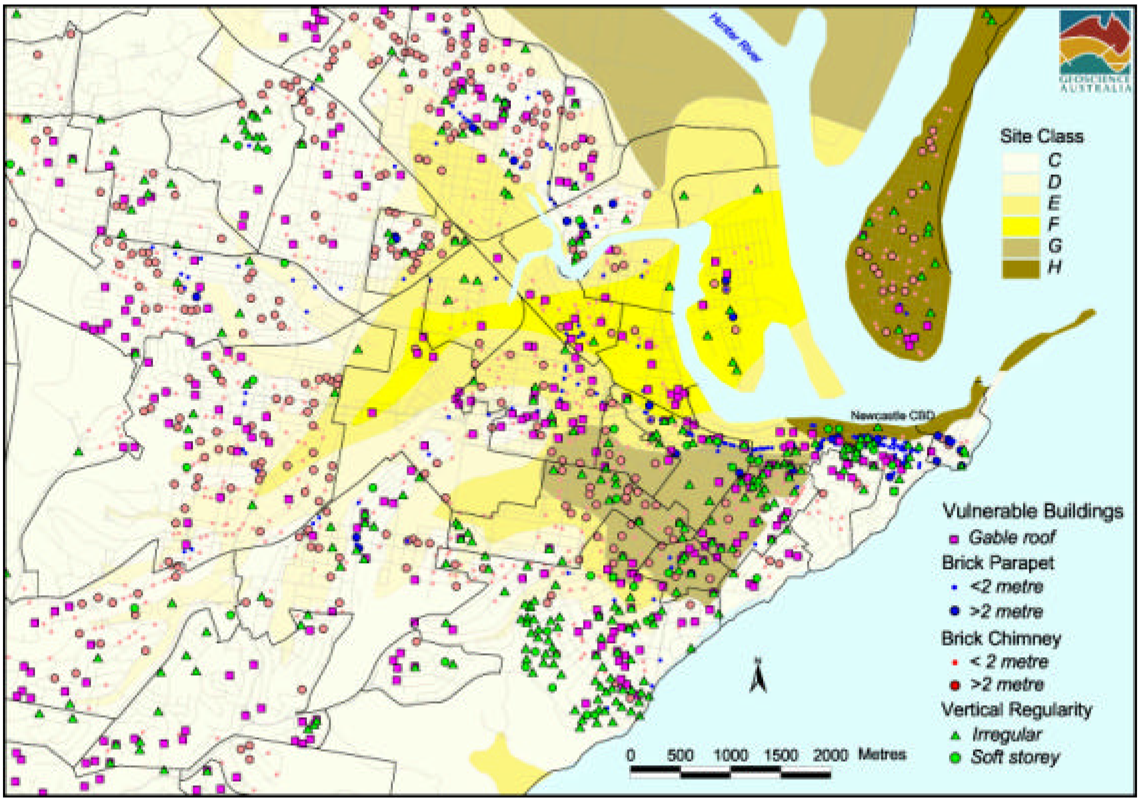


Figure G - 12: Distribution of vulnerable building elements in the Newcastle area

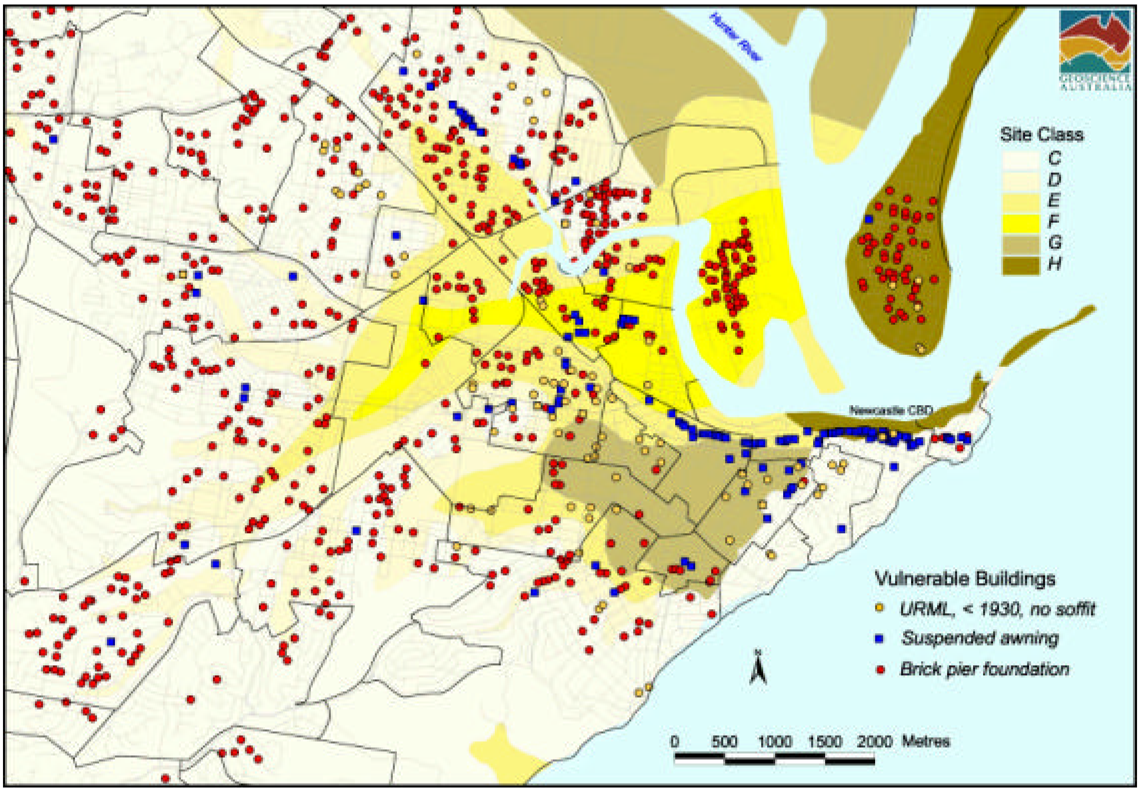


Figure G - 13: Distribution of vulnerable building elements in the Newcastle area

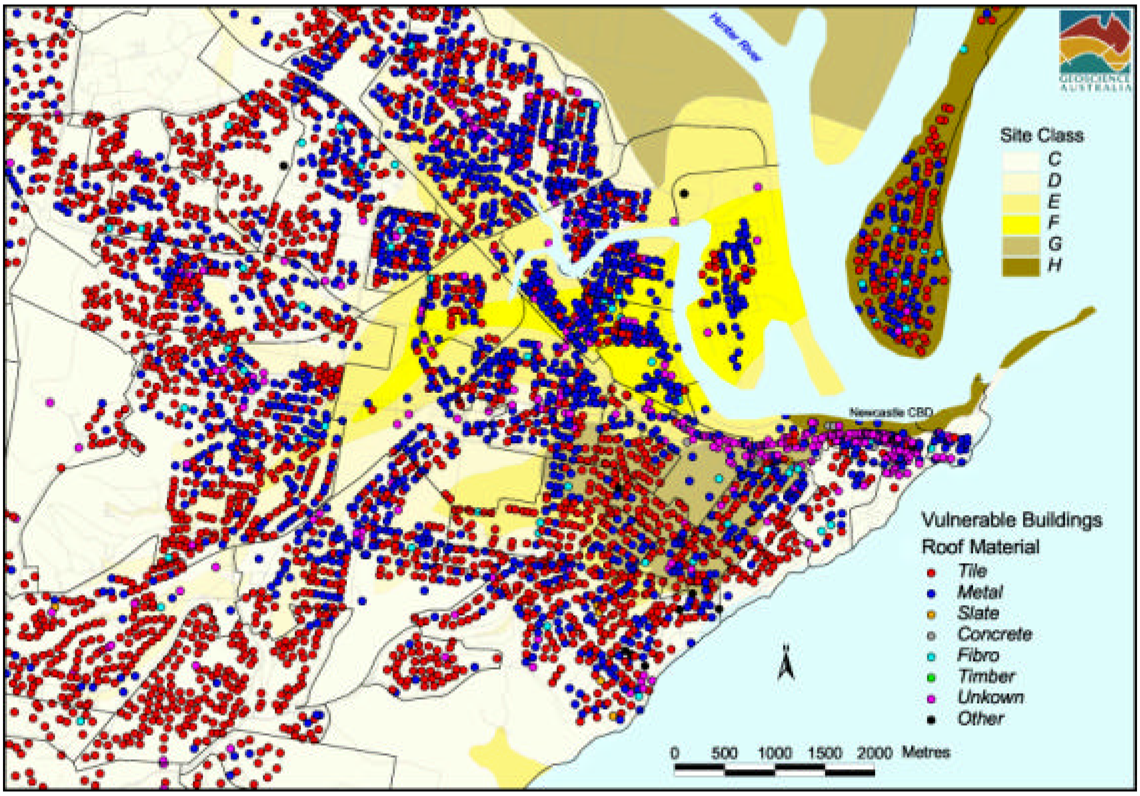


Figure G - 14: Distribution of vulnerable building elements in the Newcastle area

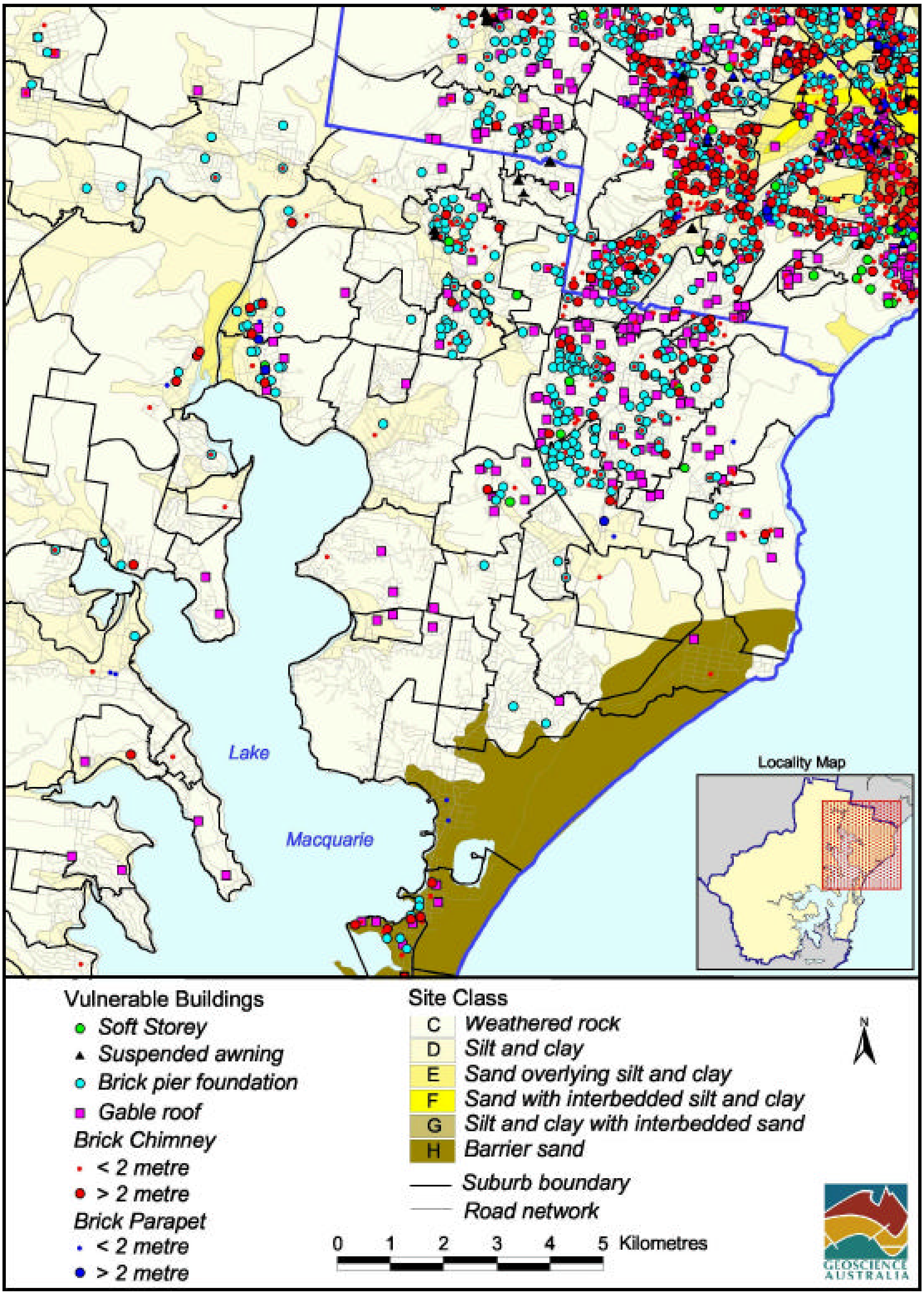


Figure G - 15: Distribution of vulnerable building elements in the northern Lake Macquarie area

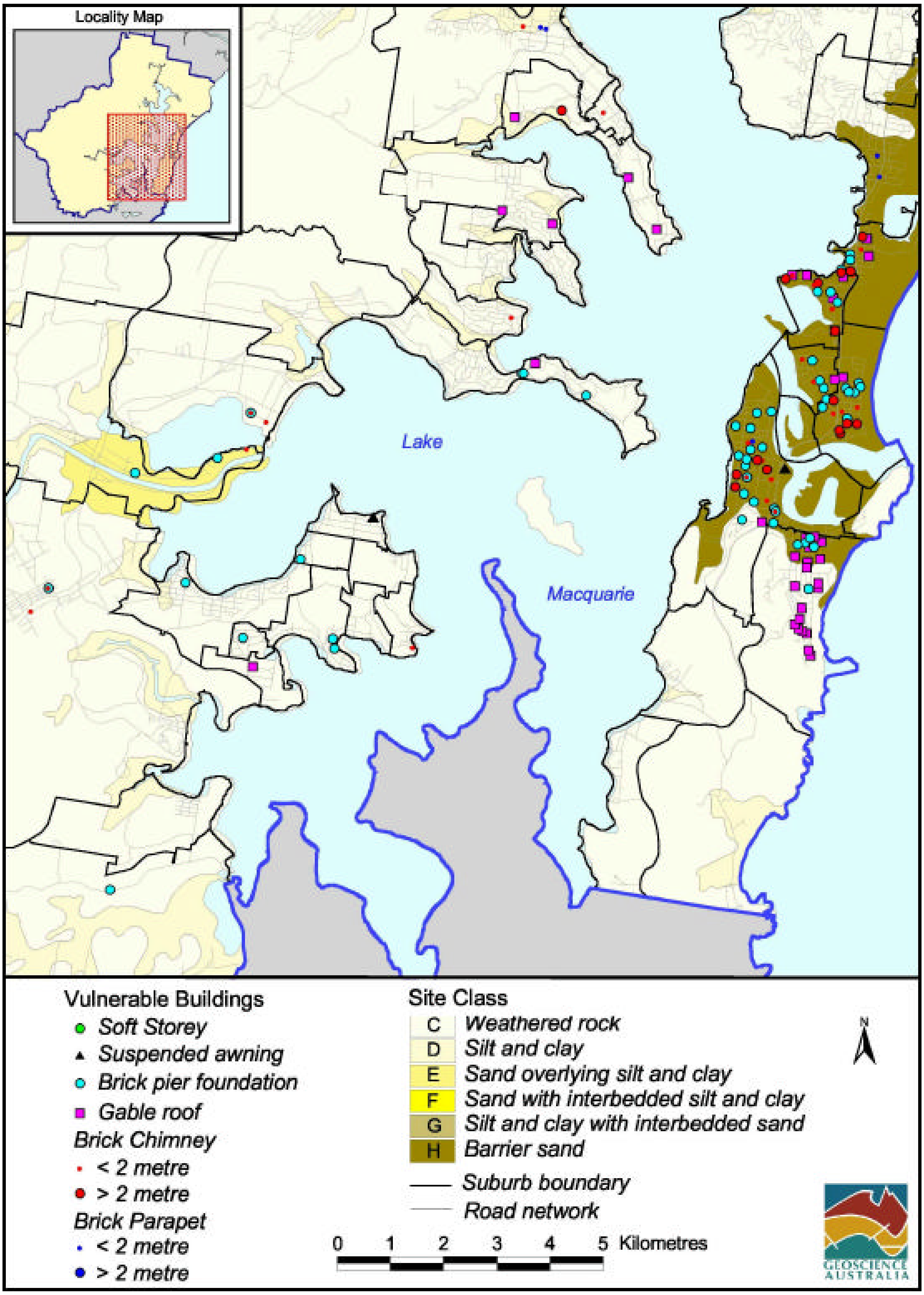


Figure G - 16: Distribution of vulnerable building elements in the northern Lake Macquarie area

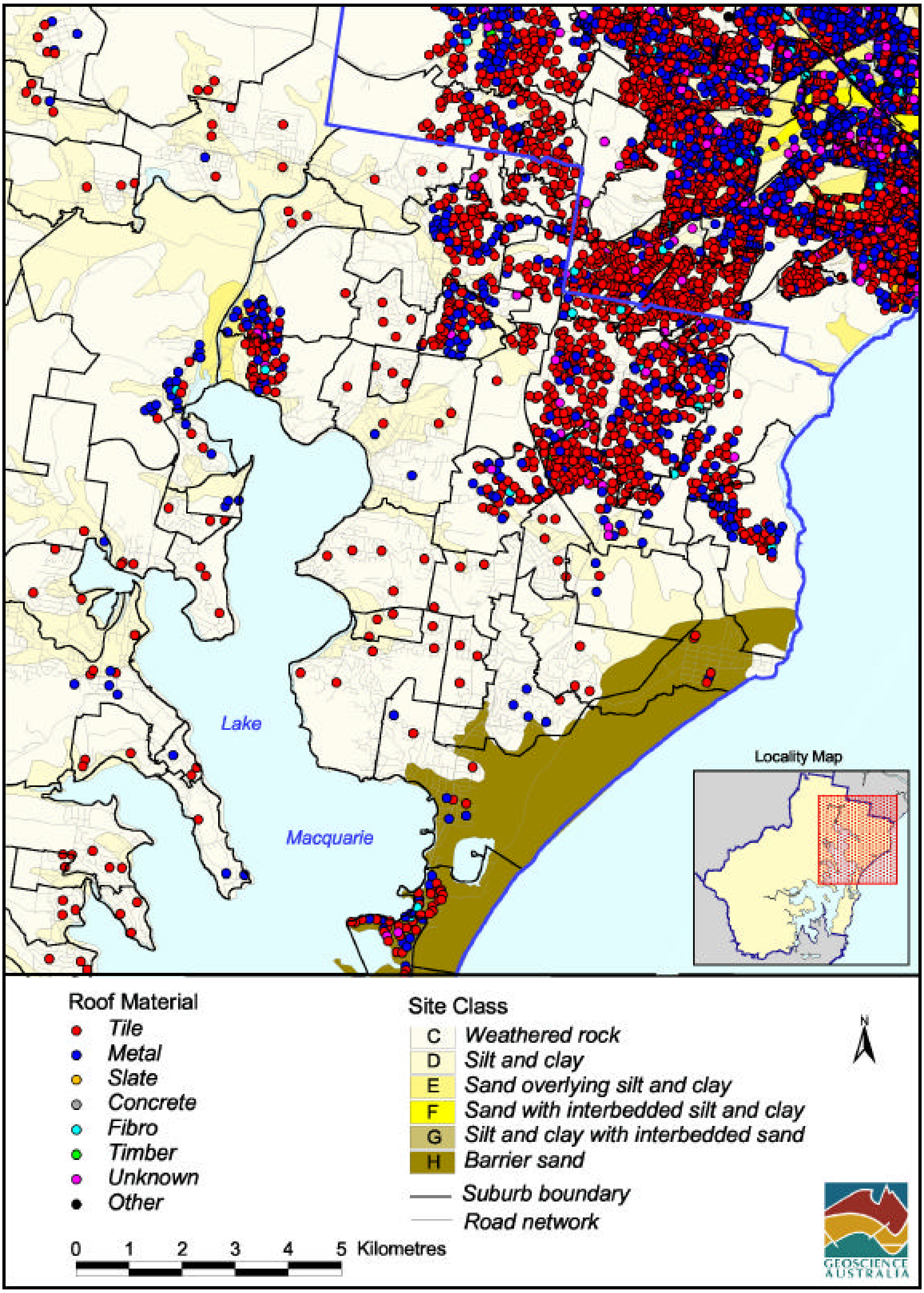


Figure G - 17: Distribution of vulnerable building elements in the southern Lake Macquarie area

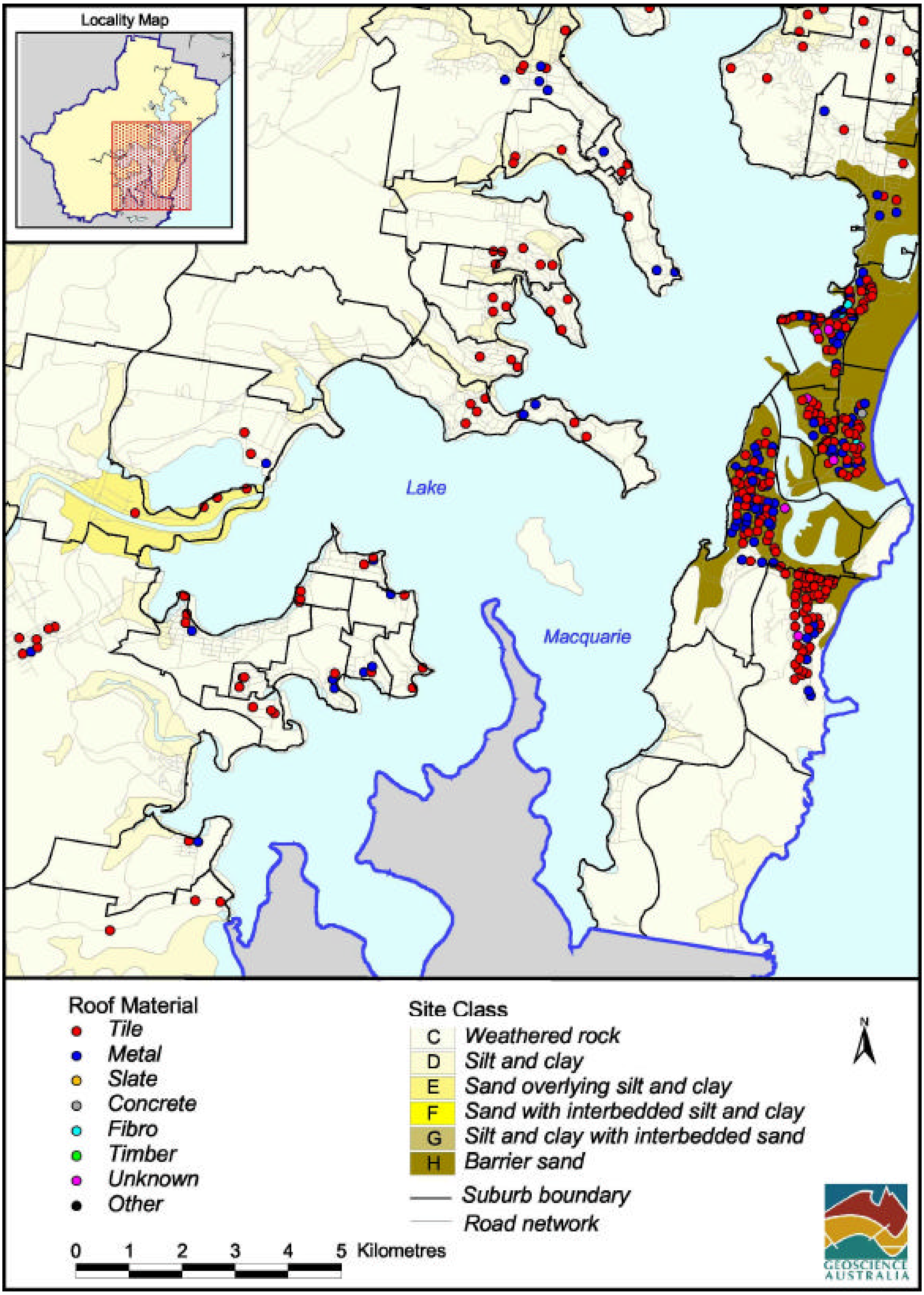


Figure G - 18: Distribution of vulnerable building elements in the southern Lake Macquarie area

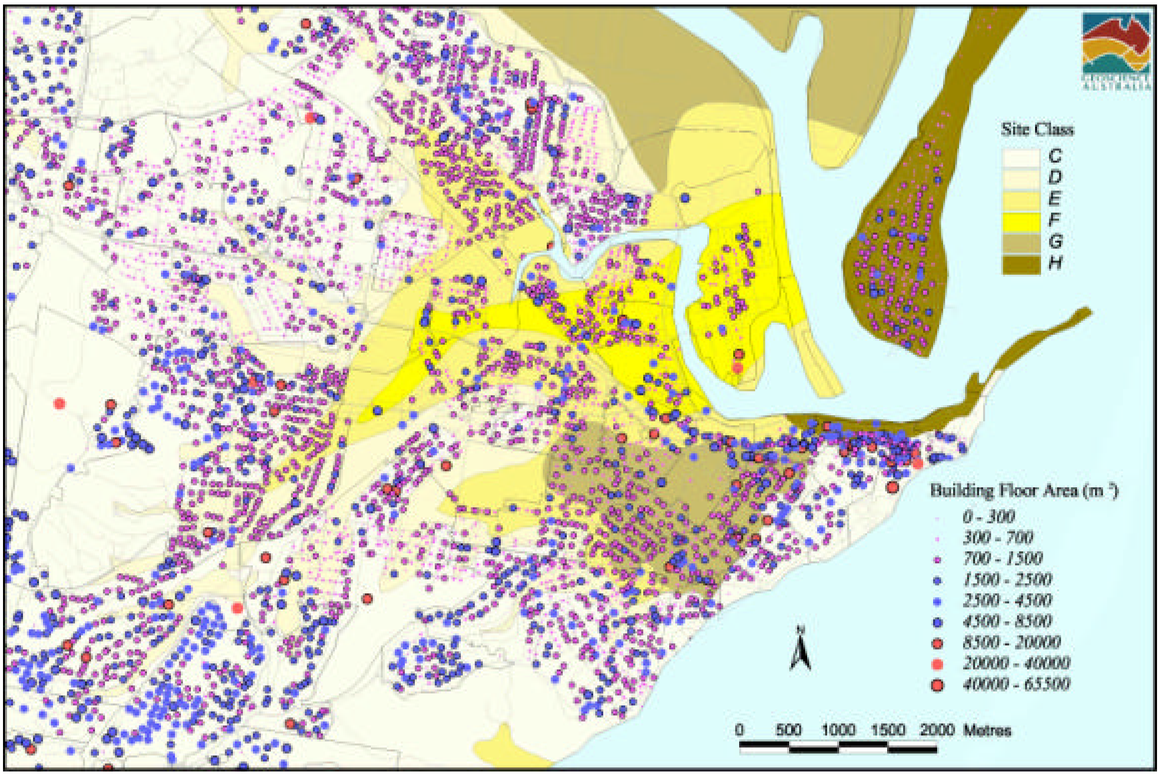


Figure G - 19: Distribution of survey sites in the Newcastle area

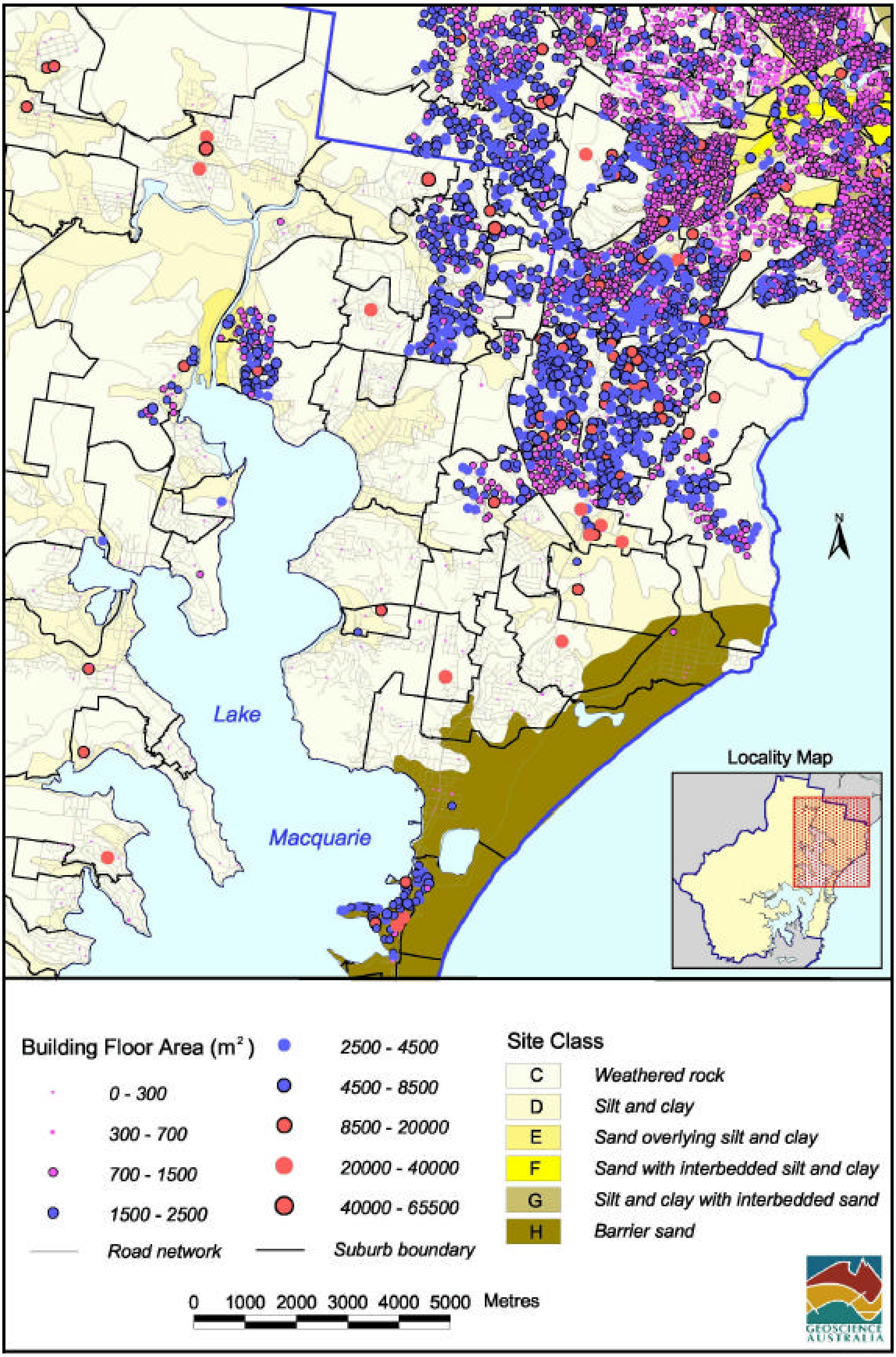


Figure G - 20: Distribution of survey sites in the northern Lake Macquarie area

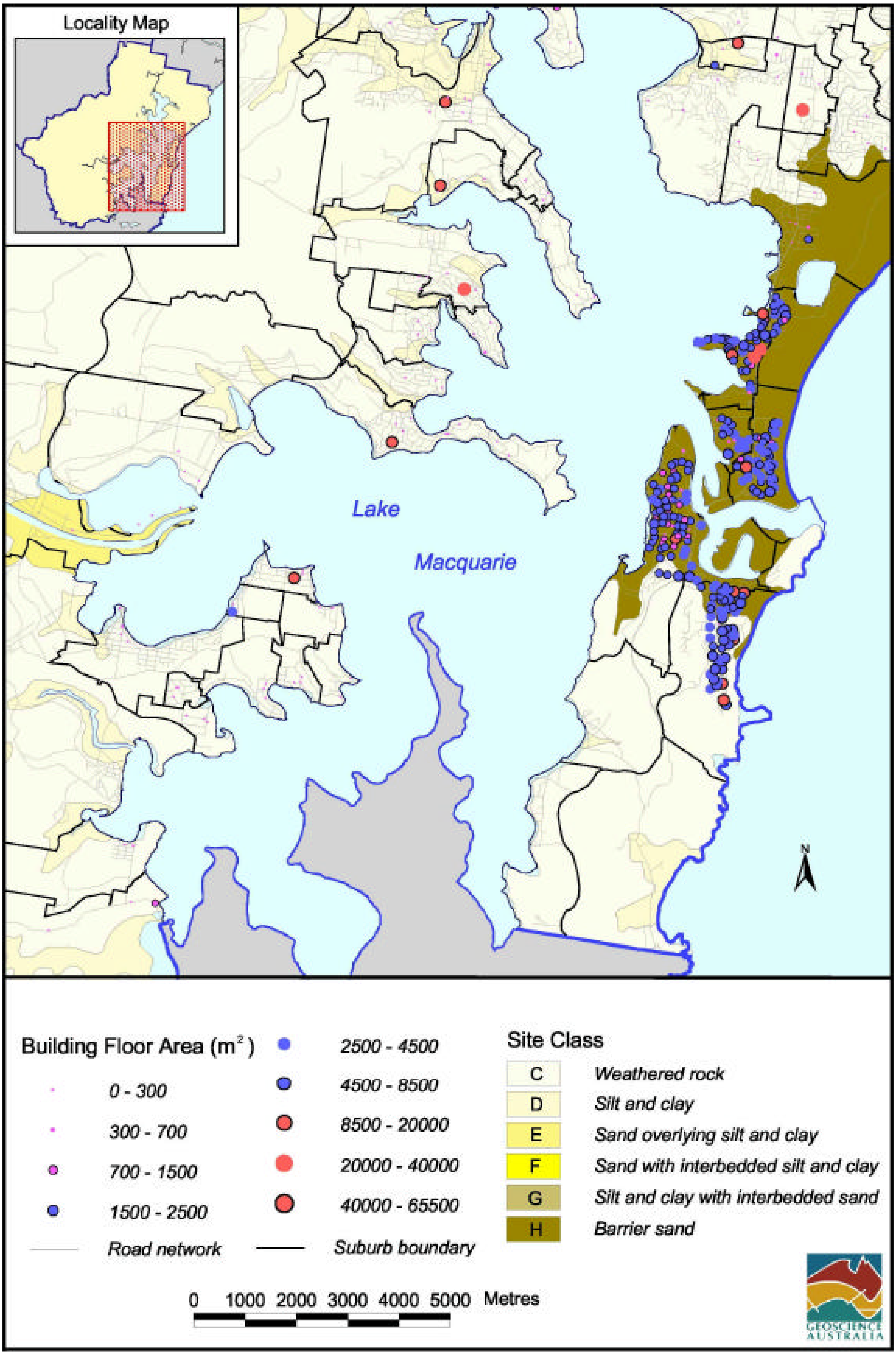


Figure G - 21: Distribution of survey sites in the southern Lake Macquarie area

The structural type and the usage of a building are important indicators of building earthquake performance. For the performance modelling methodology used in the risk assessment process, the structural type determines the structural performance characteristics and the usage type determines the non-structural performance characteristics and the relative value of the structural, non-structural and contents components of the building.

The structural type and usage definitions used within the risk assessment process are based on definitions employed in HAZUS (National Institute of Building Sciences, 1999). Hence, from the building data which was collected, buildings were classified into the relevant HAZUS classes, according to HAZUS class definitions. There is some difficulty in assigning HAZUS classes based upon survey data which gathers information only about the exterior of a building. The greatest problem is in being able to determine the structural class based upon only information about the external cladding, the estimated building age and other relevant information. A particularly common problem is in being able to determine whether a building is a timber farmed brick veneer or a double-leafed unreinforced masonry structure. To aid the classification process, the local building expertise of Mr. Robert Boyce of the City of Newcastle, was called upon. Mr. Boyce was able to provide an estimate of the building type percentages, given an exterior skin of brickwork and the building age. These estimates are given in Table G - 13. Also, for buildings with an external brick skin, more than two storeys high and built after 1950, it is assumed that the structure is a reinforced concrete frame with masonry infill walls.

Table G - 13: Classification of building type given an exterior brick skin

Age	Unreinforced masonry (Double brick or English bond)	Timber frame (Brick veneer)	Reinforced concrete frame with masonry infill (if above 2 storeys)
Up to 1900	100%	0%	0%
1901 up to 1930	100%	0%	0%
1931 up to 1950	90%	10%	0%
1951 up to 1960	80%	20%	100%
1961 up to 1970	10%	90%	100%
1971 up to 1980	1%	99%	100%
1981 up to 1990	1%	99%	100%
1991 up to 2000	1%	99%	100%
Under Construction	1%	99%	100%

For larger commercial buildings, the structural type is not always obvious either. Hence the assumptions expressed in Table G - 14 have been made for classification according to HAZUS structural types. Where a building structural type can not be classified upon this criteria, the structure is assumed to be a "W1" type if the building is used for accommodation purposes, otherwise it is assumed to be a reinforced concrete moment resiting frame, classified according to the number of storeys. The classification method adopted to determine the appropriate HAZUS building usage type is shown in Table G - 15. Where a building usage type can not be classified upon this criteria, it is assumed that the building is a "RES1" type if the building is used for accommodation purposes, otherwise it is assumed to be a "GOV1" type. It should be noted that not all HAZUS structural and usage types are used, due to mainly the non-existence of many types. It may also be noted that not all the detail collected by the survey process is actually used in building type classification. However, it is hoped that with further research, building vulnerability types may be developed that make use of more of the information, especially where particular building attributes are known to make structures highly vulnerable.

The spatial distribution of buildings are mapped in Figure G - 22 - Figure G - 29 according to HAZUS building structural type and building usage.

Table G - 14: Classification of HAZUS structural types

HAZUS structural type	Brief description	Number of storeys	Surveyed external wall type	Number of classifications
W1	Wood, Light Frame	1-2	Timber, Fibro, Masonite, Brick (according to age), Metal (if for accommodation)	4711
S1L	Steel Moment Frame	1-3	Metal	6
S1M	Steel Moment Frame	4-7	Metal	1
S1H	Steel Moment Frame	>7	Metal	1
S3	Steel Light Frame	1	Metal	28
C1L	Reinforced Concrete Moment Resisting Frame	1-3	Glass, Reinforced Concrete (If "SOFT STOREY", "IRREGULAR" or "OPEN", otherwise 50% chance C1L or C2L)	64
C1M	Reinforced Concrete Moment Resisting Frame	4-7	Glass, Reinforced Concrete (If "SOFT STOREY", "IRREGULAR" or "OPEN", otherwise 50% chance C1M or C2M)	13
C1H	Reinforced Concrete Moment Resisting Frame	>7	Glass, Reinforced Concrete (If "SOFT STOREY", "IRREGULAR" or "OPEN", otherwise 50% chance C1H or C2H)	6

HAZUS structural type	Brief description	Number of storeys	Surveyed external wall type	Number of classifications
C2L	Concrete Shear Walls	1-3	Glass, Reinforced Concrete (50% chance C1L or C2L)	19
C2M	Concrete Shear Walls	4-7	Glass, Reinforced Concrete (50% chance C1M or C2M)	5
C2H	Concrete Shear Walls	>7	Glass, Reinforced Concrete (50% chance C1H or C2H)	4
C3L	Concrete Frame Buildings with Unreinforced Masonry Infill Walls	1-3	R\C Frame with Brick\Masonry Infill, Brick (according to age and height)	83
C3M	Concrete Frame Buildings with Unreinforced Masonry Infill Walls	4-7	R\C Frame with Brick\Masonry Infill, Brick (according to age)	21
C3H	Concrete Frame Buildings with Unreinforced Masonry Infill Walls	>7	R\C Frame with Brick\Masonry Infill, Brick (according to age)	16
PC1	Precast Concrete Tilt-Up Walls	Any	Pre-Cast Concrete	30
URML	Unreinforced Masonry Bearing Walls	1-2	Masonry, Stone and Brick (according to age)	1218
URMM	Unreinforced Masonry Bearing Walls	>3	Masonry, Stone and Brick (according to age)	89

Table G - 15: Classification of HAZUS usage types

HAZUS usage type	Brief description	Surveyed Industry	Surveyed Category	Surveyed Type	Number of classifications
RES1	Single Family Dwelling (Detached House)	Accommodation	House	Single	4935
RES2	Mobile Home	Accommodation	Caravan Park	Any	4
RES3	Multi-Family Dwelling (Apartments/Flats)	Accommodation	House	Attached, Multiple or Duplex	410
RES4	Temporary Lodging (Hotel/Motel)	Accommodation	Hotel or Motel	Any	43
RES6	Nursing Home	Accommodation	Hostel	Any	5
COM1	Retail Trade (Shops)	Any	Any	Shop, Mall or Supermarket	224
COM4	Professional/Technical Services (Offices)	Any	Any	Office	106
COM6	Hospital	Medical	Any	Hospital	10
COM7	Medical Office/Clinic	Medical	Any	Surgery, Centre, Home, Clinic or Hospice	58
COM8	Entertainment and Recreation	Community	Any	Any	122

HAZUS structural type	Brief description	Surveyed Industry	Surveyed Category	Surveyed Type	Number of classifications
IND1	Heavy Industry (Factory)	Any	Automobiles or Other	Any	16
IND2	Light Industry (Factory)	Manufacturing	Any	Any	15
IND3	Food/Drugs/Chemicals (Factory)	Storage or….	Food or…..	Service Station	26
REL1	Church	Any	Religion	Any	84
GOV1	General Government Services (Office)	Government	Any	Any	127
GOV2	Emergency Response (Police/Fire Station)	Safety	Any	Any	19
EDU1	Schools	Education	Pre-School, Childcare, School or Convent	Any	103
EDU2	Colleges and Universities	Education	University or College	Any	8

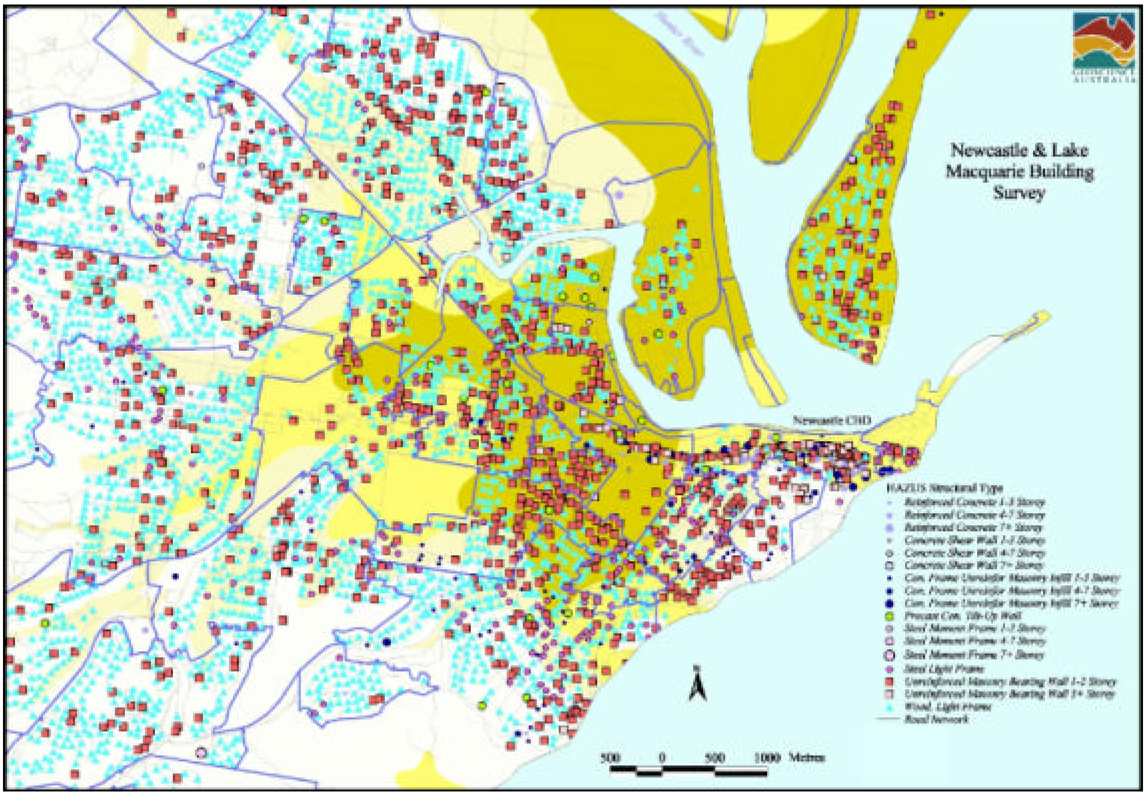


Figure G - 22: Distribution of HAZUS building structural type in the Newcastle area

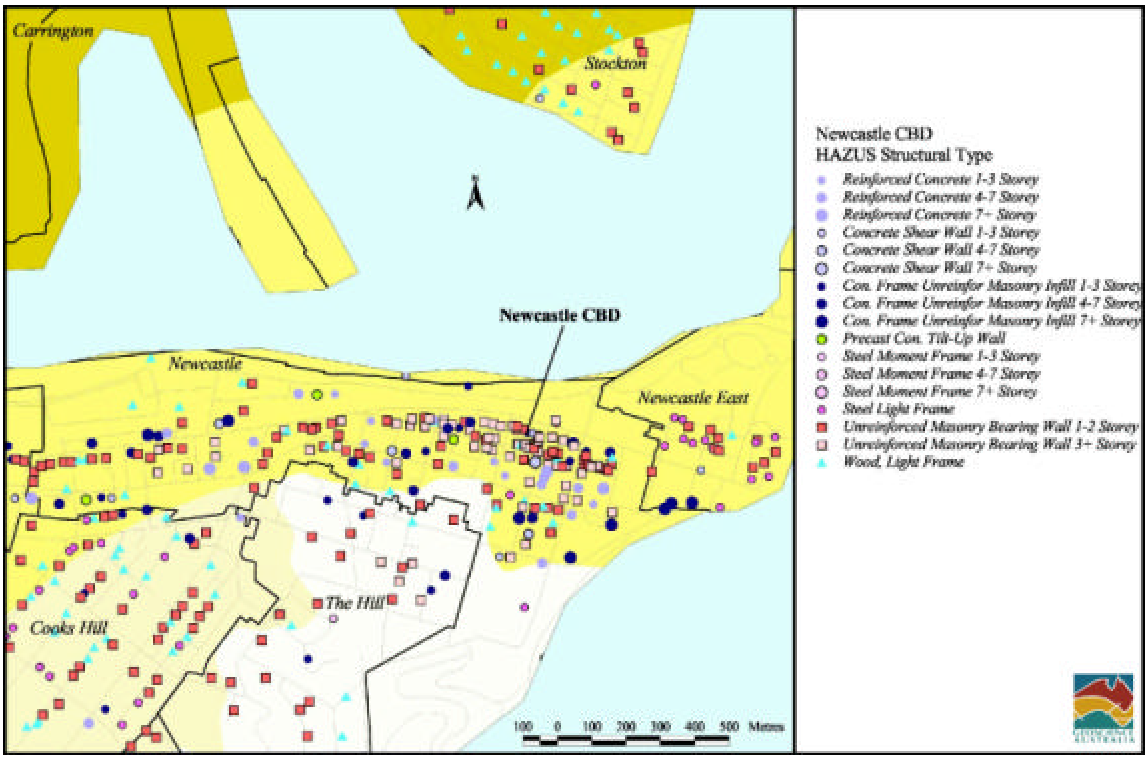


Figure G - 23: Distribution of HAZUS building structural type in the Newcastle CBD

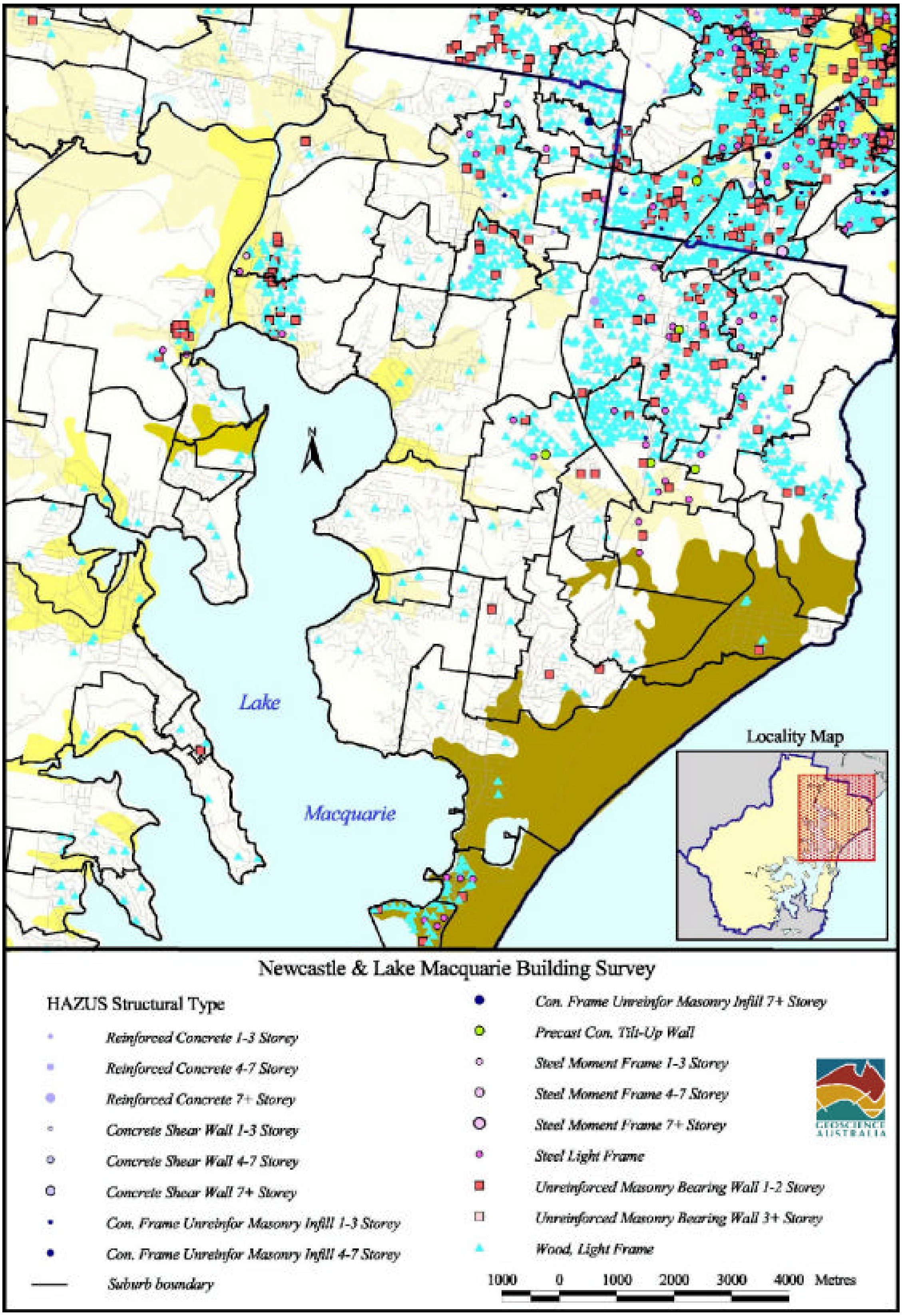


Figure G - 24: Distribution of HAZUS building structural type in the northern Lake Macquarie area

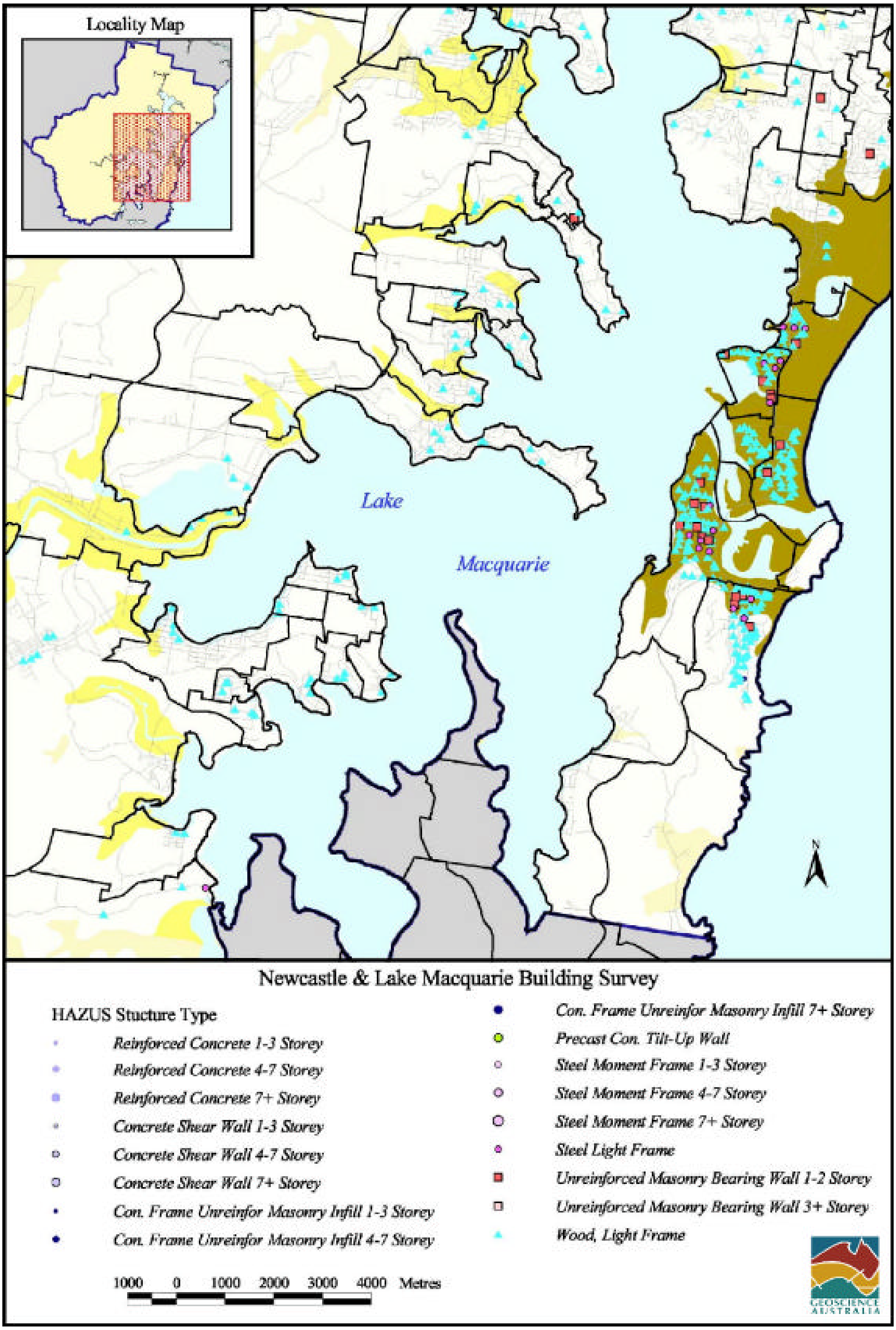


Figure G - 25: Distribution of HAZUS building structural type in the southern Lake Macquarie area

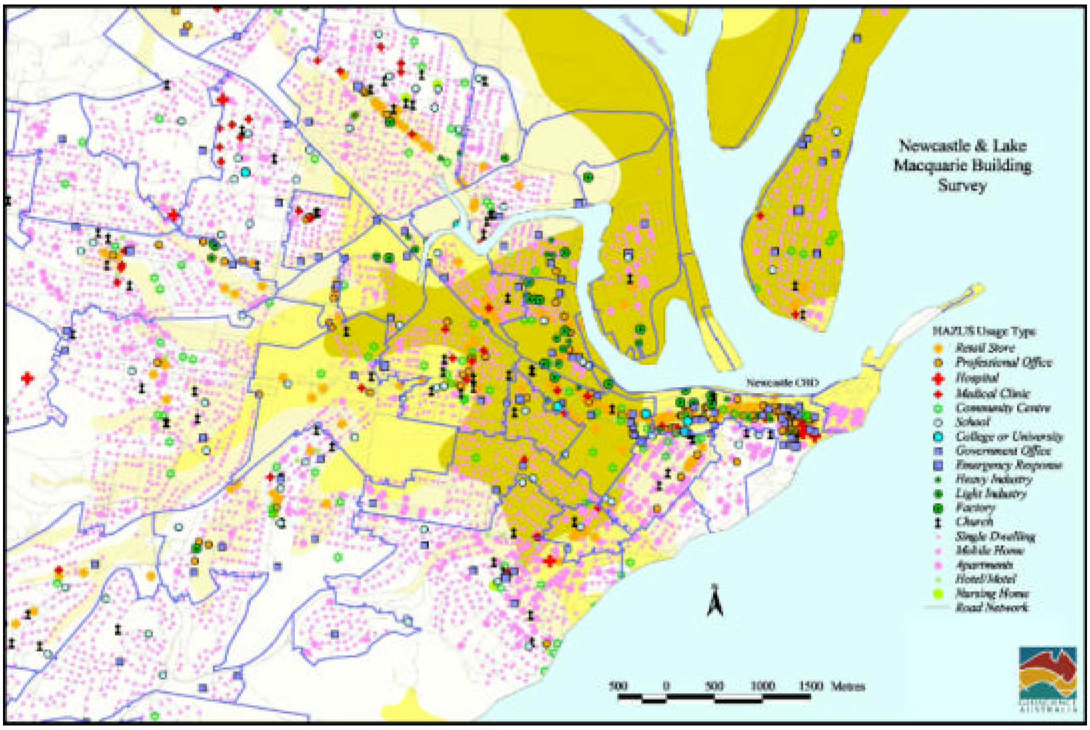


Figure G - 26: Distribution of HAZUS building usage type in the Newcastle area

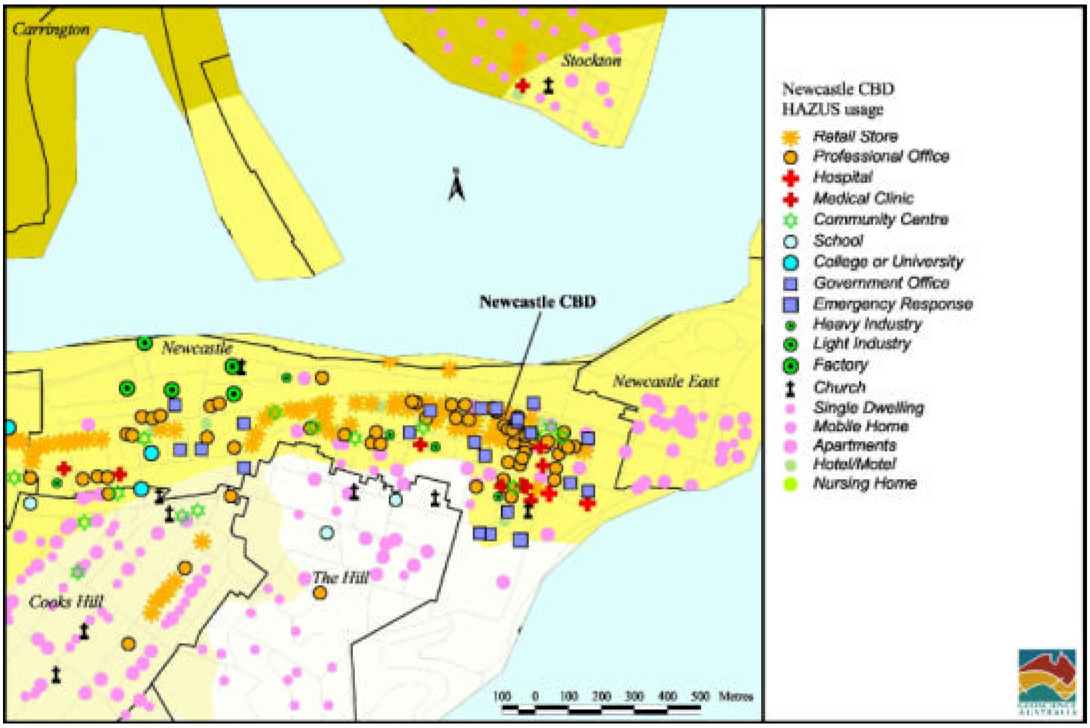


Figure G - 27: Distribution of HAZUS building usage type in the Newcastle CBD

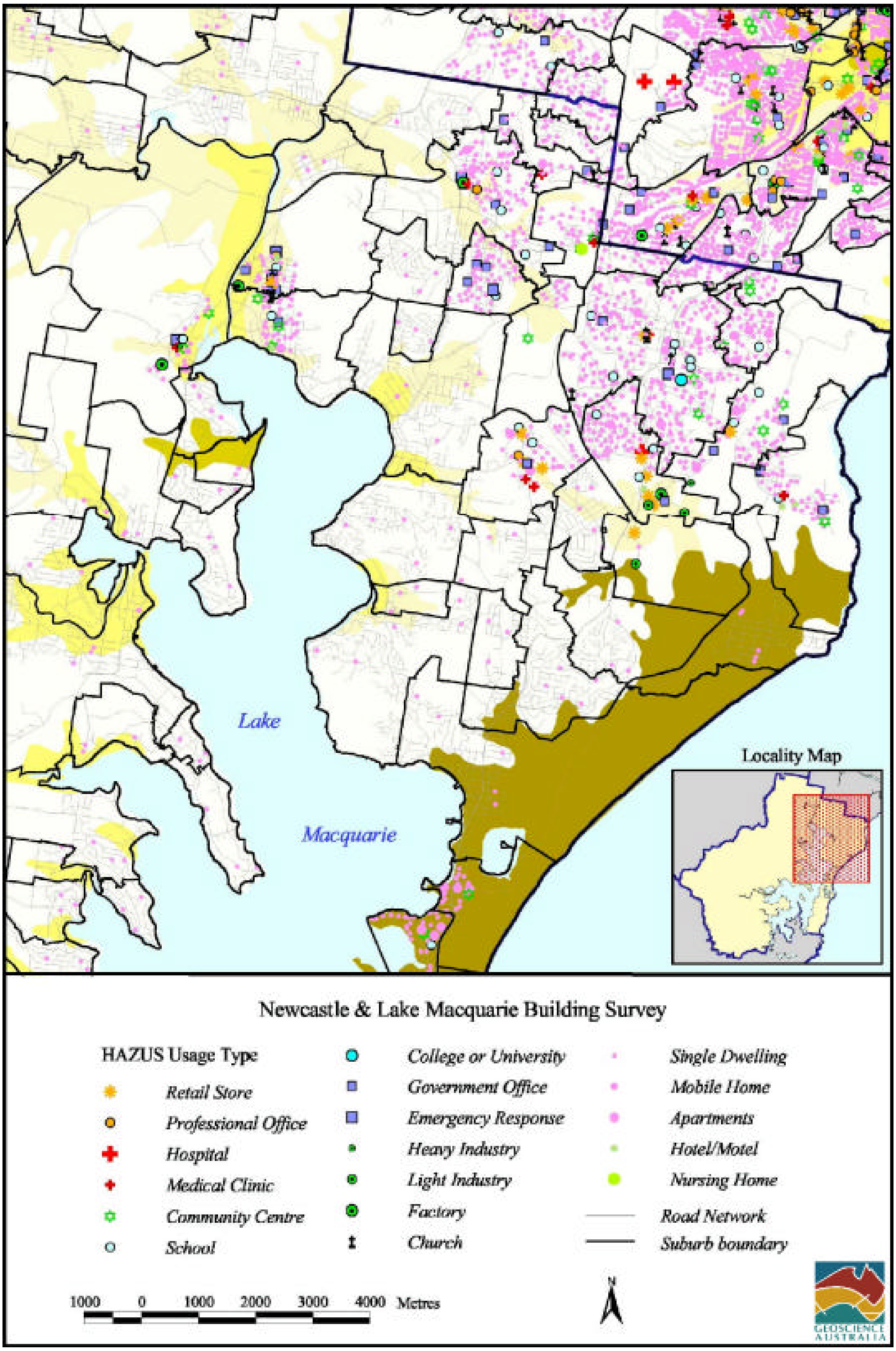


Figure G - 28: Distribution of HAZUS building usage type in the northern Lake Macquarie area

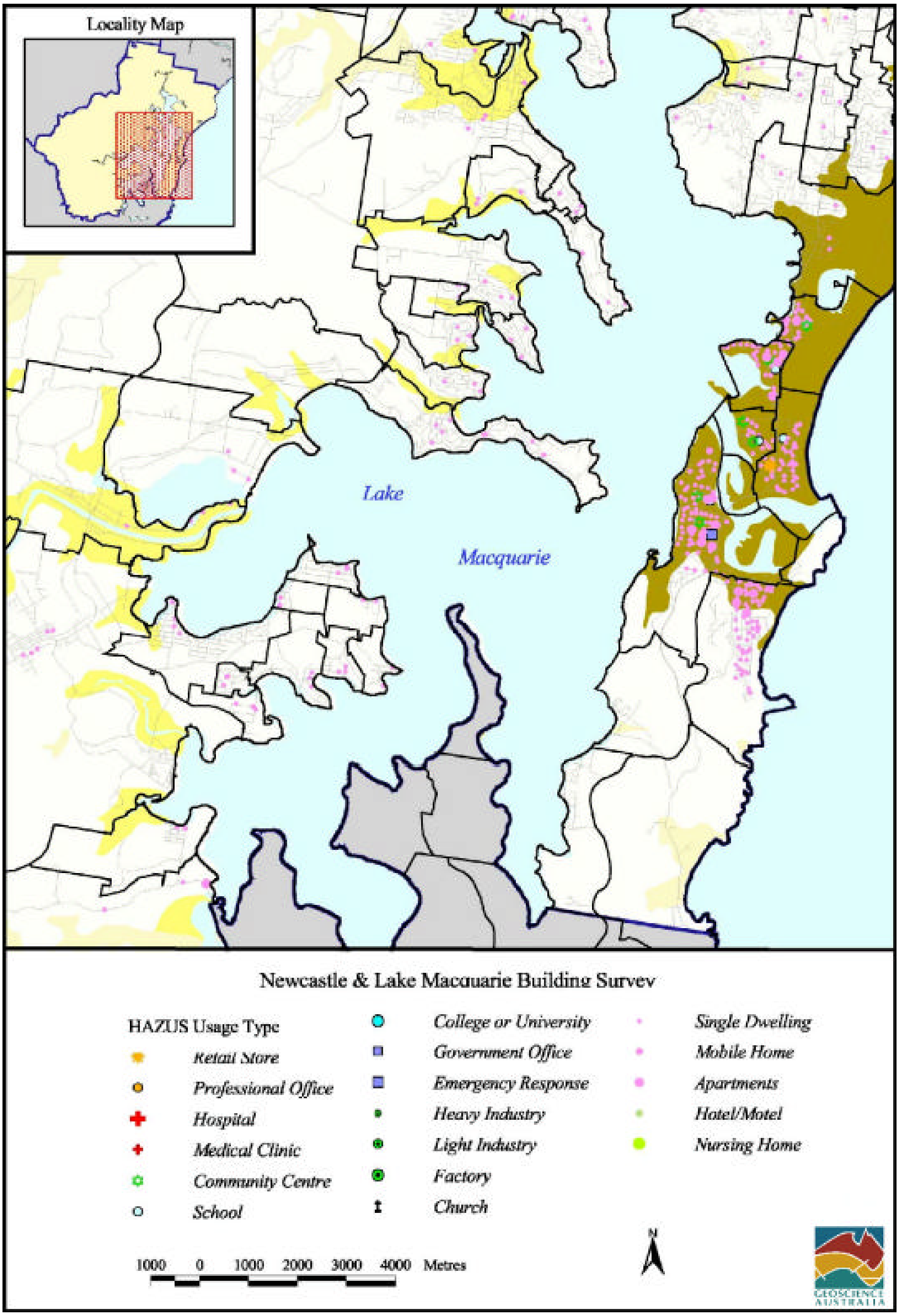


Figure G - 29: Distribution of HAZUS building usage type in the southern Lake Macquarie area

Appendix H - DATA AND INFORMATION SOURCES

This appendix is mainly aimed at the Geographic Information Systems (GIS) profession. It gives a run-down of what hardware, software and datasets were used to undertake the Earthquake Risk Assessment of Newcastle and Lake Macquarie.

Hardware:

- PC – Silicon Graphics Workstation
- 18 Giga byte Unix storage disk
- Aero2100 Palmtop PC
- Garmond Differential GPS
- 1 Mega Pixil Digital Camera
- HP800 – Colour DesignJet Plotter

Software:

- Windows 95 / NT / 2000 / CE
- Exceed Version 6.2
- Solaris Version 8
- ArcView 3.2a
- Extensions include Spatial Analyst and ECW for ArcView
- ArcInfo Version 8.0.2
- ArcPad Version 5.0.1
- MAPINFO Version 6
- ER Mapper Version 5.5
- ERDAS Imagine Version 8.4
- Microsoft products including Excel, Word

Database:

- Building Inventory - September 2000 (GA)
- Microtremor Survey - 1999 (GA)
- National UBD raster - June 2000 (Telstra)
- Aerial orthophotos – 2000 (Land Property Information)
- DEM – 2000 (Land Property Information)
- Vector Boundaries (Land Property Information)
- Building Damage – 1989-90 (Newcastle City Council)
- Insurance data – 1989-90 (NRMA)

For the risk assessment to be modelled a building inventory database was collected through the Cities Projects' Data Acquisition Units. It was acquired over a period of 3 weeks comprising 5 staff. A total of 6339 building points were collected. For a more detailed explanation of what was collected refer back to Chapter 5.

Figure H - 1 shows the total coverage of this survey. Some suburbs were missed due to time restraints and permission clearance. These areas are shown on some of the previous figures in this report as not classified. Also in some of the same figures, certain suburbs may have been not classified due to their low building count over the total area of the suburb, removing these suburbs tends to create a more precise picture.

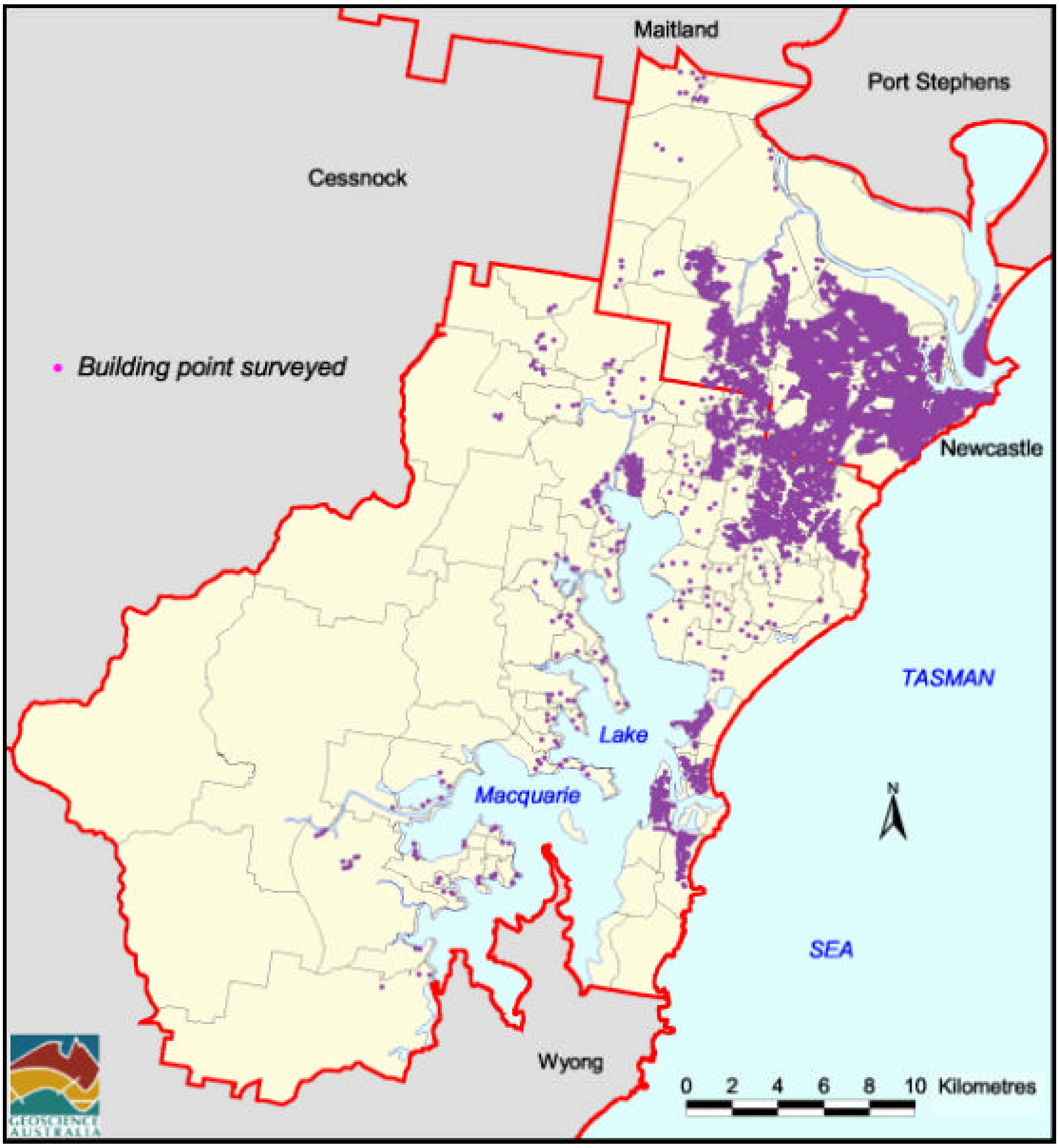


Figure H - 1: Surveyed building point locations total of 6339

The National UBD raster dataset was sourced for this assessment to help with the collection method in the field. It aided the surveyor with the combined effort of the GPS, allowing the precise location to be easily acquired and visually checked, increasing the data precision and quality of the dataset. Figure H - 2 shows the UBD raster image on the Palmtop PC with surveyed sites already completed.

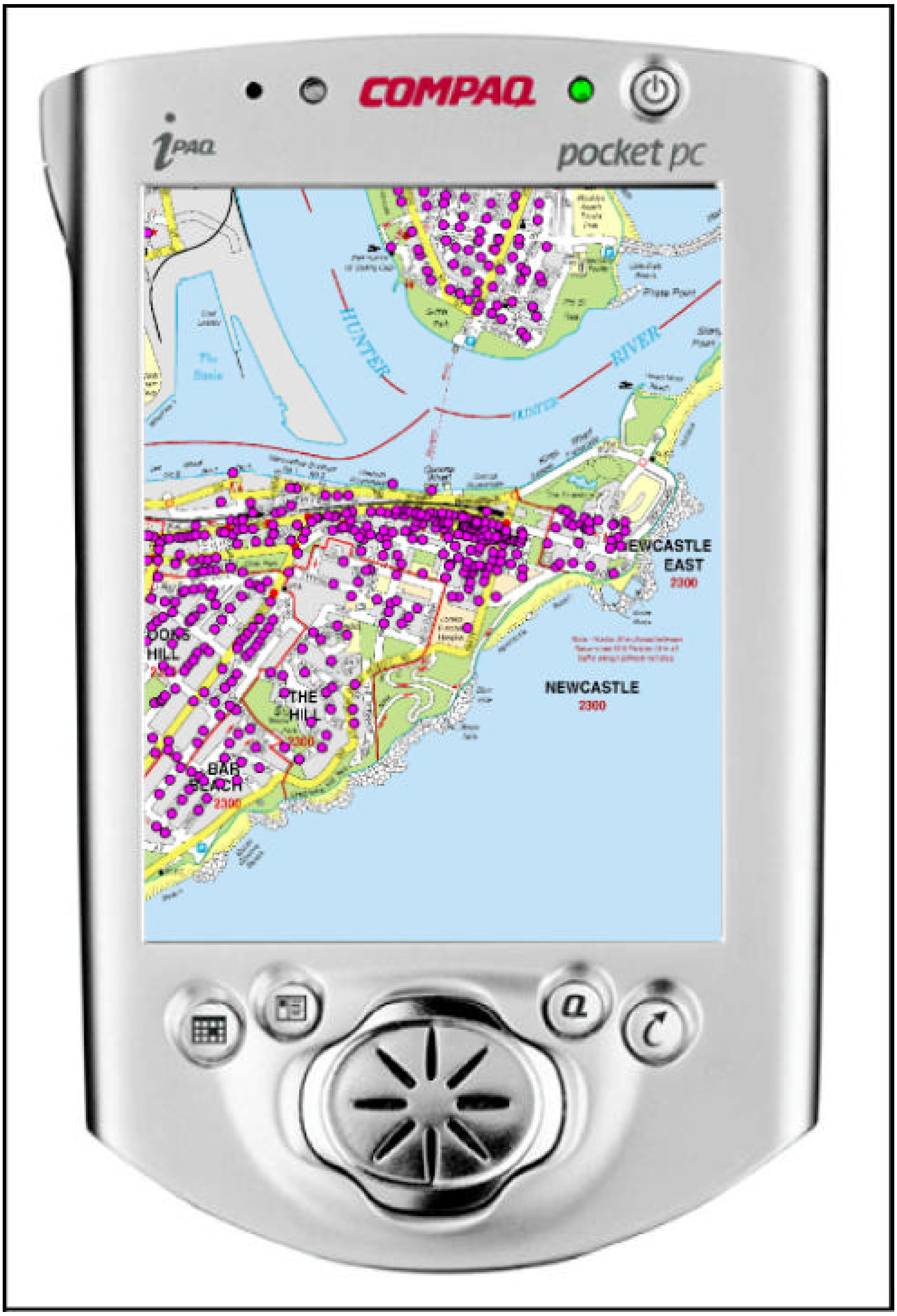


Figure H - 2: PalmTop PC with points collected in the field

Due to the file size of the raster images, we had to clip the images to fit onto the Palmtop PC, this problem can be overcome by using more expensive Pamltop PC's running faster chips, or having the ability to save the images into a different format such as MrSID. As our Data Acquisition Units were built to a strict budget we were driven towards the more labour intensive handling of the raster images.

Price list of One Unit:

- Compaq Aero 2100 - $740.00
- Differential GPS - $450.00
- ESRI ArcPad Software - $940.00
- Kodak Digital Camera - $550.00

The aerial orthophoto's were received from the LPI in MrSid format on CD. They were then re-compressed using ER Mapper and saved as ECW and placed onto our Unix disk. This allowed easier handling between our different software packages. The images were used for a heads up count of building numbers in each suburb, also for display purposes and to visually check data locations. Figure H - 3 shows the aerial photo

Figure H - 3: Aerial orthophoto of an area in Lake Macquarie with surveyed building points

The Vector boundaries acquired from LPI consisted of:

- Local Government Boundaries
- Culture

- Drainage
- Easements
- State Election Boundary
- Mine Subsidence
- National Parks
- Cadastral Boundaries
- Parish Boundaries
- Suburb Boundaries

The main vector coverages used for this assessment from the LPI are the local government boundaries as this defined the study area to work in, also the cadastral boundary cover. This was used to cross check the total building count for each particular suburb with the aerial photos. The building count for each particular suburb needed to be well defined, as it played a major part in determining the 'multiple factor' in the risk model.

The Damage Building database which was supplied by the Newcastle City Council consisted of some 8735 entries. It was in the format of a spreadsheet and hence had no spatial concept. This dataset needed to be spatially located for us to visually compare the damage location sites with our modelled damage. An attribute in the spreadsheet called lot number allowed us to join it with another attribute of similar style in the cadastre database. Some 6214 points matched automatically while the remainders didn't due to their incorrect naming or mismatched attribute. Figure H - 4 shows the building damage database with the attribute of damage shown as a red, amber, blue, green dot.

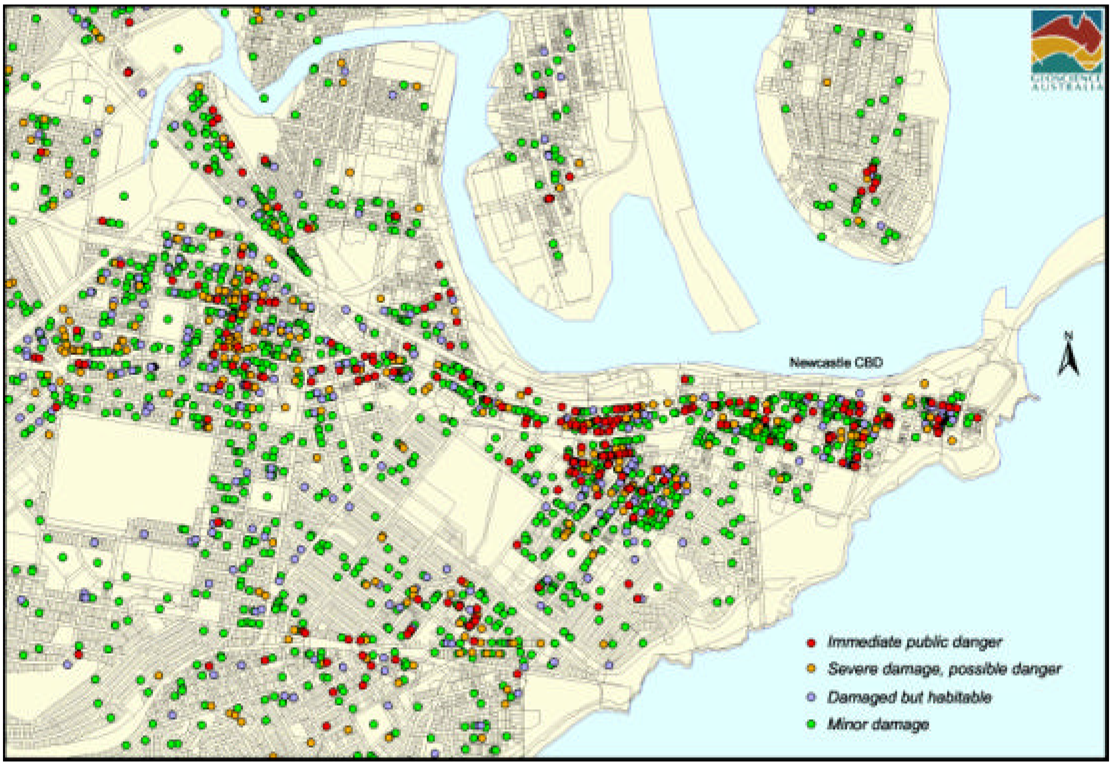


Figure H - 4: Newcastle City Council damage database spatially located

This appendix is by no-means the entire list of data sources but a good outline of what data was acquired and value added.

Appendix I - EXTRACTS OF KEY REPORTS ON THE 1989 NEWCASTLE EARTHQUAKE

I.1 Introduction

Several of the reports and documents relating to the Newcastle 1989 earthquake are so significant and are of such direct relevance to the present work that considerable excerpts from them are quoted below for easy reference. The reports/documents included in this Appendix are:

The Newcastle Earthquake Database (Newcastle Regional Library, 1999).

IEAUST 1990 Report (Melchers, 1990).

NSW PWD Report (NSW PWD, 1992).

The Centre For Earthquake Research In Australia Report (CERA, 1995).

'Earthquake Tremors in The Hunter Valley Since White Settlement' (Hunter, 1991).

Some additional reference to page numbers is given to improve access, referencing and readability.

I.2 Information Resources on the Newcastle Earthquake

Welcome to this interactive CD-ROM containing comprehensive information resources on the Newcastle Earthquake. The 1989 Newcastle earthquake was the first earthquake in Australia to cause death and destruction - 13 people died, more than 160 people sustained injuries and over 10,000 buildings in Newcastle suffered modest to substantial damage with insurance pay outs exceeding the billion dollar mark. The earthquake measuring 5.6 on the Richter scale struck Newcastle, Australia's sixth largest city on 28 December 1989 and shattered the myth that disastrous earthquakes never occur in Australia.

I.2.1 The Newcastle Earthquake Database

The Earthquake Database is a collection of electronic resources on the 1989 Newcastle Earthquake. It comprises of bibliographical information, abstracts and full text documents, images, and excerpts of sound and video clips relating to the first disastrous earthquake in Australia.

The overall goal of the Earthquake Database project is to improve community awareness of risk, preparedness and response to natural disasters by focussing on the experience of the 1989 Newcastle earthquake.

I.2.2 The Following Types of Information are Available:

- Published materials
- Photographs and pictures
- Oral history interviews
- Radio broadcasts
- Video recordings

Topics Include:

- seismology
- earthquake engineering
- emergency management

- social impact
- insurance
- economic aspects
- seismic history
- heritage issues
- health and psychology
- recovery and renewal

Full text and digitised information

This CD-ROM is based on materials available at the Newcastle Region Library. Full text materials, images and other information have been reproduced with the permission of copyright owners specifically for this project.

A number of bibliographical entries in this CD-ROM do not have full text documentation or other associated formats attached. This is because permission is not available at present for their reproduction from copyright owners or it is an unpublished format that is not suitable for reproduction.

Images have been electronically scanned from hardcopy versions that are available in the Library's collection. Whilst every effort has been made to reproduce images in a reasonable quality, this has not always been possible because of the poor original quality of the available source in our collection.

The following materials are not available in their entirety in this CD-ROM:

1. Unpublished and primary material have been indexed and abstracted in the database but have not been reproduced for confidentiality purposes or because they are of an archival nature. Please contact the Newcastle Region Library directly for access to these materials.
2. Video and audio recordings have been indexed and excerpts of these recordings have been digitised for inclusion in this CD-ROM. The entire recordings could not be reproduced as they are too lengthy or cannot be reproduced for legal reasons. Users who wish to listen or view sound and video recordings in their entirety, are asked to contact the Newcastle Region Library for access.

Sponsors

The project was largely made possible through grant funding from the Australian IDNDR Committee.

The project also received support from the following:

The Institution of Engineers, Australia (Newcastle Branch)

The Insurance Council of Australia

Newcastle City Council

I.2.3 Newcastle Earthquake Database CD ROM Project Team

Project Librarian	Ajita Lewis

IT Support	David Tsang
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Scanning Technician	Darryl Soo
Cover Design	Nick Eterovic

Newcastle Region Library
PO Box 489
Newcastle NSW 2300
Australia

I.3 IEAust 1990 Report

I.3.1 Preface

The present report is the outcome of the offer made by the President of the Institution of Engineers, Australia to the Premier of New South Wales that a study be commissioned on the significance of the Newcastle earthquake in relation to building regulations and related matters.

On 10 January 1990 the Acting-Premier accepted the Institution's offer. A Steering Committee was appointed by the President. It agreed on 15 January 1990 to the study objective and terms of reference given below.

The Steering Committee appointed a joint Study Team consisting of personnel drawn from the University of Newcastle and the National Building Technology Centre, CSIRO, Sydney. The report was written by members of the Department of Civil Engineering and Surveying, The University of Newcastle, using data and information obtained from a wide variety of sources but principally 'with contributions from NBTC-CSIRO; NSW Public Works Department; Newcastle City Council; Bureau of Mineral Resources, Canberra; Seismology Research Centre. Melbourne; Mine Subsidence Board, Newcastle, and The University of Newcastle as well as some commissioned work.

OBJECTIVE: To determine the significance of the damage in relation to current building regulations and existing building stock.

I.3.2 Terms of Reference:

(1) To record, classify and map the general pattern of damage (R2, R15).

(2) To estimate, if able, the maximum ground accelerations experienced in the areas of serious damage (Rl, R3.3, R3.4).

(3) To study the overall performance of modern structures in the areas of serious damage (R2, R4.1, R4.2, R4.3, R.4-4, R8.1, R8.2, R8.3, R8.4).

(4) To investigate in detail typical damage to modern structures (R8.1, R8.3. R8.4).

(5) To study the overall performance of older structures (R4.1. R4.2. R4.3. R4.5).

(6) To investigate in detail typical damage to older structures (R4.5, R.4.6).

(7) To investigate behaviour of structures with a post-disaster function (R4.2, R4.3. R6.1, R6.2).

(8) To determine to what extent local ground and geological conditions may have contributed to the severity of the ground shaking in the areas of serious damage (Rl. R2, R3.1, R3.3, R3.4).

(9) In consultation with seismologists, to assess the risk of a similar or greater intensity earthquake occurring in major centres of population where the current perceived risk of earthquakes is low (R3.1).

(10) To make recommendations on the adequacy of current building regulations in areas of perceived low earthquake risk (R2, R3.1, R3.2, R4.1, R4.2, R4.3, R5.1, R7.1, R8.3, R9, R12).

(11) To make recommendations regarding the safety of existing buildings in respect of earthquakes throughout Australia (R3.1, R3.2, R4.1, R4.2, R4.3, R4.4, R4.5, R5.1, RIO).

In the above Terms of Reference, cross-reference is made to the relevant Recommendations of the Study.

I.3.3 Conclusions and Recommendations

I.3.3.1 Seismological Information

Cl.l Seismological information about the Newcastle earthquake has been characterised by the scarcity of recorded data from Australian and in particular regional sources (Ch.3). This has hampered statistical and engineering studies and has provided little information for improvement of the Earthquake Code (Ch.3).

C1.2 No major urban area in Australia has an adequate earthquake monitoring network (Ch.3).

Rl The seismological data collection, processing, interpretation and information dissemination facilities for Australia should be properly established and maintained on a national basis, using international criteria for such facilities as a guide [ToR 2, 9], NSW. AUS.

I.3.3.2 Earthquake Design Requirements For Newcastle

C2.1 Given the previous history of lack of significant earthquake damage in the Newcastle and surrounding regions, there was a perception that Newcastle was a region of low seismic risk. This perception has changed since the occurrence of the earthquake on 28 December 1989 (Ch.3, 9).

C2.2 In general, damage to modern buildings in Newcastle was confined to non-structural aspects and is broadly in accordance with structural engineering expectations, given that the buildings were not specifically designed to be earthquake resistant (Ch.5).

C2.3 The Newcastle observations show a high degree of correlation between areas of significant damage and areas in which the foundation material consists of alluvial soil strata and/or fill. This aspect is not properly considered in the current Earthquake Code (Ch.3, 4).

C2.4 There appears to be little correlation in Newcastle between significant damage and areas known to be undermined due to previous mining activities. This suggests that past mining and mine subsidence were not significant factors in contributing to damage (Ch.4).

R2 As an interim measure before the Earthquake Code is revised, the Newcastle region should be considered to be in zone A as defined in AS2121-1979 except for the alluvial soil and filled areas where the interim zoning should be zone 1 (Ch.3. 4, Set. 10.2). [ToR 1. 3, 8, 10], BR.

I.3.3.3 Minimum Earthquake Design Requirements For Australia

C3.1 Because recorded earthquake history in Australia is short, there is a large degree of uncertainty associated with predictions of proneness to earthquake activity for much of Australia. Seismological information indicates that an earthquake similar to that which occurred in Newcastle could occur in other parts of Australia. Hence some base level of earthquake resistant structural design requirement is desirable for all parts of Australia (Ch.3, 10).

C3.2 A large part of the damage observed in Newcastle is related to masonry construction. Much of this is non-structural. It is considered that the damage caused to modern construction would have been less had some low level structural engineering design requirement existed for lateral loading on masonry and other forms of non-ductile construction. This could have been achieved if the Earthquake Code had rated the Newcastle region Zone A (or higher) (Ch.5, 10). It is further considered that modern construction in Newcastle is not substantially different from that in other parts of Australia.

R3.1 It is recommended that minimum structural engineering design requirements for non-ductile construction should be specified for all parts of Australia. It is considered that this should correspond to zone A of AS2121-1979 except for alluvial and/or filled areas where it should be zone 1 (see also R3.2), (Ch.3, 10). [ToR 8. 9. 10, II], BR. SAA.

R3.2 The requirements for zones A and 1 should consider potentially unstable as well as non-ductile materials and should consider the need to design for structural forms known to have undesirable earthquake response (Ch.5, Set. 10.4), [ToR 10. 11]. BR, SAA.

R3.3 In the current revision of the Earthquake Code specific provision should be made for the amplification effects associated with alluvial soils and filled areas. Such provision should consider the experiences of and observations in Newcastle as well as recent overseas experiences (Set. 3.8, 4.2). [ToR 2. 8], SAA.

R3.4 Local Councils and Government departments with building jurisdiction should be required to prepare maps and/or establish data hanks specifically for information about the extent, depth and geo technical characteristics of areas of alluvium and fill obtained from all geo technical investigations under their jurisdiction. The maps and/or data banks should be publicly accessible (Ch.3, 4), [ToR 2. 8], BR.

Note: No specific recommendation is made whether R3.1 and R3.2 are incorporated in the revised Earthquake Code or in future revisions of material codes. This matter should be considered by Standards Australia (Set.10.3).

I.3.3.4 Existing Buildings

C4 Most masonry construction in Newcastle predates the existence of the Earthquake Code. Much of the damage is related to the quality of the original construction and the state of the structure at the time the earthquake occurred. There is widespread evidence of material deterioration and this is considered to be a factor in the scale of the damage. There was evidence of material deterioration already before the occurrence of the earthquake (Ch.5). Taken together, these factors may have implications for the safety of remaining buildings in Newcastle. They also have wider implications since the building stock in Newcastle is not, on average, necessarily very different in type and age to that elsewhere in Australia.

R4.1 Apart from domestic dwellings, all structures in Newcastle and other areas affected by the earthquake should be inspected for structural safety. Damaged parts should be removed and rebuilt or repaired, all to the satisfaction of the Local Council or appropriate authority and in accordance with the Interim Earthquake structural requirements of R2 or to the Earthquake Code when revised (Set.9.3. 10.6. 10.8). [ToR 3, 5. 10, II], BR, HOC. PTO. ACS.

R4.2 It is considered that in general upgrading of existing buildings, structures and facilities in Newcastle for earthquake resistance is not justified- However, upgrading should be evaluated for:

1. buildings which have suspended awnings or parapets or other projections likely to be dangerous to the public under earthquake conditions;

2. buildings, structures and facilities having a possible post-disaster or lifeline function (eg. Hospitals, fire-stations etc.).

3. buildings and places of public assembly and where significant loss of life may be incurred in an earthquake event, and

4. buildings and structures containing or supporting hazardous materials or processes.

(Set.9.3, 10.6). [ToR 3. 5. 7, 10, II], BR. NCC, FWD. ACS.

R4.3 Specific procedures and rules should be established for the upgrading program of R4.2 (Set. 10.6). [ToR 3, 5. 7, 10. II], BR, NOC. PWD. ACS.

R4.4 Consideration should be given to extending the policy in R4.2 and R4.3 to all other parts of Australia (Set.9.3. 10.6), [ToR 3. II], BR, ACS, PWD. SAA-

R4.5 Consideration should be given to the introduction of a program of building inspection for structural safety by suitably qualified engineers for areas in Australia having corrosive environments and/or with known or suspected problems of structural deterioration. It is suggested that the first such inspection should occur not more than 40 years after construction, with subsequent inspections at shorter periods (Set-10.8). (see also K7 below), [ToR 5. 6. 11]. BR.

R4.6 Research should be undertaken on the rates of structural deterioration of existing buildings, the methods for detection of such deterioration and on methods of economic repair (Set.10.8). [ToR 6. 11].

I.3.3.5 Domestic Construction

C5 Serious structural damage to domestic construction was mostly confined to cavity brick construction and to a lesser degree to brick-veneer construction. Weatherboard construction generally behaved well. Conclusion C4 also applies to domestic construction. Improved understanding of earthquake behaviour of conventional Australian domestic construction is required.

R5.1 Earthquake design provisions of the 'deemed-to-comply' type and corresponding to Recommendations R3.1 and R3.2 should be incorporated into requirements for domestic construction. It is considered that this should be done through development of an Australian Standard for structural engineering aspects of domestic construction (Ch.5. 10). This standard should also consider other natural hazards [ToR 10]. SAA.

R5.2 NBTC-CSIRO or a similar organisation should be invited to prepare a report on available information and research requirements for the improvement of the earthquake resistance of Australian forms of domestic construction.

I.3.3.6 Post-Disaster Function And Special Function Buildings

C6.1 Buildings having a post-disaster and other special function suffered relatively little structural damage in the Newcastle earthquake. However, their operational functions were affected and in some cases, such as at the Royal Newcastle Hospital, severely so. Further, the potential for disruption to essential services such as ambulance, fire-brigade, telephone services etc. whether due to structural damage or other causes is considered to have been substantial and is very likely to have been revealed had the earthquake been slightly more severe or of longer duration (Ch.6).

C6.2 It is not clear that the factors for post-disaster and other special function buildings in the Windloading Code (AS1170.2) and in the Earthquake Code (AS2121-1979) are wholly compatible considering that there are different conditions to be met (Set.9.3).

R6.1 Reviews should be undertaken of the structural and functional adequacy of all buildings and systems having a post-disaster function, considering all relevant hazard-scenarios. Where inadequacies are revealed, appropriate measures should be instituted (Ch.6). [ToR 7]. PWD. ACS.

R6.2 A review should be undertaken of the appropriate level of risk associated with the post-disaster function factor for AS2121 and its compatibility with that in AS1170.2 (Ch-6, Set.9.3). [ToR 7], SAA.

I.3.3.7 Safety Assessment

C7.1 Existing powers of Local Councils do not appear to be wholly adequate to deal with buildings considered by Council to be potentially unsafe. This matter is particularly acute in the aftermath of a major disaster (Set.10.8).

C7.2 In relation to approval. Inspection and certification of new and existing buildings for structural safety, it is not clear that engineers with appropriate qualifications and experience can be identified under existing systems of professional recognition. This also applies to certification of structural design and construction for new buildings and building alterations (Ch.5, 10).

R7.1 The powers of Local Councils to enforce compliance with structural safety requirements (including those under R4.5) should be improved. This applies in particular to situations where public safety is considered by Council to be at risk (Set. 10.8), [ToR 10], BR.

R7.2 Structural safety approvals, inspection, supervision, and certification should be carried out by engineers appropriately qualified and experienced as defined by the relevant professional body (i.e. The Institution of Engineers. Australia) (Set. 10.9), [ToR 10]. BR.

R7.3 Consideration should be given to establishment of a. national register of structural engineers complying with requirements under R7.2. The register should be recognized at all levels of government (Set. 10.9).

I.3.3.8 Quality In Design And Construction

C8 There is inadequate understanding at most levels in the building industry of the need to achieve high quality of construction. There is also inadequate appreciation at the unskilled and skilled trade level of the rationale for specific practices prescribed in building specifications. The problem appears to be particularly acute in relation to masonry construction, but is also of importance in concrete construction (Ch.5).

R8.1 The requirements of current Masonry Codes should be observed at all levels in the building industry for all forms of masonry construction [ToR 3. 4].

R8.2 Trade courses in masonry construction should be mandatory for bricklayers. Such courses should consider basic structural engineering aspects associated with masonry construction (e.g. an

overview of the requirements of. and reasons for, the principal requirements of masonry Codes) (Ch.5), [ToR 3. 4].

R8.3 Requirements generally similar to *VS* 2 for operatives in concrete construction [ToR 3, 4].

R8.4 Undergraduate programs in civil and in structural engineering should he encouraged to consider earthquake engineering, masonry construction, and quality management in their syllabi (Ch.5, 9.2). [ToR 3, 4].

I.3.3.9 Risk Management For Buildin gs

C9 Risk management for buildings may be uneven across building jurisdictions due to different policies, procedures and practices. This applies state-wide and nationally to building approvals, structural design, inspection and supervision and control of risk after construction (Set.9.5),

R9 It is recommended that the Building Regulation Review Task Force take note of this matter [ToR 10].

I.3.3.10 Industrial Facilities And Lifel ines

C10.1 Industrial facilities and lifelines generally suffered little structural damage and what there was is consistent with damage elsewhere in Newcastle. However, damage with potentially serious consequences was caused to mechanical and electrical equipment (Ch.7. 8).

C10.2 Underground facilities and mines appeared initially to have suffered little damage. Some damage is becoming evident but it is of a relatively minor nature to date. However, the full extent of damage is unlikely to be revealed for some time.

RIO All architects and engineers should be made aware that the need to design for earthquakes also applies to mechanical, electrical and other equipment [ToR 10. 11].

I.3.3.11 Counter-Disaster Aspects

Cll Counter-disaster agencies were able to handle the situation in Newcastle reasonably well, at least from the perspective of building and structural safety. However, it is considered that this may not necessarily have been the case had the damage and the concomitant loss of life and injuries been significantly greater. Further, sufficient structural engineering and earthquake engineering expertise was not immediately available (Ch.l, Set.9.6).

Rll-1 It is considered appropriate for counter-disaster agencies to study the Newcastle experience and to incorporate the findings in their counter-disaster plans (Set.9.6)

R11.2 Engineers and building inspectors should be attached to the State Emergency System, with the special function to perform initial emergency building appraisals in disaster areas (Set.9.6).

R11.3 The following should be established by the national or state counter-disaster systems: (i) guidelines for professional engineering and scientific input to various natural or other hazard scenarios, (ii) a national register or network of specialist engineering and scientific expertise available to counter-disaster organizations, and (iii) mechanisms to bring such expertise into action when required (Set. 9.6).

I.3.3.12 Demolition And Rebuilding

C12 Demolition and rebuilding commenced in Newcastle immediately after the earthquake. Some of the rebuilding is to unknown standard, although most probably conforms to building and structural standards in force prior to the earthquake.

R12 Uniform national policies and procedures need to be established at all levels of building jurisdiction and in conjunction with counter-disaster organizations for the control of demolition and rebuilding immediately after a disaster event (Set. 10.10), [ToR 10]. BR.

I.3.3.13 Insurance

C13.1 The Newcastle earthquake has exposed the insurance industry to significant claims in respect to property and consequential losses, greater than might have been expected on the basis of previous -experience in Australia. This is considered to be partly the result of past insurance practices (Set.9.5). It has also led to pressure on building owners to settle insurance claims quickly, despite some evidence of continuing damage (Ch.4).

C13.2 The degree of under-insurance in Newcastle was found to be significant but is considered to be not atypical for Australia generally. This has complicated insurance settlement and rebuilding and has, in some cases, led to repair of some buildings to suspect standards (Set.9.5).

R13.1 The insurance industry should be encouraged by government to consider realistic variables in setting premiums and levels of deductibles. This may require legislation. The variables which should be considered include at least: (i) geotechnical conditions at the insured site. (ii) building age, and (iii) structural condition of the property (Set. 10.8). NSW. AUS.

R13-2 The insurance industry should be encouraged to take a realistic attitude to the question of under-insurance and assist building owners in determining appropriate valuations. It should also review its settlement procedures in the light of the Newcastle experience.

I.3.3.14 Heritage Buildings And Issues

C14 The existence of earthquake-damaged old buildings in Newcastle led to time-consuming debate and discussion about heritage issues. This could have been avoided if policies and procedures had been available.

R14 Policies, guidelines and economic systems should be developed to allow prompt decisions with regard to the preservation of buildings with heritage (or potential heritage) classification (Set.10.7).

I.3.3.15 Further Work

C15 The present report has been completed with the information available at the time of writing. Further detailed studies are being undertaken by various organizations and individuals.

R15 It is recommended that the data collection and compilation programs and other studies being carried out by HOC, PWD. ACS and others continue to be supported by government,

The following abbreviations were used:

ACS Australian Construction Services

AUS Australian Government

BR Building Regulations

C Conclusion

Ch. Chapter

NCC Newcastle City Council

NSW Government of NSW

PWD Public Works Department

R Recommendation

SAA Standards Association of Australia

Set. Section of a Chapter

ToRTerms of Reference

I.3.4 Summary and Conclusions (page 43)

The following conclusions can be drawn from a study of the damage:

1) In general, modern buildings, both framed and loadbearing, behaved reasonably well. With a few exceptions, damage was confined to cladding and infill with the structural system carrying the earthquake forces satisfactorily.

The structural damage which did occur illustrated the desirability of symmetry in plan layout and the need to design for torsional effects on, and potential "soft storey" behaviour of the structure.

2) Most of the damage in modern structures occurred in masonry construction. In some cases this was exacerbated by poor standards of workmanship and construction, matters which need to be addressed by the masonry industry, educational institutions and others. The bulk of the damage could have been avoided by greater attention to detail with regard to tying and the transfer of horizontal forces between the frame and its cladding.

It is considered that the damage to the brittle components of modern construction would have been significantly less had some minimum horizontal capacity been provided. For brittle components, zone A of AS2121 has such a requirement.

3) The general evidence of poor standards of construction (particularly in masonry), indicates the need for the more effective implementation of current masonry codes for all forms of masonry construction at all levels of the building industry.

Trade courses in masonry should be mandatory for bricklayers, and such courses should consider the basic structural engineering aspects associated with masonry construction. In addition, undergraduate programs in Civil and Structural Engineering should be encouraged to consider earthquake engineering, masonry construction, and quality management in their syllabi.

4) Older buildings were more extensively damaged, mostly due to problems with both structural and non-structural masonry. Corrosion of wall ties was widespread, resulting in facade failure in many cases. This problem was exacerbated by inadequate placement of wall ties, soft and eroded lime mortar joints, bad workmanship and general deterioration. It is significant to note that irrespective of the earthquake zoning for Newcastle, implementation of AS2121 would not have prevented this damage, as all construction took place well before its publication.

5) The widespread incidence of wall tie corrosion has significant implications for all older masonry construction. There is a need for research into the durability of wall ties together with methods of detection and the economic replacement of corroded ties in existing buildings.

6) Parapets and suspended awnings were a major source of damage. Awnings collapsed because of inadequate anchorage of the steel tiebacks which were often attached only to the masonry facade. Since these types of detail appear to be widespread in Australia, there is an immediate need for a program to check the adequacy of these forms of construction wherever they have been used.

7) Damage to domestic structures was considerable, particularly for the older cavity brick structures. The more modern brick veneer houses performed better, although damage to the brick veneer was sometimes sustained. Timber houses exhibited the best performance, with relative movement between the more flexible timber structure and its footings or any adjoining brickwork being the main symptoms of distress.

It is clear from the extent of damage sustained by houses in Newcastle that there is a need for some minimum standards of earthquake resistant construction for housing. This is particularly the case for the more brittle form of cavity brick construction, which is still widely used in many parts of Australia.

It is considered desirable to develop a set of simple "deemed to comply" rules for domestic construction which could be applied at the planning and design stage. These rules could incorporate details for all forms of extreme loading, including earthquake. The cost per dwelling of incorporating these provisions should be negligible, as mainly attention to detail would be involved.

8) Some damage was the direct result of weakening of the structure due to structural alterations. To ensure that the structural integrity of the building is maintained, all alterations should be designed and supervised by an experienced structural engineer.

Newcastle Hospital as the principal public hospital in the Newcastle region. The hospital suffered only very minor structural damage, but considerable non-structural damage (e.g. racking of masonry infill panels) as described in Section 5.3.3.

There was also very considerable damage to mechanical plant and equipment, largely due to shifting off vibration isolation pads. For example, several of the air-conditioning units moved by as much as 250 mm. This caused damage to the attached ducting. Electrical wiring and piping attached to masonry infill panels were also damaged when the panels themselves were displaced and racked. The loss of such equipment and services could have had serious implications for an operational hospital.

I.3.4.1 6.5.5 Other Hospitals

Other hospitals in the Newcastle region, including; Western Suburbs, Belmont, Christo Road and Lingard Hospitals suffered no significant damage, and were all in a position to accept a limited number of patients if the need had arisen.

I.3.4.2 6.6 HALLS AND PLACES OF PUBLIC ASSEMBLY

School halls and auditoriums are often used as local emergency shelters in times of natural disasters. In general, all school halls survived the earthquake with no significant damage. The reason for this appears to be that most halls are of recent construction, and typically of an engineered steel or reinforced concrete framed design. The relatively favourable structural behaviour of the school halls was highlighted in some cases by the extensive damage caused to adjacent school classrooms, particularly those of older construction (see Set.5.4.5).

I.3.4.3 6.7 CONCLUSIONS AND RECOMMENDATIONS

Major structural and non-structural damage was sustained to several important buildings with a post-disaster function. Damage to hospitals, possibly the most important class of building with a post-disaster function, resulted in the closure of several wards, some temporary evacuations, and considerable (and possible life threatening) hindrance to their operations.

It is considered that the damage to fire, ambulance and hospital buildings would have been much greater if the earthquake had been of a moderately higher intensity or longer duration. The precise effect that this might have had on the operation of such facilities can only be speculated; it is considered that greater attention needs to be given to the risk level appropriate to this class of structure. Current SAA structural standards recognize post-disaster functions and make some allowance for this in setting design load levels for structural design. These standards should be reviewed in the light of the Newcastle earthquake. Consideration should also be given to a program of inspection and possibly upgrading of existing facilities (including mechanical and other equipment) to new earthquake and other hazard design standards.

I.3.4.4 7.6 CONCLUSION AND RECOMMENDATIONS (Page 63)

The greatest damage to industries, if the significant effects of power failure are ignored, resulted from cracking and, in some cases, collapse of masonry infill. Lack of adequate restraint to masonry from the supporting structure appears to account for most of this damage. It is clear that for building construction aspects the conclusions and recommendations of Chapter 5 apply here also.

There is a further aspect, however, and that is the design for hazards associated with an industrial facility (e.g. a chemical plant) as influenced by its structural system. The present SAA Earthquake Code (or other loading codes) does not address this situation.

Regarding plant and equipment, it would appear that the potential for loss of life, injuries and damage was far greater than the actual damage due to a number of fortuitous circumstances, not the least being the fact that the earthquake occurred during the Christmas-New Year holiday period when many plants are closed and not operational. It is considered that much of the (potential) damage could have been avoided if the requirements of AS2121 had been invoked using the lowest non-zero zoning (i.e. zone A) and if mechanical and other plant had been perceived as non-ductile elements. This aspect needs review in the current revision of the Earthquake Code. Further, mechanical and electrical engineers need to be alerted to the need to design for potential earthquake effects.

I.3.4.5 8.7 CONCLUSIONS AND RECOMMENDATIONS (Page 68)

In a sense Newcastle was fortunate that there was not greater damage to its lifelines. Such damage might have been expected when comparison is made to other earthquake events in other parts of the world. In making such comparisons it is important to recognize that the earthquake magnitude was relatively small by world standards. Nevertheless, it is considered that damage would have been significantly greater had the earthquake been of slightly greater intensity or longer duration or both. It is also likely that more damage will be revealed with time, particularly for lifelines on or buried in the ground.

It is considered likely that some of the damage, particularly that to mechanical and electrical equipment could have been prevented if a minimum earthquake design requirement had existed for such equipment. It is also important to note that mechanical and electrical engineers should be aware of the relevance of the Earthquake Code to plant and electrical equipment when considering building services. Further, it is recommended that where appropriate, lifeline systems be reviewed as to their capacity to with-stand low to moderate earthquake activity. In the case of buried services, it is unlikely that changes in design standards are required.

I.3.4.6 9.4 RISK MANAGEMENT IN STRUCTURAL ENGINEERING (Page 72)

The risk of failure of buildings and structures and hence the risk of death and injury for their users is controlled through a number of factors which together may be viewed as a risk management system for structures. The factors of importance are:

(i) the actual loads acting on the structure (including their magnitude, duration, frequency);

(ii) the strengths of the various materials of which buildings are constructed, including deterioration effects and any prior damage;

(iii) structural engineering design rules as laid down in building regulations and design codes;

(iv) the risk levels implicit in structural engineering design rules;

(v) interpretation of codes, conservatism in design and costs perceptions by design engineers;

(vi) inspection and checking processes during design and construction or subsequently;

(vii) quality management systems, including quality control, etc. during construction;

(viii) building maintenance procedures and practices;

(ix) insurance policies and practices;

(x) post-disaster safety measures.

The factors relating to earthquake levels, structural resistance and design codes will be addressed in detail in Chapter 10, as will related matters such as maintenance of building quality. Of the remaining matters, the principles, policies and the practices used for the implementation of building regulations and Australian Standards are of interest, as are insurance policies and practices (Set.9.5) and post-disaster measures (Set.9.6).

It is understood that an examination of building regulatory matters is within the scope of the Building Regulations Review Task Force established during 1989. Nevertheless, some brief observations will indicate areas of concern which it is considered are relevant to the structural safety of buildings and which are related to the present study.

1. It appears that each local authority and each state and federal authority with legislative responsibility for building approval can institute its own policies and procedures. Apart from any economic and administrative implications, this means that at the design stage structural risk management can be uneven across the various building jurisdictions.

2. Similarly, inspection and supervision during construction of buildings is the norm in all building jurisdictions, although local councils, at least, are not obliged to inspect, nor is there a minimum laid down. Further, the qualifications and expertise of persons carrying-out such inspections and supervision need not necessarily relate to assessment of structural safety. It follows that this aspect of building structural risk management can be very uneven across building jurisdictions.

3. Further, control of risk at later times, through management and inspection of the building or structure for continued safety, is not yet widely adopted, even in structural engineering generally. Exceptions are special structures such as bridges and floating structures (ships, offshore oilrigs etc.). However, inspection of buildings for continued safety is a feature in New Zealand and California in relation to safety of buildings under earthquake conditions. Some research into appropriate policies, practices and procedures for Australia would be useful in this area.

4. The standard of quality management during construction is a matter of considerable concern to many in the building industry. Its importance has become even clearer as a result of the Newcastle earthquake. Much of the widespread but mainly minor damage has been attributed to poor quality of construction (see Chapter 5). It is

considered that urgent attention should be given to means and procedures to enhance quality in building construction.

I.3.4.7 9.5 BUILDING INSURANCE

Risk management for buildings includes the aspect of insurance. If buildings of high risk are equally treated for insurance purposes as buildings of low risk, there is little incentive for owners or society to be concerned about building quality maintenance. The Newcastle earthquake could, and should, have an impact on insurance practices.

The cost of damage sustained in Newcastle is more than an order of magnitude larger than that of the 1954 Adelaide earthquake (of the order of 40-50 million dollars in today's values). The Newcastle losses are likely to be comparable to those of Cyclone Tracy and the 1983 Ash Wednesday bushfires. Based on this estimate, it is likely that most underwriting companies with a significant exposure in Newcastle will have exceeded their own exposure limits and will be depending on the international reinsurance industry to meet a proportion of the loss.

Previous estimates by the insurance companies of the probable maximum losses due to earthquake have been based on the Adelaide earthquake. However, since then the value of construction has increased in real terms at a greater rate than the population, the value of contents has increased relative to the building value and the insurance practice has changed from indemnity insurance being the most common to replacement insurance being the most common. As a result, exposure has increased dramatically and this, together with the possibility of an upward revision of earthquake occurrence risk estimates, is likely to have a significant effect on premiums and insurance practices. The Newcastle earthquake provides the insurance industry with a opportunity to improve the basis for estimating probable maximum losses. This should be done by rigorous analysis and should take account of variables such as geotechnical conditions, building age and quality of construction and condition at the time of the earthquake. If policy conditions, premium levels and deductible levels were to also take such variables into account, the insurance industry could play a significant long-term role in maintaining building standards.

One further issue the insurance industry needs to address is the question of under-insurance; the Newcastle experience has shown this to be a significant proportion (20-30% uninsured, about 40% under insured). Under the present system there is little guidance to building owners as to when they face the risk of under-insurance.

I.3.4.8 9.6 Counter-Disaster Measures

Counter-disaster measures and their management form a component of the overall management of building risk. The demolition of buildings very early after the earthquake event in Newcastle raised important questions about the effectiveness of the present counter-disaster systems in their capacity to assess buildings and their safety after a natural disaster. This issue is addressed in this Section.

The counter-disaster system consists of the Natural Disaster Organization and the Australian Counter Disaster College, State counter disaster organizations and locally-based groups of State Emergency Service volunteers. Planning for future major disasters takes place largely against a background of previous disasters such as bushfires, tropical cyclones and floods. The Newcastle earthquake was the first major earthquake disaster experienced within the lifetime of Australia's current counter disaster system. It was an event for which experience with the other major disasters was not necessarily a reasonable guide, particularly for three important aspects; (i) the fact that there is no warning of impending earthquake occurrence, (ii) that building safety needed to be considered, and (iii) the possibility of after-shocks.

As in other disaster situations, there was the need to rescue those trapped by collapsed structures, to clear away debris from the streets, to restore essential services, to provide relief to the injured and homeless and to make provision for the dead. There was the added problem that every building had to be considered potentially structurally unsafe until inspected and determined otherwise. Unsafe buildings or parts thereof need to be shored or otherwise rendered safe or the surrounding area barricaded to prevent entry. All of these operations should be considered hazardous in themselves due to the possibility of after-shocks.

There is no doubt that the situation in Newcastle was handled successfully by the available resources. However, the situation could have been considerably different had the earthquake occurred at a different time of day (see Ch.l) or had been of greater intensity or duration or had significant after-shocks occurred (Ch.3). As it was, the situation caused considerable stress to those involved on counter-disaster management. Structural engineering expertise was not immediately at hand, at least in the quantity required. The fact that earthquake engineering expertise exists in Australia was also not identified until much later. In view of these observations, it would be appropriate for counter-disaster organizations to study the Newcastle response and to incorporate the findings into their counter-disaster plans. It is submitted that such findings should have applications beyond earthquake events.

As a contribution to such a review, the following is recommended for consideration:

1. Involvement of building inspectors and engineers in the State Emergency Service system, with the special function to perform initial emergency building appraisal in disaster areas.
2. Establishment of guidelines for professional engineering input to various natural or other hazard scenarios, establishment of a national register of specialist engineering expertise available to counter-disaster organization and establishment of mechanisms to bring such expertise into play when required.

I.3.4.9 9.7 CONCLUSION

In this Chapter the question of overall risk and risk management in buildings and structural engineering was addressed. Several important issues were identified:

1. Risks, including earthquake risks, must be perceived to exist before rational decisions can be made about them. This requires education at various levels and appropriate framing of minimum design requirements.
2. If insufficient data about potential consequences are available, decisions about structural risks may need to be based on comparisons to other risks. However, allowance should still be made for building failures with potentially severe consequences (e.g. post-disaster structures, places of public assembly and buildings with hazardous operations or contents).
3. Risk management for buildings and structures has many components. Of particular concern are the regulations and standards themselves, the policies made to implement them, and the implementation of the policies in practice. All of these matters deserve attention and should be referred to the Building Regulations Review Task Force.
4. Building insurance practices have the potential to play a significant long-term role in quality and safety maintenance of buildings. Specific recommendations are made in Section 9.5.
5. Counter-disaster policies and practices should be reviewed in the light of the Newcastle earthquake. Some specific recommendations are made in Section 9.6.

I.3.4.10 10.10 DEMOLITION AND REBUILDING (Page 85)

Within days of the earthquake and even while the city was still barricaded, rebuilding work had commenced in Newcastle. Demolition was also in progress on various sites, even before any demolition the Newcastle City Council had issued permits. Almost without exception, building owners were keen to repair their buildings and continue with their lives. Such action has also been noted in the aftermath of the recent San Francisco earthquake. However, it raises the question whether it is sensible to repair to old standards and whether such construction in times of considerable stress on council officials can be properly controlled and inspected. There have been a number of reports of very poorly executed repairs and others of debatable standard.

There is no doubt that NOC can respond to this situation in due course and demand (perhaps partial) demolition or further repairs in the interest of public safety. However, this is an unsatisfactory way of proceeding and one likely to be unpopular (if only through lack of understanding of the issues involved). The real question is simply what should be the rules and requirements for rebuilding after a disastrous event and before interim rules for rebuilding (such as discussed in Set.10.2 above) can be properly formulated.

It is considered that this matter ought to be investigated by the existing counter-disaster organizations in conjunction with relevant state and federal departments responsible for building construction both at local government level and higher. Uniform national policies and procedures need to be developed so that these can be implemented by emergency services and building regulators in the immediate aftermath of a disaster.

I.3.4.11 10.11 CONCLUSION

This Chapter has been concerned with particular aspects and deficiencies of building regulations and standards which it is considered require attention.

The following are the principal points which were addressed:

1. Newcastle should be given an interim earthquake structural design requirement corresponding to zone A of AS2121-1979 except in alluvial and/or filled areas where it should be zone 1.

2. A minimum structural engineering design requirement for non-ductile construction should be specified for all parts of Australia. It is considered that this requirement should correspond to zone A of AS2121-1979, except for alluvium and/or filled areas where it should be zone 1.

3. The requirements for zones A and 1 should consider potentially unstable as well as brittle materials and should consider the need to design for structural forms potentially having undesirable earthquake response.

4. 'Deemed-to-comply' requirements corresponding in intent to the minimum earthquake structural design standards specified above should be developed for domestic construction. Research may be needed to make this feasible.

5. Existing building stock in Newcastle and elsewhere should be upgraded to the new earthquake zoning requirements only to the extent corresponding to building repairs, alterations, additions or usage changes. However, buildings, structures and facilities with special functions or dangerous features should be upgraded completely as soon as feasible (see Set.10.6).

6. Guidelines and economic systems should be developed for the preservation of heritage buildings.

7. Progress needs to be made on the issue of proper identification of engineers with appropriate qualifications and experience to carry out structural engineering work.

8. Uniform national policies and procedures need to be developed at all levels of building jurisdiction and in conjunction with counter disaster organizations for the control of demolition and rebuilding immediately after a disaster event and before considered interim guidelines can be given.

I.4 PWD Report Jan 199 2

Report prepared by:-

The Earthquake Reconstruction Project,

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Comments were received from other Public

Works staff notably:- J. Loke and J. Mak.

Particular acknowledgment is due to the many PWD staff and contractors who have contributed to this report by way of completing questionnaire forms.

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I.4.1 Foreward

The Newcastle earthquake is unique in Australian history. It is the first to result in loss of life and significant damage to a major urban centre.

There are many lessons which have been learnt from the experience, including those relating to building design, construction and maintenance.

The earth's crust is divided into large, slowly moving plates. Earthquakes are common at the boundaries of these plates. Cities in these regions typically have stringent building codes with allowance made for earthquake loads.

Attracting international attention, the Newcastle earthquake is seen as a reminder that earthquakes away from plate boundaries do occur. While less common than earthquakes at plate boundaries, they too can be very large in magnitude. Communities can be totally unprepared for such an event, as was seen in Newcastle.

While, in international terms, the Newcastle earthquake (at Richter Scale 5.6) was relatively small in magnitude, it is nevertheless significant. Analysis of this event is of wide-reaching interest.

"The Newcastle Earthquake had important implications to many areas of low seismicity such as the UK." (EEFIT). "We have to admit the possibility of a large quake coming out of nowhere". (Finkbeiner, USA). These papers and other studies discuss the need for retrofitting old buildings to improve earthquake resistance and for incorporating minimum detailing requirements into building codes.

Public Works has been involved with the inspection of over 1000 public buildings, which include structures of many different designs, materials, ages and methods of construction. A survey of 650 damaged State Government buildings was carried out during 1991 in the course of managing repair works.

It is the purpose of this report to present statistical data relating to these buildings, particularly in connection with key features which have been linked to earthquake vulnerability. The report briefly considers the implication of the Newcastle experience on the management of other State Government building stock.

The report consists of two parts:-

Volume I contains analysis and discussion of the data.

Volume II contains the original data collected in the survey.

Further information has been collected on other State Government properties (including undamaged buildings). It is expected that this will be incorporated into the database at a later date.

I.4.2 Executive Summary

In January 1990, Public Works established an earthquake project team in Newcastle. The team's dual role was to co-ordinate funding for the repair of State Government properties and to manage reconstruction programmes for various government departments. Funding was provided on a dollar-for-dollar basis by State and Federal Governments through the New South Wales Treasury Managed Fund.

Public Works has been involved with the inspection of over 1000 public buildings and the repair of over 600 State Government buildings.

The present report provides a brief overview of Public Works' role in the Newcastle recovery process. Funding conditions and the reconstruction process are described. The nature and scope of repair, strengthening and maintenance works are detailed.

This report presents statistical data relating to 650 damaged public buildings. The emphasis of the analysis is on key building features which have been linked to earthquake vulnerability.

The statistical analysis showed the following building properties were associated with higher than average levels of major, moderate and hazardous damage:

i) location within the Newcastle City Council area;

ii) ground foundations alluvium;

iii) building containing unreinforced masonry;

iv) storey height greater than one storey;

v) building age greater than 50 years;

vi) presence of parapets and gables on the building;

vii) in close proximity to ocean;

viii) building heritage listed.

It was quickly recognized that it would be unwise to simply replace - without upgrading - building elements damaged during the earthquake. As such, it was agreed that structural strengthening and maintenance to improve earthquake resistance, could be carried out under certain conditions.

As a result, much worthwhile improvement work has been undertaken. Some 120 buildings have benefited by the execution of strengthening works (such as tying gables to roof structures) and around 40 buildings have had structural maintenance work carried out (such as the replacement of brick ties).

'However, there have been many instances where the need for improvements has been identified but works have not been carried out because of non-compliance with the conditions of funding. In many cases buildings, although repaired, have not been examined for earthquake resistance because they were not significantly damaged in this particular event to be eligible for funding to carry out upgrading works.

The report recommends the establishment of an upgrading programme for public buildings to improve earthquake resistance. Studies to date indicate that buildings in the following categories are most in need of attention: high occupancy buildings; buildings with post-disaster functions; heritage listed buildings and buildings with elements inherently weak in earthquakes, such as parapets and chimneys.

The report identifies building elements particularly susceptible to deterioration and recommends that a systematic and ongoing structural maintenance programme be established.

The viewpoints of the Institution of Engineers, Australia and the Newcastle City Council regarding such a programme are provided for comparison.

I.5 The Centre for Earthq uake Research in Australia

FINAL REPORT ON EARTHQUAKE ZONATION MAPPING

OF THE CITY OF NEWCASTLE

NEW SOUTH WALES

FOR

NEWCASTLE CITY COUNCIL

COMPLIED BY

THE CENTRE FOR EARTHQUAKE RESEARCH IN AUSTRALIA

BRISBANE

MAY 1995

NEWZON NCC/CERA-IDNDR MAR95 JR

I.5.1 Acknowledgments

The Newcastle Earthquake Zonation Study has been realised through teamwork.

The Study team would like firstly to acknowledge the contribution made immediately after the 1989 earthquake by the Mayor, Alderman John McNaughton, the then head of Newcastle SES, the late Mr Don Geddes, the then Director of Health and Building Services, Mr Harold Stuart, and the Council and other officers of the City of Newcastle in their concern for the community with their later consideration to commission this Study.

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EMERGENCY MANAGEMENT AUSTRALIA AUSTRALIAN IDNDR COORDINATION COMMITTEE DESIGNATED AS

PROJECT 3/91: EARTHQUAKE ZONATION OF URBANISED AREAS IN AUSTRALIA PHASE 3 (1993-1994)

NEWZON NCC/CERA-IDNDR MAR95 JR

I.5.2 Executive Summary

I.5.2.1 1. The Project

The vulnerability of the City of Newcastle to severe earthquake damage was clearly evidenced in the 28 December 1989 Newcastle earthquake. It is most important that this project of earthquake zonation mapping of The City of Newcastle be undertaken in view of the knowledge gained from this 1989 earthquake, the now known history of major earthquakes and their consequent damage to the communities in the Newcastle-Hunter region and the information base that the 1989 Newcastle earthquake has given to both Australia and the international community at-large.

The 1989 Newcastle earthquake was the catalyst for a program of earthquake zonation mapping in Australia facilitated by Emergency Management Australia (EMA) under the United Nations International Decade for Natural Disaster Reduction (IDNDR) (1990-2000). The contribution of this earthquake zonation mapping to this international program has been sponsored and funded by the Newcastle City Council, and forms part of the 3rd Phase of the Project "Earthquake Zonation Mapping of Urban Areas in Australia".

I.5.2.2 2. Hazard Mitigation for Newcastle

The Report increases the awareness of the potential earthquake hazard in the region and so provides information for emergency management planning, local and state government, engineering, land-use planning and socio-economic programming. This information can be applied in a practical manner to assist in developing and implementing preparedness and mitigation plans and actions so as to reduce the potential losses from future earthquake occurrences. Earthquake zonation mapping is indeed a required necessity.

Earthquakes are the most devastating natural disaster known to human civilisation. Recent earthquakes on continents in urbanised areas; such as the 1989 Newcastle earthquake in Australia and those 1993 earthquakes in Okishura (Japan) and the 1995 Kobe earthquake in Japan, are further reminders of the potential havoc that can be caused. Australia is not immune from this natural phenomenon and must be prepared for future effects to the national community.

The potential earthquake effects assessed in this study are derived through a multi-disciplinary method. The approach is one of integrating the necessary research, technical information and experiences from the 1989 Newcastle and other devastating earthquakes worldwide, with the practical requirements of the user community - the emergency management authorities. The aspect of involving such authorities as active participants in the project, and not just as readers of a final report, is a necessity in such earthquake mitigation procedures. This has led to modifications to the methodology stages, in this case, specifically related to a single local government authority.

The City of Newcastle, Australia's sixth largest city, serves a vital socio-economic purpose for both its local region, the Hunter Valley, and the nation of Australia. The City contains all aspects of commerce and industry, including major steel manufacture plants, one of Australia's major export coal and primary produce ports, aluminium smelters, and associated industry and manufacturing, and thereby supports a significant domestic population and local infrastructure. Of vital importance is the awareness of emergency management to monitor sustainable development. The scope of any natural disaster, most particularly an earthquake, is clearly increasing as time goes on. The problems of both awareness to and preparedness for a potential earthquake disaster has now been addressed by the community through relevant, national, state and local programmes.

I.5.2.3 3. Community Vulnerability

The important issues relating to the vulnerability of community and it's facilities to earthquakes included:

(i) geological situation - e.g. surface soil types, active surface fault, or "blind" source; alluvial deposits; stone stability and landslides; terrain and topography.

(ii) built environment - e.g. age, type, style, construction and maintenance of engineered and non-engineered structures and surface underground infrastructure.

(iii) past earthquake history - not only for the local area or region but also for similar continental areas worldwide.

This Newcastle project illustrates the vital role played by geology, particularly the alluvial deposits in the coastal environment. The major damage caused in Newcastle was due to amplification, of the wave motion, in addition to poor building construction and maintenance and the lack of knowledge of any earthquake history relevant to the Hunter region prior to the 1989 occurrence.

Past earthquake experiences in the region and their relationship to geological structures, both on land and offshore, provide the basis for evaluating potential earthquake sources. This, together with both the existing and planned built environment for the region, dictates the expected vulnerability levels which can be prepared as generalised earthquake zonation especially also where located on alluvial sediments or in steep terrain. For this study, the mapping assessment is based on a Richter Magnitude ML 6.0 earthquake within a radius of 50 km of the Newcastle Central Business District (CBD). Ground motions leading to vulnerability levels for an expected earthquake of a particular magnitude can be scaled up or down, accordingly, using a known relationship for attenuation of earthquake energy with distance for Newcastle.

Areas of high vulnerability can expect damage levels to some buildings and infrastructure. particularly in the CBD, and areas of high urbanisation located on alluvial sediments. Some damage to underground infrastructure could also be expected.

Both of these were indeed the effects experienced in the 1989 Newcastle and previous historical earthquakes. With the extensive local knowledge gained in the response to and recovery phases of the 1989 earthquake, this Report provides the City of Newcastle with quantitative information source to further augment local emergency management and city planning procedures for the betterment of the community.

I.5.2.4 4. Recommendations

The implementation of such a Study and the Report thereof must be considered at the highest level possible to enable the community to receive the maximum benefit available. The following recommendations as ascertained from undertaking the Study should be implemented.

1. That the Newcastle City Council adopt the Report and the findings contained therein.

2. That the contents of the Report be used to develop future land use and strategic planning for the development of the City of Newcastle.

3 That the Newcastle and Hunter regional emergency service organisations, regional services and infrastructure provision agencies, and relevant state and federal government departments and agencies operating in Newcastle and Hunter regions use the findings of the Study to develop their future plans and management strategies, and

4. That a full Hunter regional earthquake zonation study should be recommended and undertaken to assess the earthquake vulnerability of the entire region, and to prepare regional planning strategies and management for all aspects of development in the Hunter region.

I.6 The Earth was Raised up in Waves Like the Sea … Earthquake Tremors Felt in the Hunter Valley Since White Settlement

Cynthia Hunter, 1991

I.6.1 Foreword

Earthquakes are not popularly associated with Australia. Students of geology are still taught that Australia is the quiet country, slowly drifting north astride the Australian plate at the speed of a growing fingernail. The occurrence of the Newcastle earthquake on 28 December 1989 has not dispelled this myth entirely. It was a relatively small earthquake, and the death toll low compared with the 655 000 reported deaths at Tangshan, China in 1976. And earthquakes were unheard of in the district... or were they? This book answers that question, and gives a fascinating insight into the people and their lifestyles over the past 150 years.

Cynthia Hunter's research has unearthed several reports of an earthquake that was felt only five months after the landing of the first fleet in Sydney Cove in 1788. I have had the pleasure of reading Governor Phillip's account of the earthquake in his original letter to Lord Sydney, now held at the UK Public Records Office in London. Some 50 years later in 1837, the first European settlers in Adelaide felt the ground shake for 20 seconds during a local earthquake. Adelaide has the dubious distinction of being the first Australian city to suffer significant earthquake damage, as a result of a magnitude 5.5 earthquake close to the city on 1 March 1954. In the Adelaide city area, chimneys and parapets in older buildings collapsed and cracks appeared in walls of old domestic brick and stone dwellings. The 1989 Newcastle earthquake affected similar types of buildings but far more severely.

One of the world's first seismographic stations was established at California's Lick Observatory in 1883; five years later the first Australian seismograph was installed at Sydney Observatory. These early instruments were very insensitive, recording only large or very close moderate sized earthquakes. Sometimes, the only clue that an earthquake had occurred was when it was reported in the press by someone who had felt it. Newspaper accounts are often the only record of Australia's pre 1960 earthquakes, and finding them requires dedicated and diligent research. Adequate monitoring was lacking until the early 1960s, when the Commonwealth Government's Bureau of Mineral Resources undertook to install a network of seismographs in Australia to monitor both local and worldwide earth-quakes.

Cynthia Hunter's book is a scholarly historical study of the early earthquakes felt in the Hunter region. It will interest seismologists as well as the general reader. Isoseismal maps show the distribution and intensity of shaking. They can be compiled where there are enough reports, as there have been for the 1989 Newcastle earthquake, and the resultant map is reprinted in the book. From such maps the earthquake's magnitude, epicentre and approximate focal depth can be inferred. Cynthia Hunter's research is already enabling seismologists to make a more educated analysis of the seismic risk in Newcastle than was previously possible. The benefits of this research will flow on to engineering standards and the Australian Building Code and therefore the wider community.

The book is stimulating reading for anyone interested in Australian history, in the evolution of building styles and material, colourful settlers, visiting explorers and notorious bushrangers. The Newcastle earthquake showed that similar studies of early earthquake history should be undertaken in each Australian city, so that better risk assessment improves the safety and well being of our population. It should be compulsory reading for all town planners.

Kevin McCue

Australian Seismological Centre

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I.6.2 Preface

In December 1989 the Hunter Valley community was paid an unwelcome visit by a fatal and destructive earthquake. At the time, popular knowledge about previous quakes in the Valley was almost non-existent. As a student of regional history, I was prompted to recall descriptions of early nineteenth century quakes amongst my research material. These interesting old records assumed a new relevance after the December 1989 earthquake. Copies of them were forwarded to the media and a few of the seismological research centres which had responded so unreservedly to the predicament in which Newcastle was unexpectedly placed. Dr Jack Rynn, Research Fellow (Seismology) at the University of Queensland, encouraged me to undertake what proved to be a fruitful paper-chase through old scientific journals, books and newspapers to locate as complete a record as possible of past tremors. The results of this search form the basis of a retrospective study of earthquake activity in the Valley (Rynn, J. M. W. and Hunter, C., The Historical Records of Earthquake Activity in the Newcastle and Lower Hunter Valley Regions, New South Wales, 1990 (in preparation)). Additionally, this research has enabled me to compile the following narrative of past Hunter Valley earth tremors. Earthquakes are not merely geological events of time and place, but are episodes of human experience; written accounts of them reflect the nature of the society which they disturb so alarmingly.

Cynthia Hunter

June 1991

I.6.3 1989

A bad earthquake at once destroys the oldest associations: the world the very emblem of all that is solid, has moved beneath our feet... one second of time has conveyed to the mind a strange idea of insecurity, which hours of reflection would never have created.

Charles Darwin. Journal of Researches into the Geology and Natural History of the Various Countries visited by HMS Beagle from 1832 to 1836. *1839, p369.*

On 28 December 1989 at 10.27 a.m. an earthquake was felt over much of eastern New South Wales stretching south to Batemans Bay, north to Armidale and west to Dubbo. This earthquake was unlike any other in Australia's history because the convulsion released its tremendous energy beneath a principal city and its nearby suburbs. Falling shop awnings and the collapse of part of a major public venue killed twelve and injured about a hundred and sixty citizens. The cost for insurance companies to satisfy earthquake-related property damage claims will eventually be computed. The complexity of managing the crisis precipitated by the quake, and the inventory - will it ever be completed? - of the devastation attributable to it, reveal the vulnerability of a populous and technology-dependent urban area. Every facet of damage has opened a window on some aspect of almost 190 years of settlement, reminding us that the Hunter Valley was occupied for the exploitation of resources, and that the subjugation by Europeans of the wide, silty estuary was always conditional; in the past, great floods have told us that.

Telex services and telephones cast forth news of the earthquake, and full-colour, moving images of the havoc were almost instantaneously transmitted by satellite to media databases around the world. Over the following months the procedures and terminology of insurance services became commonplace in the Hunter Valley community. The quake was Australia's largest insurance loss.

Following the Newcastle and district earthquake most people wondered why the convulsion was as great a shock to the store of knowledge in our heads as it was to the earth and buildings thereon. What was immediately apparent was that some pages were missing from our history books! Not even trivial anecdotes remained in folklore. It was as if a selective process had been at work, excluding all references to earth tremors from oral and written histories, culling out observations that earthquake risk, although slight, was possible, and overlooking the fact that minor tremors had played a small role in our recorded past. Did Australian geology lose part of its memory when Reverend Clarke's research papers were consumed by fire? If Professor Cotton had published his analysis of the 1925 quake, would we have been more aware? Did the repeated assurances that 'there was no cause for alarm', so kindly given in the past by those whose expertise was sought by journalists and frightened citizens, unwittingly divert our attention from the earth's explicit messages?

Only one Hunter Valley historian, Henry William Hemsworth Huntington, included the occurrence of earthquakes in his writing. In 1897, when the people of the Newcastle region were preparing to celebrate the centenary of John Shortland's discovery of the entrance to Hunters River, Huntington wrote a History of Newcastle and the Northern Districts in one hundred parts. The episodes were printed regularly in the Newcastle Morning Herald from August 1897 to August 1898, the final one dealt with events of the 1840s.

Part 27 continued a lengthy review of the first survey of the mouth of the Hunter River undertaken in 1801. Under a sub-heading entitled 'Earthquakes in Newcastle District in 1801' Huntington wrote:

Among the most remarkable events in the early history of the northern district were two smart shocks of earthquakes in 1801. The writer has before him a long list of earthquakes throughout the colony, many of which were felt by the colonists of the northern district.

After a brief discourse on earthquakes, volcanoes and geological phenomena of the Hunter district, Huntington quoted from the journal of Mr David D Mann and other records in his possession which indicated that two tremors were felt at Newcastle in 1801. He also noted that 'after a careful examination of this subject of earthquakes, the writer has found that most earthquake shocks taking place simultaneously at the Hawkesbury and Parramatta extend their phenomena to the Hunter.'

Part 45 of the History described district events in 1804, including the visitation of an earthquake shock. Part 48 recorded the earthquake at the Upper Hunter in 1806.

Part 93 is entitled 'Newcastle Earthquakes in 1829,1837, and 1841'. The sources to which Huntington referred for his account of these quakes appear to be the 1859 Sydney Magazine of Science and Arts, contemporary newspapers, and the journals of Reverend Alfred Glennie.

A copy of Huntington's work has been in my possession for some years. I also held a copy of Dr McKinlay's letter describing the 1841 earthquake, not because of a concern about earthquakes, but because of an interest in the life of Dr McKinlay, a significant pioneer of the Williams River district. After the quake of December 1989 these documents provided the stimulus to assemble this record of tremors and quakes as they shook the Hunter Valley and its inhabitants from the earliest days of settlement. It is not claimed to be complete. Additional quakes, perceptible by human sensitivity, may be retrieved from written records by other researchers. The sum total should be a more complete understanding of our natural and social history,

In the last few decades, equipment for detecting and measuring seismic disturbance has become increasingly sophisticated and centres for research are compiling ever-expanding catalogues and up-to-date articles for publication at home and abroad. A special Seismological Society was founded in New South Wales in 1973. No one can yet predict when a quake may occur and the practical safeguards of today are the same as ever before: to build structures which can keep standing and allow the waves to pass, doing physical harm to as few people as possible, then to build again, drawing on the indomitable spirit which enables life to exist on the surface of an unquiet earth.

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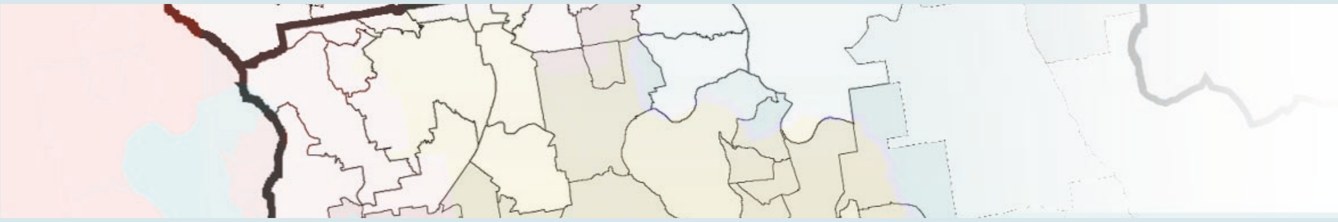

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